Annex 1

E. N. Foote, "Circumstances affecting the Heat of the Sun's Rays", *American Journal of Science and Arts,* 1856, pp. 382-383

Art. XXXI.—*Circumstances affecting the Heat of the Sun's Rays;* by Eunice Foote.

(Read before the American Association, August 23d, 1856.)

My investigations have had for their object to determine the different circumstances that affect the thermal action of the rays of light that proceed from the sun.

Several results have been obtained.

First. The action increases with the density of the air, and is diminished as it becomes more rarified.

The experiments were made with an air-pump and two cylindrical receivers of the same size, about four inches in diameter and thirty in length. In each were placed two thermometers, and the air was exhausted from one and condensed in the other. After both had acquired the same temperature they were placed in the sun, side by side, and while the action of the sun's rays rose to 110° in the condensed tube, it attained only 88° in the other. I had no means at hand of measuring the degree of condensation or rarefaction.

The observations taken once in two or three minutes, were as follows:

Exhausted Tube		Condensed Tube.	
In shade.	In sun.	In shade.	In sun.
75	80	75	80
76	82	78	95
80	82	80	100
83	86	82	105
84	88	85	110

This circumstance must affect the power of the sun's rays in different places, and contribute to produce their feeble action on the summits of lofty mountains.

Secondly. The action of the sun's rays was found to be greater in moist than in dry air.

In one of the receivers the air was saturated with moisture—in the other it was dried by the use of chlorid of calcium.

Both were placed in the sun as before and the result was as follows:

Dry Air.		Damp Air.	
In shade.	In sun.	In shade.	In sun.
75	75	75	75
78	88	78	90
82	102	82	106
82	104	82	110
82	105	82	114
88	108	92	120

The high temperature of moist air has frequently been observed. Who has not experienced the burning heat of the sun that precedes a summer's shower? The isothermal lines will, I think, be found to be much affected by the different degrees of moisture in different places.

Thirdly. The highest effect of the sun's rays I have found to be in carbonic acid gas.

One of the receivers was filled with it, the other with common air, and the result was as follows:

In Common Air.		In Carbonic Acid Gas.	
In shade.	In sun.	In shade.	In sun.
80	90	80	90
81	94	84	100
80	99	84	110
81	100	85	120

The receiver containing the gas became itself much heated—very sensibly more so than the other—and on being removed, it was many times as long in cooling.

An atmosphere of that gas would give to our earth a high temperature; and if as some suppose, at one period of its history the air had mixed with it a larger proportion than at present, an increased temperature from its own action as well as from increased weight must have necessarily resulted.

On comparing the sun's heat in different gases, I found it to be in hydrogen gas, 104°; in common air, 106°; in oxygen gas, 108°; and in carbonic acid gas, 125°.

ART. XXXII.—*Review of a portion of the Geological Map of the United States and British Provinces by Jules Marcou;** by WILLIAM P. BLAKE.

GEOLOGICAL maps of the United States published in Europe and widely circulated among European geologists, are necessarily regarded by us with no small degree of attention and curiosity. This is more especially true, when such maps embrace regions of which the geography has only recently been made known and the geology has never before been laid down on a map with any approach to accuracy.

The recent geological map and profile by M. J. Marcou, which has appeared in the Annales des Mines and in the Bulletin of

* Carte Géologique des Etats-Unis et des Provinces Anglaises de l'Amérique du Nord par Jules Marcou. *Annales des Mines*, 5e Série, T. vii, p. 329. Published also with the following:

Résumé explicatif d'une carte géologique des Etats-Unis et des provinces anglaises de l'Amérique du Nord, avec un profil géologique allant de la vallée du Mississippi aux côtes du Pacifique, et une planche de fossiles, par M. Jules Marcou *Bulletin de la Société Géologique de France.* Mai, 1855, p. 813.

Annex 2

J. Tyndall, “On the Absorption and Radiation of Heat by Gases and Vapours, and on the Physical Connexion of Radiation, Absorption, and Conduction”, *Philosophical Transactions of the Royal Society of London,* 1861, pp. 1-36, pages 1, 28-29

PHILOSOPHICAL TRANSACTIONS.

I. The Bakerian Lecture.—*On the Absorption and Radiation of Heat by Gases and Vapours, and on the Physical Connexion of Radiation, Absorption, and Conduction.* *By* John Tyndall, *Esq., F.R.S., Member of the Academies and Societies of Holland, Geneva, Göttingen, Zürich, Halle, Marburg, Breslau, la Société Philomathique of Paris, &c.; Professor of Natural Philosophy in the Royal Institution, and in the Government School of Mines.*

Received January 10,—Read February 7, 1861.

§ 1.

The researches on glaciers which I have had the honour of submitting from time to time to the notice of the Royal Society, directed my attention in a special manner to the observations and speculations of De Saussure, Fourier, M. Pouillet, and Mr. Hopkins, on the transmission of solar and terrestrial heat through the earth's atmosphere. This gave practical effect to a desire which I had previously entertained to make the mutual action of radiant heat and gases of all kinds the subject of an experimental inquiry.

Our acquaintance with this department of Physics is exceedingly limited. So far as my knowledge extends, the literature of the subject may be stated in a few words.

From experiments with his admirable thermo-electric apparatus, Melloni inferred that for a distance of 18 or 20 feet the absorption of radiant heat by atmospheric air is perfectly insensible*.

With a delicate apparatus of the same kind, Dr. Franz of Berlin found that the air contained in a tube 3 feet long absorbed 3·54 per cent. of the heat sent through it from an Argand lamp; that is to say, calling the number of rays which passed through the exhausted tube 100, the number which passed when the tube was filled with air was only 96·46†.

In the sequel I shall refer to circumstances which induce me to conclude that the

* La Thermochrose, p. 136.

† Poggendorff's Annalen, vol. xciv. p. 342.

being due to the cooling of the plate and not to absorption. It is also certain that had I used heat from a luminous source, I should have found the absorption of 0·33 per cent. considerably diminished.

§ 8.

I have now to refer briefly to a point of considerable interest as regards the effect of our atmosphere on solar and terrestrial heat. In examining the separate effects of the air, carbonic acid, and aqueous vapour of the atmosphere on the 20th of last November, the following results were obtained:—

Air sent through the system of drying tubes and through the caustic potash tube produced an absorption of about

1.

Air direct from the laboratory, containing therefore its carbonic acid* and aqueous vapour, produced an absorption of

15.

Deducting the effect of the gaseous acids, it was found that the quantity of aqueous vapour diffused through the atmosphere on the day in question, produced an absorption at least equal to thirteen times that of the atmosphere itself.

It is my intention to repeat and extend these experiments on a future occasion†; but even at present conclusions of great importance may be drawn from them. It is exceedingly probable that the absorption of the solar rays by the atmosphere, as established by M. Pouillet, is mainly due to the watery vapour contained in the air. The vast difference between the temperature of the sun at midday and in the evening, is also probably due in the main to that comparatively shallow stratum of aqueous vapour which lies close to the earth. At noon the depth of it pierced by the sunbeams is very small; in the evening very great in comparison.

The intense heat of the sun's direct rays on high mountains is not, I believe, due to his beams having to penetrate only a small depth of air, but to the comparative absence of aqueous vapour at those great elevations.

But this aqueous vapour, which exercises such a destructive action on the obscure rays, is comparatively transparent to the rays of light. Hence the differential action, as regards the heat coming from the sun to the earth, and that radiated from the earth into space, is vastly augmented by the aqueous vapour of the atmosphere.

De Saussure, Fourier, M. Pouillet, and Mr. Hopkins regard this interception of the terrestrial rays as exercising the most important influence on climate. Now if, as the above experiments indicate, the chief influence be exercised by the aqueous vapour, every variation of this constituent must produce a change of climate. Similar remarks would apply to the carbonic acid diffused through the air; while an almost inappreciable admixture of any of the hydrocarbon vapours would produce great effects on the terrestrial rays and produce corresponding changes of climate. It is not therefore necessary

* And a portion of sulphurous acid produced by the two gas-lamps used to heat the cubes.

† The peculiarities of the locality in which this experiment was made render its repetition under other circumstances necessary.

to assume alterations in the density and height of the atmosphere, to account for different amounts of heat being preserved to the earth at different times; a slight change in its variable constituents would suffice for this. Such changes in fact may have produced all the mutations of climate which the researches of geologists reveal. However this may be, the facts above cited remain; they constitute true causes, the *extent* alone of the operation remaining doubtful.

The measurements recorded in the foregoing pages constitute only a fraction of those actually made; but they fulfil the object of the present portion of the inquiry. They establish the existence of enormous differences among colourless gases and vapours as to their action upon radiant heat; and they also show, that when the quantities are sufficiently small, the absorption in the case of each particular vapour is exactly proportional to the density.

These experiments furnish us with purer cases of molecular action than have been hitherto attained in experiments of this nature. In both solids and liquids the cohesion of the particles is implicated; they mutually control and limit each other. A certain action over and above that which belongs to them separately, comes into play and embarrasses our conceptions. But in the cases above recorded the molecules are perfectly free, and we fix upon them individually the effects which the experiments exhibit. Thus the mind's eye is directed more firmly than ever on those distinctive physical qualities whereby a ray of heat is stopped by one molecule and unimpeded by another.

§ 9. *Radiation of Heat by Gases.*

It is known that the quantity of light emitted by a flame depends chiefly on the incandescence of solid matter; the brightness of an ignited jet of ordinary gas, for example, being chiefly due to the solid particles of carbon liberated in the flame.

Melloni drew a parallel between this action and that of radiant heat. He found the radiation from his alcohol lamp greatly augmented by plunging a spiral of platinum wire into the flame. He also found that a bundle of wire placed in the current of hot air ascending from an argand chimney gave a copious radiation, while when the wire was withdrawn no trace of radiant heat could be detected by his apparatus. He concluded from this experiment that air possesses the power of radiation in so feeble a degree, that our best thermoscopic instruments fail to detect this power*.

These are the only experiments hitherto published upon this subject; and I have now to record those which have been made in connexion with the present inquiry. The pile furnished with its conical reflector was placed upon a stand, with a screen of polished tin in front of it. An alcohol lamp was placed behind the screen, so that its flame was entirely hidden by the latter; on rising above the screen, the gaseous column radiated its heat against the pile and produced a considerable deflection. The same effect was produced when a candle or an ordinary jet of gas was substituted for the alcohol lamp.

* La Thermochrose, p. 94.

Annex 3

S. Arrhenius, “On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground”, *Philosophical Magazine and Journal of Science,* 1896, pp. 237-276, pages 237, 254-267

THE

LONDON, EDINBURGH, AND DUBLIN

PHILOSOPHICAL MAGAZINE

AND

JOURNAL OF SCIENCE.

[FIFTH SERIES.]

APRIL 1896.

XXXI. *On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground.* *By* Prof. SVANTE ARRHENIUS *.

I. *Introduction* : *Observations of* Langley *on Atmospherical Absorption.*

A GREAT deal has been written on the influence of the absorption of the atmosphere upon the climate. Tyndall † in particular has pointed out the enormous importance of this question. To him it was chiefly the diurnal and annual variations of the temperature that were lessened by this circumstance. Another side of the question, that has long attracted the attention of physicists, is this : Is the mean temperature of the ground in any way influenced by the presence of heat-absorbing gases in the atmosphere? Fourier‡ maintained that the atmosphere acts like the glass of a hot-house, because it lets through the light rays of the sun but retains the dark rays from the ground. This idea was elaborated by Pouillet § ; and Langley was by some of his researches led to the view, that "the temperature of the earth under direct sunshine, even though our atmosphere were present as now, would probably fall to −200° C., if that atmosphere did not possess the quality of selective

* Extract from a paper presented to the Royal Swedish Academy of Sciences, 11th December, 1895. Communicated by the Author.

† 'Heat a Mode of Motion,' 2nd ed. p. 405 (Lond., 1865).

‡ *Mém. de l'Ac. R. d. Sci. de l'Inst. de France*, t. vii. 1827.

§ *Comptes rendus*, t. vii. p. 41 (1838).

III. *Thermal Equilibrium on the Surface and in the Atmosphere of the Earth.*

As we now have a sufficient knowledge of the absorption of heat by the atmosphere, it remains to examine how the temperature of the ground depends on the absorptive power of the air. Such an investigation has been already performed by Pouillet*, but it must be made anew, for Pouillet used hypotheses that are not in agreement with our present knowledge.

In our deductions we will assume that the heat that is conducted from the interior of the earth to its surface may be wholly neglected. If a change occurs in the temperature of the earth's surface, the upper layers of the earth's crust will evidently also change their temperature; but this later process will pass away in a very short time in comparison with the time that is necessary for the alteration of the surface temperature, so that at any time the heat that is transported from the interior to the surface (positive in the winter, negative in the summer) must remain independent of the small secular variations of the surface temperature, and in the course of a year be very nearly equal to zero.

Likewise we will suppose that the heat that is conducted to a given place on the earth's surface or in the atmosphere in consequence of atmospheric or oceanic currents, horizontal or vertical, remains the same in the course of the time considered, and we will also suppose that the clouded part of the sky remains unchanged. It is only the variation of the temperature with the transparency of the air that we shall examine.

All authors agree in the view that there prevails an equilibrium in the temperature of the earth and of its atmosphere. The atmosphere must, therefore, radiate as much heat to space as it gains partly through the absorption of the sun's rays, partly through the radiation from the hotter surface of the earth and by means of ascending currents of air heated by contact with the ground. On the other hand, the earth loses just as much heat by radiation to space and to the atmosphere as it gains by absorption of the sun's rays. If we consider a given place in the atmosphere or on the ground, we must also take into consideration the quantities of heat that are carried to this place by means of oceanic or atmospheric currents. For the radiation we will suppose that

* Pouillet, *Comptes rendus*, t. vii. p. 41 (1838).

Stefan's law of radiation, which is now generally accepted, holds good, or in other words that the quantity of heat (W) that radiates from a body of the albedo $(1-\nu)$ and temperature T (absolute) to another body of the absorption-coefficient β and absolute temperature θ is

$$W=\nu\beta\gamma(T^4-\theta^4),$$

where γ is the so-called radiation constant ($1{\cdot}21\,.\,10^{-12}$ per sec. and cm.^{2}). Empty space may be regarded as having the absolute temperature 0*.

Provisionally we regard the air as a uniform envelope of the temperature θ and the absorption-coefficient α for solar heat; so that if A calories arrive from the sun in a column of 1 cm.^{2} cross-section, αA are absorbed by the atmosphere and $(1-\alpha)$A reach the earth's surface. In the A calories there is, therefore, not included that part of the sun's heat which by means of selective reflexion in the atmosphere is thrown out towards space. Further, let β designate the absorption-coefficient of the air for the heat that radiates from the earth's surface; β is also the emission-coefficient of the air for radiation of low temperature—strictly 15°; but as the spectral distribution of the heat varies rather slowly with the temperature, β may be looked on as the emission-coefficient also at the temperature of the air. Let the albedo of the earth's crust be designated by $(1-\nu)$, and the quantities of heat that are conveyed to the air and to the earth's surface at the point considered be M and N respectively. As unit of time we may take any period: the best choice in the following calculation is perhaps to take three months for this purpose. As unit of surface we may take 1 cm.^{2}, and for the heat in the air that contained in a column of 1 cm.^{2} cross-section and the height of the atmosphere. The heat that is reflected from the ground is not appreciably absorbed by the air (see p. 252), for it has previously traversed great quantities of water-vapour and carbonic acid, but a part of it may be returned to the ground by means of diffuse reflexion. Let this part not be included in the albedo $(1-\nu)$. γ, A, ν, M, N, and α are to be considered as constants, β as the independent, and θ and T as the dependent variables.

Then we find for the column of air

$$\beta\gamma\theta^4=\beta\gamma\nu(T^4-\theta^4)+\alpha A+M. \quad . \quad . \quad . \quad (1)$$

The first member of this equation represents the heat

* Langley, 'Prof. Papers,' No. 15, p. 122. "The Temperature of the Moon," p. 206.

radiated from the air (emission-coefficient β, temperature θ) to space (temperature 0). The second one gives the heat radiated from the soil (1 cm.^{2}, temperature T, albedo $1-\nu$) to the air; the third and fourth give the amount of the sun's radiation absorbed by the air, and the quantity of heat obtained by conduction (air-currents) from other parts of the air or from the ground. In the same manner we find for the earth's surface

$$\beta\gamma\nu(T^4-\theta^4)+(1-\beta)\gamma\nu T^4=(1-\alpha)\nu A+N. \quad . \quad (2)$$

The first and second members represent the radiated quantities of heat that go to the air and to space respectively, $(1-\alpha)\nu A$ is the part of the sun's radiation absorbed, and N the heat conducted to the point considered from other parts of the soil or from the air by means of water- or air-currents.

Combining both these equations for the elimination of θ, which has no considerable interest, we find for T^4

$$T^4=\frac{\alpha A+M+(1-\alpha)A(1+\nu)+N(1+1/\nu)}{\gamma(1+\nu-\beta\nu)}=\frac{K}{1+\nu(1-\beta)}. \quad (3)$$

For the earth's solid crust we may, without sensible error, put ν equal to 1, if we except the snowfields, for which we assume $\nu=0{\cdot}5$. For the water-covered parts of the earth I have calculated the mean value of ν to be 0·925 by aid of the figures of Zenker*. We have, also, in the following to make use of the albedo of the clouds. I do not know if this has ever been measured, but it probably does not differ very much from that of fresh fallen snow, which Zöllner has determined to be 0·78, *i. e.* $\nu=0{\cdot}22$. For old snow the albedo is much less or ν much greater; therefore we have assumed 0·5 as a mean value.

The last formula shows that the temperature of the earth augments with β, and the more rapidly the greater ν is. For an increase of 1° if $\nu=1$ we find the following increases for the values of $\nu=0{\cdot}925$, 0·5, and 0·22 respectively:—

β.	$\nu=0{\cdot}925$.	$\nu=0{\cdot}5$.	$\nu=0{\cdot}22$.
0·65	0·944	0·575	0·275
0·75	0·940	0·556	0·261
0·85	0·934	0 535	0·245
0·95	0·928	0·512	0·228
1·00	0·925	0·500	0·220

This reasoning holds good if the part of the earth's surface

* Zenker, *Die Vertheilung der Wärme auf der Erdoberfläche*, p. 54 (Berlin, 1888).

considered does not alter its albedo as a consequence of the altered temperature. In that case entirely different circumstances enter. If, for instance, an element of the surface which is not now snow-covered, in consequence of falling temperature becomes clothed with snow, we must in the last formula not only alter β but also ν. In this case we must remember that α is very small compared to β. For α we will choose the value 0·40 in accordance with Langley's* estimate. Certainly a great part of this value depends upon the diffusely reflected part of the sun's heat, which is absorbed by the earth's atmosphere, and therefore should not be included in α, as we have defined it above. On the other hand, the sun may in general stand a little lower than in Langley's measurements, which were executed with a relatively high sun, and in consequence of this α may be a little greater, so that these circumstances may compensate each other. For β we will choose the value 0·70, which corresponds when K = 1 and W = 0·3 (a little below the freezing-point) with the factor 1·66 (see p. 253). In this case we find the relation between T (uncovered) and T_1 (snow-covered surface) to be

$$T^4 : T_1^4 = \frac{A(1+1-0{\cdot}40)+M}{\gamma(1+1-0{\cdot}70)} : \frac{A(1+0{\cdot}50-0{\cdot}20)+M}{\gamma(1+0{\cdot}50-0{\cdot}35)} = \frac{1{\cdot}60+\phi}{1{\cdot}30} : \frac{1{\cdot}30+\phi}{1{\cdot}15},$$

if $M = \phi A$. We have to bear in mind that the mean M for the whole earth is zero, for the equatorial regions negative and for the polar regions positive. For a mean latitude M = 0, and in this case T_1 becomes 267·3 if T = 273, that is the temperature decreases in consequence of the snow-covering by 5°·7 C.† The decrease of temperature from this cause will be valid until $\phi = 1$, *i. e.* till the heat delivered by convection to the air exceeds the whole radiation of the sun. This can only occur in the winter and in polar regions.

But this is a secondary phenomenon. The chief effect that we examine is the direct influence of an alteration of β upon the temperature T of the earth's surface. If we start from a value T = 273 and $\beta = 0{\cdot}70$, we find the alteration (t) in the

* Langley, "Temperature of the Moon," p. 189. On p. 197 he estimates a to be only 0·33.

† According to the correction introduced in the sequel for the different heights of the absorbing and radiating layers of the atmosphere, the number 5°·7 is reduced to 4°·0. But as about half the sky is cloud-covered, the effect will be only half as great as for cloudless sky, *i. e.* the mean effect will be a lowering of about 2° C.

temperature which is caused by the variation of β to the following values to be

$\beta = 0{\cdot}60$	$t = -\ 5°$ C.
0·80	$+\ 5{\cdot}6$
0·90	$+11{\cdot}7$
1·00	$+18{\cdot}6$.

These values are calculated for $\nu = 1$, *i. e.* for the solid crust of the earth's surface, except the snowfields. For surfaces with another value of ν, as for instance the ocean or the snowfields, we have to multiply this value t by a fraction given above.

We have now shortly to consider the influence of the clouds. A great part of the earth's surface receives no heat directly from the sun, because the sun's rays are stopped by clouds. How great a part of the earth's surface is covered by clouds we may find from Teisserenc de Bort's work * on Nebulosity. From tab. 17 of this publication I have determined the mean nebulosity for different latitudes, and found:—

Latitude..	60.	45.	30.	15.	0.	−15.	−30.	−45.	−60.
Nebulosity.	0·603	0·48	0·402	0·511	0·581	0·463	0·53	0·701	

For the part of the earth between 60° S. and 60° N. we find the mean value 0·525, *i. e.* 52·5 per cent. of the sky is clouded. The heat-effect of these clouds may be estimated in the following manner. Suppose a cloud lies over a part of the earth's surface and that no connexion exists between this shadowed part and the neighbouring parts, then a thermal equilibrium will exist between the temperature of the cloud and of the underlying ground. They will radiate to each other and the cloud also to the upper air and to space, and the radiation between cloud and earth may, on account of the slight difference of temperature, be taken as proportional to this difference. Other exchanges of heat by means of air-currents are also, as a first approximation, proportional to this difference. If we therefore suppose the temperature of the cloud to alter (other circumstances, as its height and composition, remaining unchanged), the temperature of the ground under it must also alter in the same manner if the same supply of heat to both subsists—if there were no supply to the ground from neighbouring parts, the cloud and the ground would finally assume the same mean temperature. If, therefore, the temperature of the clouds varies in a determined manner

* Teisserenc de Bort, "Distribution moyenne de la nébulosité," *Ann. du bureau central météorologique de France*, Année 1884, t. iv. 2de partie, p. 27.

(without alteration of their other properties, as height, compactness, &c.), the ground will undergo the same variations of temperature. Now it will be shown in the sequel that a variation of the carbonic acid of the atmosphere in the same proportion produces nearly the same thermal effect independently of its absolute magnitude (see p. 265). Therefore we may calculate the temperature-variation in this case as if the clouds covered the ground with a thin film of the albedo 0·78 ($\nu=0{\cdot}22$, see p. 256). As now on the average $K=1$ and $W=1$ nearly, and in this case β is about 0·79, the effect on the clouded part will be only 0·25 of the effect on parts that have $\nu=1$. If a like correction is introduced for the ocean ($\nu=0{\cdot}925$) on the supposition that the unclouded part of the earth consists of as much water as of solid ground (which is approximately true, for the clouds are by preference stored up over the ocean), we find a mean effect of, in round numbers, 60 p. c. of that which would exist if the whole earth's surface had $\nu=1$. The snow-covered parts are not considered, for, on the one hand, these parts are mostly clouded to about 65 p. c.; further, they constitute only a very small part of the earth (for the whole year on the average only about 4 p. c.), so that the correction for this case would not exceed 0·5 p. c. in the last number 60. And further, on the border countries between snowfields and free soil secondary effects come into play (see p. 257) which compensate, and perhaps overcome, the moderating effect of the snow.

In the foregoing we have supposed that the air is to be regarded as an envelope of perfectly uniform temperature. This is of course not true, and we now proceed to an examination of the probable corrections that must be introduced for eliminating the errors caused by this inexactness. It is evident that the parts of the air which radiate to space are chiefly the external ones, and on the other hand the layers of air which absorb the greatest part of the earth's radiation do not lie very high. From this cause both the radiation from air to space ($\beta\gamma\theta^4$ in eq. 1) and also the radiation of the earth to the air ($\beta\gamma\nu(T^4-\theta^4)$ in eq. 2), are greatly reduced, and the air has a much greater effect as protecting against the loss of heat to space than is assumed in these equations, and consequently also in eq. (3). If we knew the difference of temperature between the two layers of the air that radiate to space and absorb the earth's radiation, it would be easy to introduce the necessary correction in formulæ (1), (2), and 3). For this purpose I have adduced the following consideration.

As at the mean composition of the atmosphere ($K=1$,

W = 1) about 80 p. c. of the earth's radiation is absorbed in the air, we may as mean temperature of the absorbing layer choose the temperature at the height where 40 p. c. of the heat is absorbed. Since emission and absorption follow the same quantitative laws, we may as mean temperature of the emitting layer choose the temperature at the height where radiation entering from space in the opposite direction to the actual emission is absorbed to the extent of 40 p. c.

Langley has made four measurements of the absorptive power of water-vapour for radiation from a hot Leslie cube of 100° C.* These give nearly the same absorption-coefficient if Pouillet's formula is used for the calculation. From these numbers we calculate that for the absorption of 40 p. c. of the radiation it would be necessary to intercalate so much water-vapour between radiator and bolometer that, when condensed, it would form a layer of water 3·05 millimetres thick. If we now suppose as mean for the whole earth K = 1 and W = 1 (see Table VI.), we find that vertical rays from the earth, if it were at 100°, must traverse 305 metres of air to lose 40 p. c. Now the earth is only at 15° C., but this cannot make any great difference. Since the radiation emanates in all directions, we have to divide 305 by 1·61 and get in this way 209 metres. In consequence of the lowering of the quantity of water-vapour with the height † we must apply a slight correction, so that the final result is 233 metres. Of course this number is a mean value, and higher values will hold good for colder, lower for warmer parts of the earth. In so small a distance from the earth, then, 40 p. c. of the earth's radiation should be stopped. Now it is not wholly correct to calculate with Pouillet's formula (it is rather strange that Langley's figures agree so well with it), which gives necessarily too low values. But, on the other hand, we have not at all considered the absorption by the carbonic acid in this part, and this may compensate for the error mentioned. In the highest layers of the atmosphere there is very little water-vapour, so that we must calculate with carbonic acid as the chief absorbent. From a measurement by Ångström ‡, we learn that the absorption-coefficients of water-vapour and of carbonic acid in equal quantities (equal number of molecules) are in the proportion 81 : 62. This ratio is valid for the least hot radiator that Ångström used, and there is no doubt

* Langley, "Temperature of the Moon," p. 186.

† Hann, *Meteorologische Zeitschrift*, xi. p. 196 (1894).

‡ Ångström, *Bihang till K. Vet.-Ak. Handl.* Bd. xv. Afd. 1, No. 9, pp. 11 and 18 (1889).

that the radiation of the earth is much less refrangible. But in the absence of a more appropriate determination we may use this for our purpose ; it is probable that for a less hot radiator the absorptive power of the carbonic acid would come out a little greater compared with that of water-vapour, for the absorption-bands of CO_2 are, on the whole, less refrangible than those of H_2O (see pp. 246–248). Using the number 0·03 vol. p. c. for the quantity of carbonic acid in the atmosphere, we find that rays which emanate from the upper part of the air are derived to the extent of 40 p. c. from a layer that constitutes 0·145 part of the atmosphere. This corresponds to a height of about 15,000 metres. Concerning this value we may make the same remark as on the foregoing value. In this case we have neglected the absorption by the small quantities of water-vapour in the higher atmosphere. The temperature-difference of these two layers—the one absorbing, the other radiating—is, according to Glaisher's measurements* (with a little extrapolation), about 42° C.

For the clouds we get naturally slightly modified numbers. We ought to take the mean height of the clouds that are illuminated by the sun. As such clouds I have chosen the summits of the cumuli that lie at an average height of 1855 metres, with a maximum height of 3611 metres and a minimum of 900 metres†. I have made calculations for mean values of 2000 and 4000 metres (corresponding to differences of temperature of 30° C. and 20° C. instead of 42° C. for the earth's surface).

If we now wish to adjust our formulæ (1) to (3), we have in (1) and (2) to introduce θ as the mean temperature of the radiating layer and $(\theta+42)$, $(\theta+30)$, or $(\theta+20)$ respectively for the mean temperature of the absorbing layer. In the first case we should use $\nu=1$ and $\nu=0{\cdot}925$ respectively, in the second and the third case $\nu=0{\cdot}22$.

We then find instead of the formula (3)

$$T^4=\frac{K}{1+\nu(1-\beta)},$$

another very similar formula

$$T^4=\frac{K}{1+c\nu(1-\beta)}, \quad \cdots \quad (4)$$

* Joh. Müller's *Lehrbuch d. kosmischen Physik*, 5te Aufl. p. 539 (Braunschweig, 1894).

† According to the measurements of Ekholm and Hagström, *Bihang till K. Sv. Vet-Ak. Handlingar*, Bd. xii. Afd. 1, No. 10, p. 11 (1886).

where c is a constant with the values 1·88, 1·58, and 1·37 respectively for the three cases *. In this way we find the following corrected values which represent the variation of temperature, if the solid ground changes its temperature 1° C. in consequence of a variation of β as calculated by means of formula (3).

TABLE V.—*Correction Factors for the Radiation.*

$\beta =$	Solid ground, $\nu=1$.	Water, $\nu=0{\cdot}925$.	Snow, $\nu=0{\cdot}5$.	Clouds ($\nu=0{\cdot}22$) at a height of		
				0 m.	2000 m.	4000 m.
0·65	1·53	1·46	0·95	0·49	0·42	0·37
0·75	1·60	1·52	0·95	0·47	0·40	0·35
0·85	1·69	1·59	0·95	0·46	0·38	0·33
0·95	1·81	1·68	0·94	0·43	0·36	0·31
1·00	1·88	1·74	0·94	0·41	0·35	0·30

If we now assume as a mean for the whole earth $K=1$ and $W=1$, we get $\beta=0{\cdot}785$, and taking the clouded part to be 52·5 p. c. and the clouds to have a height of 2000 metres, further assuming the unclouded remainder of the earth's surface to consist equally of land and water, we find as average variation of temperature

$$1{\cdot}63\times 0{\cdot}2385+1{\cdot}54\times 0{\cdot}2385+0{\cdot}39\times 0{\cdot}525=0{\cdot}979,$$

or very nearly the same effect as we may calculate directly from the formula (3). On this ground I have used the simpler formula.

In the foregoing I have remarked that according to my estimation the air is less transparent for dark heat than on Langley's estimate and nearly in the proportion 37·2 : 44. How great an influence this difference may exercise is very easily calculated with the help of formula (3) or (4). According to Langley's valuation, the effect should be nearly 15 p. c. greater than according to mine. Now I think that my estimate agrees better with the great absorption that Langley has found for heat from terrestrial radiating bodies (see p. 260), and in all circumstances I have preferred to slightly underestimate than to overrate the effect in question.

* $1{\cdot}88=\left(\frac{288}{246}\right)^4$, $1{\cdot}58=\left(\frac{276}{246}\right)^4$, and $1{\cdot}37=\left(\frac{266}{246}\right)^4$. 246° is the mean absolute temperature of the higher radiating layer of the air.

IV. *Calculation of the Variation of Temperature that would ensue in consequence of a given Variation of the Carbonic Acid in the Air.*

We now possess all the necessary data for an estimation of the effect on the earth's temperature which would be the result of a given variation of the aërial carbonic acid. We only need to determine the absorption-coefficient for a certain place with the help of Table III. if we know the quantity of carbonic acid (K=1 now) and water-vapour (W) of this place. By the aid of Table IV. we at first determine the factor ρ that gives the mean path of the radiation from the earth through the air and multiply the given K- and W-values by this factor. Then we determine the value of β which corresponds to ρK and ρW. Suppose now that the carbonic acid had another concentration K_1 (*e.g.* $K_1 = 1{\cdot}5$). Then we at first suppose W unaltered and seek the new value of ρ, say ρ_1, that is valid on this supposition. Next we have to seek β, which corresponds to $\rho_1 K_1$ ($1{\cdot}5\rho_1$) and $\rho_1 W$. From formula (3) we can then easily calculate the alteration (t) (here increase) in the temperature at the given place which will accompany the variation of β from β to β_1. In consequence of the variation (t) in the temperature, W must also undergo a variation. As the relative humidity does not vary much, unless the distribution of land and water changes (see table 8 of my original memoir), I have supposed that this quantity remains constant, and thereby determined the new value W_1 of W. A fresh approximation gives in most cases values of W_1 and β_1 which may be regarded as definitive. In this way, therefore, we get the variation of temperature as soon as we know the actual temperature and humidity at the given place.

In order to obtain values for the temperature for the whole earth, I have calculated from Dr. Buchan's charts of the mean temperature at different places in every month * the mean temperature in every district that is contained between two parallels differing by 10 and two meridians differing by 20 degrees, (*e. g.*, between 0° and 10° N. and 160° and 180° W.). The humidity has not as yet been sufficiently examined for the whole earth; and I have therefore collected a great many measurements of the relative humidity at different places (about 780) on the earth and marked them down in maps of the world, and thereafter estimated the mean values for every district. These quantities I have tabulated for the four seasons, Dec.-Feb., March–May, June–Aug., and Sept.–Nov. The detailed table and the observations used are to be found in my original memoir: here I reproduce only the mean values for every tenth parallel (Table VI.).

* Buchan: Report on the Scientific Results of the Voyage of H.M.S. 'Challenger,' Physics and Chemistry, vol. ii., 1889.

TABLE VI.—*Mean Temperature, Rela*

Latitude.	Mean Temperature.					Mean Re	
	Dec.–Feb.	March–May.	June–Aug.	Sept.–Nov.	Mean of the year.	Dec.–Feb.	March–May.
70	−21·1	− 8·3	+ 7·5	− 6·0	− 7·0	86	81
60	−11·2	+ 0·2	+13·5	+ 2·2	+ 1·2	83	74
50	− 1·4	+ 7·8	+18·7	+ 9·7	+ 8·7	78	73
40	+ 8·4	+14·5	+21·8	+16·6	+15·3	73	68
30	+17·0	+21·5	+26·0	+23·0	+21·9	71	68
20	+23·2	+25·5	+26·8	+25·9	+25·4	74	73
10	+25·5	+25·8	+25·4	+25·5	+25·5	77	78
0	+25·7	+25·5	+24·0	+25·0	+25·1	81	81
−10	+24·9	+24·0	+20·8	+23·1	+23·2	79	78
−20	+22·4	+20·5	+16·4	+19·3	+19·7	75	79
−30	+17·5	+15·2	+11·3	+14·2	+14·5	75	80
−40	+11·6	+ 9·5	+ 5·9	+ 8·2	+ 8·7	81	81
−50	+ 5·3	+ 2·0	− 0·4	+ 1·6	+ 2·1	83	79
−60							

* From the figures for temperature and relative humidity I have

tive and Absolute Humidity.*

elative Humidity.			Mean Absolute Humidity.				
June–Aug.	Sept.–Nov.	Mean of the year.	Dec.–Feb.	March–May.	June–Aug.	Sept.–Nov.	Mean of the year.
77	84	82	1·15	2·14	6·22	2·84	3·09
76	80	78·2	2·22	3·82	8·82	4·7	4·9
69	76	74	3·86	5·98	10·8	7·16	6·95
67	71	69·7	6·53	8·63	13·4	10·13	9·7
70	73	70·5	10·36	12·63	17·1	15·0	13·8
78	77	75·5	15·3	17·0	19·6	16·8	17·2
82	81	79·5	17·7	18·9	19·9	19·3	18·9
82	80	81	19·4	19·0	17·9	18·3	18·7
80	77	78·5	18·0	17·1	14·6	16·0	16·4
80	75	77·2	14·8	14·0	11·1	13·0	13·2
80	79	78·5	11·1	10·4	8·1	9·6	9·8
83	79	81	8·34	7·08	5·94	6·63	6·99
—	—	—	5·74	4·46	—	—	—

calculated the absolute humidity in grams per cubic metre.

TABLE VII.—*Variation of Temperature cause*

Latitude.	Carbonic Acid = 0·67.					Carbonic Acid = 1·5.					Car				
	Dec.–Feb.	March–May.	June–Aug.	Sept.–Nov.	Mean of the year.	Dec.–Feb.	March–May.	June–Aug.	Sept.–Nov.	Mean of the year.	Dec.–Feb.				
70	−2·9	−3·0	−3·4	−3·1	−3·1	3·3	3·4	3·8	3·6	3·52	6·0				
60	−3·0	−3·2	−3·4	−3·3	−3·22	3·4	3·7	3·6	3·8	3·62	6·1				
50	−3·2	−3·3	−3·3	−3·4	−3·3	3·7	3·8	3·4	3·7	3·65	6·1				
40	−3·4	−3·4	−3·2	−3·3	−3·32	3·7	3·6	3·3	3·5	3·52	6·0				
30	−3·3	−3·2	−3·1	−3·1	−3·17	3·5	3·3	3·2	3·5	3·47	5·6				
20	−3·1	−3·1	−3·0	−3·1	−3·07	3·5	3·2	3·1	3·2	3·25	5·2				
10	−3·1	−3·0	−3·0	−3·0	−3·02	3·2	3·2	3·1	3·1	3·15	5·0				
0	−3·0	−3·0	−3·1	−3·0	−3·02	3·1	3·1	3·2	3·2	3·15	4·9				
−10	−3·1	−3·1	−3·2	−3·1	−3·12	3·2	3·2	3·2	3·2	3·2	5·0				
−20	−3·1	−3·2	−3·3	−3·2	−3·2	3·2	3·2	3·4	3·3	3·27	5·2				
−30	−3·3	−3·3	−3·4	−3·4	−3·35	3·4	3·5	3·7	3·5	3·52	5·5				
−40	−3·4	−3·4	−3·3	−3·4	−3·37	3·6	3·7	3·8	3·7	3·7	5·8				
−50	−3·2	−3·3	—	—	—	3·8	3·7	—	—	—	6·0				
−60															

d by a given Variation of Carbonic Acid.

bonic Acid = 2·0.				Carbonic Acid = 2·5.					Carbonic Acid = 3·0.				
May.	June–Aug.	Sept.–Nov.	Mean of the year.	Dec.–Feb.	March–May.	June–Aug.	Sept.–Nov.	Mean of the year.	Dec.–Feb.	March–May.	June–Aug.	Sept.–Nov.	Mean of the year.
6·1	6·0	6·1	6·05	7·9	8·0	7·9	8·0	7·95	9·1	9·3	9·4	9·4	9·3
6·1	5·8	6·1	6·02	8·0	8·0	7·6	7·9	7·87	9·3	9·5	8·9	9·5	9·3
6·1	5·5	6·0	5·92	8·0	7·9	7·0	7·9	7·7	9·5	9·4	8·6	9·2	9·17
5·8	5·4	5·6	5·7	7·9	7·6	6·9	7·3	7·42	9·3	9·0	8·2	8·8	8·82
5·4	5·0	5·2	5·3	7·2	7·0	6·6	6·7	6·87	8·7	8·3	7·5	7·9	8·1
5·0	4·9	5·0	5·02	6·7	6·6	6·3	6·6	6·52	7·9	7·5	7·2	7·5	7·52
5·0	4·9	4·9	4·95	6·6	6·4	6·3	6·4	6·42	7·4	7·3	7·2	7·3	7·3
4·9	5·0	5·0	4·95	6·4	6·4	6·6	6·6	6·5	7·3	7·3	7·4	7·4	7·35
5·0	5·2	5·1	5·07	6·6	6·6	6·7	6·7	6·65	7·4	7·5	8·0	7·6	7·62
5·3	5·5	5·4	5·35	6·7	6·8	7·0	7·0	6·87	7·9	8·1	8·6	8·3	8·22
5·6	5·8	5·6	5·62	7·0	7·2	7·7	7·4	7·32	8·6	8·7	9·1	8·8	8·8
6·0	6·0	6·0	5·95	7·7	7·9	7·9	7·9	7·85	9·1	9·2	9·4	9·3	9·25
6·1	—	—	—	7·9	8·0	—	—	—	9·4	9·5	—	—	—

By means of these values, I have calculated the mean alteration of temperature that would follow if the quantity of carbonic acid varied from its present mean value (K = 1) to another, viz. to K = 0·67, 1·5, 2, 2·5, and 3 respectively. This calculation is made for every tenth parallel, and separately for the four seasons of the year. The variation is given in Table VII.

A glance at this Table shows that the influence is nearly the same over the whole earth. The influence has a minimum near the equator, and increases from this to a flat maximum that lies the further from the equator the higher the quantity of carbonic acid in the air. For K = 0·67 the maximum effect lies about the 40th parallel, for K = 1·5 on the 50th, for K = 2 on the 60th, and for higher K-values above the 70th parallel. The influence is in general greater in the winter than in the summer, except in the case of the parts that lie between the maximum and the pole. The influence will also be greater the higher the value of ν, that is in general somewhat greater for land than for ocean. On account of the nebulosity of the Southern hemisphere, the effect will be less there than in the Northern hemisphere. An increase in the quantity of carbonic acid will of course diminish the difference in temperature between day and night. A very important secondary elevation of the effect will be produced in those places that alter their albedo by the extension or regression of the snow-covering (see p. 257), and this secondary effect will probably remove the maximum effect from lower parallels to the neighbourhood of the poles *.

It must be remembered that the above calculations are found by interpolation from Langley's numbers for the values K = 0·67 and K = 1·5, and that the other numbers must be regarded as extrapolated. The use of Pouillet's formula makes the values for K = 0·67 probably a little too small, those for K = 1·5 a little too great. This is also without doubt the case for the extrapolated values, which correspond to higher values of K.

We may now inquire how great must the variation of the carbonic acid in the atmosphere be to cause a given change of the temperature. The answer may be found by interpolation in Table VII. To facilitate such an inquiry, we may make a simple observation. If the quantity of carbonic acid decreases from 1 to 0·67, the fall of temperature is nearly the same as the increase of temperature if this quantity augments to 1·5. And to get a new increase of this order of magnitude (3°·4), it will be necessary to alter the quantity of carbonic acid till it reaches a value nearly midway between 2 and 2·5.

* See Addendum, p. 275.

Thus if the quantity of carbonic acid increases in geometric progression, the augmentation of the temperature will increase nearly in arithmetic progression. This rule—which naturally holds good only in the part investigated—will be useful for the following summary estimations.

V. 5. *Geological Consequences.*

I should certainly not have undertaken these tedious calculations if an extraordinary interest had not been connected with them. In the Physical Society of Stockholm there have been occasionally very lively discussions on the probable causes of the Ice Age; and these discussions have, in my opinion, led to the conclusion that there exists as yet no satisfactory hypothesis that could explain how the climatic conditions for an ice age could be realized in so short a time as that which has elapsed from the days of the glacial epoch. The common view hitherto has been that the earth has cooled in the lapse of time; and if one did not know that the reverse has been the case, one would certainly assert that this cooling must go on continuously. Conversations with my friend and colleague Professor Högbom, together with the discussions above referred to, led me to make a preliminary estimate of the probable effect of a variation of the atmospheric carbonic acid on the temperature of the earth. As this estimation led to the belief that one might in this way probably find an explanation for temperature variations of 5°–10° C., I worked out the calculation more in detail, and lay it now before the public and the critics.

From geological researches the fact is well established that in Tertiary times there existed a vegetation and an animal life in the temperate and arctic zones that must have been conditioned by a much higher temperature than the present in the same regions *. The temperature in the arctic zones appears to have exceeded the present temperature by about 8 or 9 degrees. To this genial time the ice age succeeded, and this was one or more times interrupted by interglacial periods with a climate of about the same character as the present, sometimes even milder. When the ice age had its greatest extent, the countries that now enjoy the highest civilization were covered with ice. This was the case with Ireland, Britain (except a small part in the south), Holland, Denmark, Sweden and Norway, Russia (to Kiev,

* For details *cf.* Neumayr, *Erdgeschichte*, Bd. 2, Leipzig, 1887; and Geikie, 'The Great Ice-Age,' 3rd ed. London, 1894; Nathorst, *Jordens historia*, p. 989, Stockholm, 1894.

Annex 3

S. Arrhenius, “On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground”, *Philosophical Magazine and Journal of Science,* 1896, pp. 237-276, pages 237, 254-267

THE

LONDON, EDINBURGH, AND DUBLIN

PHILOSOPHICAL MAGAZINE

AND

JOURNAL OF SCIENCE.

[FIFTH SERIES.]

APRIL 1896.

XXXI. *On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground.* *By* Prof. SVANTE ARRHENIUS *.

I. *Introduction* : *Observations of* Langley *on Atmospherical Absorption.*

A GREAT deal has been written on the influence of the absorption of the atmosphere upon the climate. Tyndall † in particular has pointed out the enormous importance of this question. To him it was chiefly the diurnal and annual variations of the temperature that were lessened by this circumstance. Another side of the question, that has long attracted the attention of physicists, is this : Is the mean temperature of the ground in any way influenced by the presence of heat-absorbing gases in the atmosphere? Fourier‡ maintained that the atmosphere acts like the glass of a hot-house, because it lets through the light rays of the sun but retains the dark rays from the ground. This idea was elaborated by Pouillet § ; and Langley was by some of his researches led to the view, that "the temperature of the earth under direct sunshine, even though our atmosphere were present as now, would probably fall to −200° C., if that atmosphere did not possess the quality of selective

* Extract from a paper presented to the Royal Swedish Academy of Sciences, 11th December, 1895. Communicated by the Author.

† 'Heat a Mode of Motion,' 2nd ed. p. 405 (Lond., 1865).

‡ *Mém. de l'Ac. R. d. Sci. de l'Inst. de France*, t. vii. 1827.

§ *Comptes rendus*, t. vii. p. 41 (1838).

III. *Thermal Equilibrium on the Surface and in the Atmosphere of the Earth.*

As we now have a sufficient knowledge of the absorption of heat by the atmosphere, it remains to examine how the temperature of the ground depends on the absorptive power of the air. Such an investigation has been already performed by Pouillet*, but it must be made anew, for Pouillet used hypotheses that are not in agreement with our present knowledge.

In our deductions we will assume that the heat that is conducted from the interior of the earth to its surface may be wholly neglected. If a change occurs in the temperature of the earth's surface, the upper layers of the earth's crust will evidently also change their temperature; but this later process will pass away in a very short time in comparison with the time that is necessary for the alteration of the surface temperature, so that at any time the heat that is transported from the interior to the surface (positive in the winter, negative in the summer) must remain independent of the small secular variations of the surface temperature, and in the course of a year be very nearly equal to zero.

Likewise we will suppose that the heat that is conducted to a given place on the earth's surface or in the atmosphere in consequence of atmospheric or oceanic currents, horizontal or vertical, remains the same in the course of the time considered, and we will also suppose that the clouded part of the sky remains unchanged. It is only the variation of the temperature with the transparency of the air that we shall examine.

All authors agree in the view that there prevails an equilibrium in the temperature of the earth and of its atmosphere. The atmosphere must, therefore, radiate as much heat to space as it gains partly through the absorption of the sun's rays, partly through the radiation from the hotter surface of the earth and by means of ascending currents of air heated by contact with the ground. On the other hand, the earth loses just as much heat by radiation to space and to the atmosphere as it gains by absorption of the sun's rays. If we consider a given place in the atmosphere or on the ground, we must also take into consideration the quantities of heat that are carried to this place by means of oceanic or atmospheric currents. For the radiation we will suppose that

* Pouillet, *Comptes rendus*, t. vii. p. 41 (1838).

Stefan's law of radiation, which is now generally accepted, holds good, or in other words that the quantity of heat (W) that radiates from a body of the albedo $(1-\nu)$ and temperature T (absolute) to another body of the absorption-coefficient β and absolute temperature θ is

$$W=\nu\beta\gamma(T^4-\theta^4),$$

where γ is the so-called radiation constant ($1{\cdot}21\,.\,10^{-12}$ per sec. and cm.^{2}). Empty space may be regarded as having the absolute temperature 0*.

Provisionally we regard the air as a uniform envelope of the temperature θ and the absorption-coefficient α for solar heat; so that if A calories arrive from the sun in a column of 1 cm.^{2} cross-section, αA are absorbed by the atmosphere and $(1-\alpha)$A reach the earth's surface. In the A calories there is, therefore, not included that part of the sun's heat which by means of selective reflexion in the atmosphere is thrown out towards space. Further, let β designate the absorption-coefficient of the air for the heat that radiates from the earth's surface; β is also the emission-coefficient of the air for radiation of low temperature—strictly 15°; but as the spectral distribution of the heat varies rather slowly with the temperature, β may be looked on as the emission-coefficient also at the temperature of the air. Let the albedo of the earth's crust be designated by $(1-\nu)$, and the quantities of heat that are conveyed to the air and to the earth's surface at the point considered be M and N respectively. As unit of time we may take any period: the best choice in the following calculation is perhaps to take three months for this purpose. As unit of surface we may take 1 cm.^{2}, and for the heat in the air that contained in a column of 1 cm.^{2} cross-section and the height of the atmosphere. The heat that is reflected from the ground is not appreciably absorbed by the air (see p. 252), for it has previously traversed great quantities of water-vapour and carbonic acid, but a part of it may be returned to the ground by means of diffuse reflexion. Let this part not be included in the albedo $(1-\nu)$. γ, A, ν, M, N, and α are to be considered as constants, β as the independent, and θ and T as the dependent variables.

Then we find for the column of air

$$\beta\gamma\theta^4=\beta\gamma\nu(T^4-\theta^4)+\alpha A+M. \quad . \quad . \quad . \quad (1)$$

The first member of this equation represents the heat

* Langley, 'Prof. Papers,' No. 15, p. 122. "The Temperature of the Moon," p. 206.

radiated from the air (emission-coefficient β, temperature θ) to space (temperature 0). The second one gives the heat radiated from the soil (1 cm.^{2}, temperature T, albedo $1-\nu$) to the air; the third and fourth give the amount of the sun's radiation absorbed by the air, and the quantity of heat obtained by conduction (air-currents) from other parts of the air or from the ground. In the same manner we find for the earth's surface

$$\beta\gamma\nu(T^4-\theta^4)+(1-\beta)\gamma\nu T^4=(1-\alpha)\nu A+N. \quad . \quad (2)$$

The first and second members represent the radiated quantities of heat that go to the air and to space respectively, $(1-\alpha)\nu A$ is the part of the sun's radiation absorbed, and N the heat conducted to the point considered from other parts of the soil or from the air by means of water- or air-currents.

Combining both these equations for the elimination of θ, which has no considerable interest, we find for T^4

$$T^4=\frac{\alpha A+M+(1-\alpha)A(1+\nu)+N(1+1/\nu)}{\gamma(1+\nu-\beta\nu)}=\frac{K}{1+\nu(1-\beta)}. \quad (3)$$

For the earth's solid crust we may, without sensible error, put ν equal to 1, if we except the snowfields, for which we assume $\nu=0{\cdot}5$. For the water-covered parts of the earth I have calculated the mean value of ν to be 0·925 by aid of the figures of Zenker*. We have, also, in the following to make use of the albedo of the clouds. I do not know if this has ever been measured, but it probably does not differ very much from that of fresh fallen snow, which Zöllner has determined to be 0·78, *i. e.* $\nu=0{\cdot}22$. For old snow the albedo is much less or ν much greater; therefore we have assumed 0·5 as a mean value.

The last formula shows that the temperature of the earth augments with β, and the more rapidly the greater ν is. For an increase of 1° if $\nu=1$ we find the following increases for the values of $\nu=0{\cdot}925$, 0·5, and 0·22 respectively:—

β.	$\nu=0{\cdot}925$.	$\nu=0{\cdot}5$.	$\nu=0{\cdot}22$.
0·65	0·944	0·575	0·275
0·75	0·940	0·556	0·261
0·85	0·934	0 535	0·245
0·95	0·928	0·512	0·228
1·00	0·925	0·500	0·220

This reasoning holds good if the part of the earth's surface

* Zenker, *Die Vertheilung der Wärme auf der Erdoberfläche*, p. 54 (Berlin, 1888).

considered does not alter its albedo as a consequence of the altered temperature. In that case entirely different circumstances enter. If, for instance, an element of the surface which is not now snow-covered, in consequence of falling temperature becomes clothed with snow, we must in the last formula not only alter β but also ν. In this case we must remember that α is very small compared to β. For α we will choose the value 0·40 in accordance with Langley's* estimate. Certainly a great part of this value depends upon the diffusely reflected part of the sun's heat, which is absorbed by the earth's atmosphere, and therefore should not be included in α, as we have defined it above. On the other hand, the sun may in general stand a little lower than in Langley's measurements, which were executed with a relatively high sun, and in consequence of this α may be a little greater, so that these circumstances may compensate each other. For β we will choose the value 0·70, which corresponds when K = 1 and W = 0·3 (a little below the freezing-point) with the factor 1·66 (see p. 253). In this case we find the relation between T (uncovered) and T_1 (snow-covered surface) to be

$$T^4 : T_1^4 = \frac{A(1+1-0{\cdot}40)+M}{\gamma(1+1-0{\cdot}70)} : \frac{A(1+0{\cdot}50-0{\cdot}20)+M}{\gamma(1+0{\cdot}50-0{\cdot}35)} = \frac{1{\cdot}60+\phi}{1{\cdot}30} : \frac{1{\cdot}30+\phi}{1{\cdot}15},$$

if $M = \phi A$. We have to bear in mind that the mean M for the whole earth is zero, for the equatorial regions negative and for the polar regions positive. For a mean latitude M = 0, and in this case T_1 becomes 267·3 if T = 273, that is the temperature decreases in consequence of the snow-covering by 5°·7 C.† The decrease of temperature from this cause will be valid until $\phi = 1$, *i. e.* till the heat delivered by convection to the air exceeds the whole radiation of the sun. This can only occur in the winter and in polar regions.

But this is a secondary phenomenon. The chief effect that we examine is the direct influence of an alteration of β upon the temperature T of the earth's surface. If we start from a value T = 273 and $\beta = 0{\cdot}70$, we find the alteration (t) in the

* Langley, "Temperature of the Moon," p. 189. On p. 197 he estimates a to be only 0·33.

† According to the correction introduced in the sequel for the different heights of the absorbing and radiating layers of the atmosphere, the number 5°·7 is reduced to 4°·0. But as about half the sky is cloud-covered, the effect will be only half as great as for cloudless sky, *i. e.* the mean effect will be a lowering of about 2° C.

temperature which is caused by the variation of β to the following values to be

$\beta = 0{\cdot}60$	$t = -\ 5°$ C.
0·80	$+\ 5{\cdot}6$
0·90	$+11{\cdot}7$
1·00	$+18{\cdot}6$.

These values are calculated for $\nu = 1$, *i. e.* for the solid crust of the earth's surface, except the snowfields. For surfaces with another value of ν, as for instance the ocean or the snowfields, we have to multiply this value t by a fraction given above.

We have now shortly to consider the influence of the clouds. A great part of the earth's surface receives no heat directly from the sun, because the sun's rays are stopped by clouds. How great a part of the earth's surface is covered by clouds we may find from Teisserenc de Bort's work * on Nebulosity. From tab. 17 of this publication I have determined the mean nebulosity for different latitudes, and found:—

Latitude..	60.	45.	30.	15.	0.	−15.	−30.	−45.	−60.
Nebulosity.	0·603	0·48	0·402	0·511	0·581	0·463	0·53	0·701	

For the part of the earth between 60° S. and 60° N. we find the mean value 0·525, *i. e.* 52·5 per cent. of the sky is clouded. The heat-effect of these clouds may be estimated in the following manner. Suppose a cloud lies over a part of the earth's surface and that no connexion exists between this shadowed part and the neighbouring parts, then a thermal equilibrium will exist between the temperature of the cloud and of the underlying ground. They will radiate to each other and the cloud also to the upper air and to space, and the radiation between cloud and earth may, on account of the slight difference of temperature, be taken as proportional to this difference. Other exchanges of heat by means of air-currents are also, as a first approximation, proportional to this difference. If we therefore suppose the temperature of the cloud to alter (other circumstances, as its height and composition, remaining unchanged), the temperature of the ground under it must also alter in the same manner if the same supply of heat to both subsists—if there were no supply to the ground from neighbouring parts, the cloud and the ground would finally assume the same mean temperature. If, therefore, the temperature of the clouds varies in a determined manner

* Teisserenc de Bort, "Distribution moyenne de la nébulosité," *Ann. du bureau central météorologique de France*, Année 1884, t. iv. 2de partie, p. 27.

(without alteration of their other properties, as height, compactness, &c.), the ground will undergo the same variations of temperature. Now it will be shown in the sequel that a variation of the carbonic acid of the atmosphere in the same proportion produces nearly the same thermal effect independently of its absolute magnitude (see p. 265). Therefore we may calculate the temperature-variation in this case as if the clouds covered the ground with a thin film of the albedo 0·78 ($\nu=0{\cdot}22$, see p. 256). As now on the average $K=1$ and $W=1$ nearly, and in this case β is about 0·79, the effect on the clouded part will be only 0·25 of the effect on parts that have $\nu=1$. If a like correction is introduced for the ocean ($\nu=0{\cdot}925$) on the supposition that the unclouded part of the earth consists of as much water as of solid ground (which is approximately true, for the clouds are by preference stored up over the ocean), we find a mean effect of, in round numbers, 60 p. c. of that which would exist if the whole earth's surface had $\nu=1$. The snow-covered parts are not considered, for, on the one hand, these parts are mostly clouded to about 65 p. c.; further, they constitute only a very small part of the earth (for the whole year on the average only about 4 p. c.), so that the correction for this case would not exceed 0·5 p. c. in the last number 60. And further, on the border countries between snowfields and free soil secondary effects come into play (see p. 257) which compensate, and perhaps overcome, the moderating effect of the snow.

In the foregoing we have supposed that the air is to be regarded as an envelope of perfectly uniform temperature. This is of course not true, and we now proceed to an examination of the probable corrections that must be introduced for eliminating the errors caused by this inexactness. It is evident that the parts of the air which radiate to space are chiefly the external ones, and on the other hand the layers of air which absorb the greatest part of the earth's radiation do not lie very high. From this cause both the radiation from air to space ($\beta\gamma\theta^4$ in eq. 1) and also the radiation of the earth to the air ($\beta\gamma\nu(T^4-\theta^4)$ in eq. 2), are greatly reduced, and the air has a much greater effect as protecting against the loss of heat to space than is assumed in these equations, and consequently also in eq. (3). If we knew the difference of temperature between the two layers of the air that radiate to space and absorb the earth's radiation, it would be easy to introduce the necessary correction in formulæ (1), (2), and 3). For this purpose I have adduced the following consideration.

As at the mean composition of the atmosphere ($K=1$,

W = 1) about 80 p. c. of the earth's radiation is absorbed in the air, we may as mean temperature of the absorbing layer choose the temperature at the height where 40 p. c. of the heat is absorbed. Since emission and absorption follow the same quantitative laws, we may as mean temperature of the emitting layer choose the temperature at the height where radiation entering from space in the opposite direction to the actual emission is absorbed to the extent of 40 p. c.

Langley has made four measurements of the absorptive power of water-vapour for radiation from a hot Leslie cube of 100° C.* These give nearly the same absorption-coefficient if Pouillet's formula is used for the calculation. From these numbers we calculate that for the absorption of 40 p. c. of the radiation it would be necessary to intercalate so much water-vapour between radiator and bolometer that, when condensed, it would form a layer of water 3·05 millimetres thick. If we now suppose as mean for the whole earth K = 1 and W = 1 (see Table VI.), we find that vertical rays from the earth, if it were at 100°, must traverse 305 metres of air to lose 40 p. c. Now the earth is only at 15° C., but this cannot make any great difference. Since the radiation emanates in all directions, we have to divide 305 by 1·61 and get in this way 209 metres. In consequence of the lowering of the quantity of water-vapour with the height † we must apply a slight correction, so that the final result is 233 metres. Of course this number is a mean value, and higher values will hold good for colder, lower for warmer parts of the earth. In so small a distance from the earth, then, 40 p. c. of the earth's radiation should be stopped. Now it is not wholly correct to calculate with Pouillet's formula (it is rather strange that Langley's figures agree so well with it), which gives necessarily too low values. But, on the other hand, we have not at all considered the absorption by the carbonic acid in this part, and this may compensate for the error mentioned. In the highest layers of the atmosphere there is very little water-vapour, so that we must calculate with carbonic acid as the chief absorbent. From a measurement by Ångström ‡, we learn that the absorption-coefficients of water-vapour and of carbonic acid in equal quantities (equal number of molecules) are in the proportion 81 : 62. This ratio is valid for the least hot radiator that Ångström used, and there is no doubt

* Langley, "Temperature of the Moon," p. 186.

† Hann, *Meteorologische Zeitschrift*, xi. p. 196 (1894).

‡ Ångström, *Bihang till K. Vet.-Ak. Handl.* Bd. xv. Afd. 1, No. 9, pp. 11 and 18 (1889).

that the radiation of the earth is much less refrangible. But in the absence of a more appropriate determination we may use this for our purpose ; it is probable that for a less hot radiator the absorptive power of the carbonic acid would come out a little greater compared with that of water-vapour, for the absorption-bands of CO_2 are, on the whole, less refrangible than those of H_2O (see pp. 246–248). Using the number 0·03 vol. p. c. for the quantity of carbonic acid in the atmosphere, we find that rays which emanate from the upper part of the air are derived to the extent of 40 p. c. from a layer that constitutes 0·145 part of the atmosphere. This corresponds to a height of about 15,000 metres. Concerning this value we may make the same remark as on the foregoing value. In this case we have neglected the absorption by the small quantities of water-vapour in the higher atmosphere. The temperature-difference of these two layers—the one absorbing, the other radiating—is, according to Glaisher's measurements* (with a little extrapolation), about 42° C.

For the clouds we get naturally slightly modified numbers. We ought to take the mean height of the clouds that are illuminated by the sun. As such clouds I have chosen the summits of the cumuli that lie at an average height of 1855 metres, with a maximum height of 3611 metres and a minimum of 900 metres†. I have made calculations for mean values of 2000 and 4000 metres (corresponding to differences of temperature of 30° C. and 20° C. instead of 42° C. for the earth's surface).

If we now wish to adjust our formulæ (1) to (3), we have in (1) and (2) to introduce θ as the mean temperature of the radiating layer and $(\theta+42)$, $(\theta+30)$, or $(\theta+20)$ respectively for the mean temperature of the absorbing layer. In the first case we should use $\nu=1$ and $\nu=0{\cdot}925$ respectively, in the second and the third case $\nu=0{\cdot}22$.

We then find instead of the formula (3)

$$T^4=\frac{K}{1+\nu(1-\beta)},$$

another very similar formula

$$T^4=\frac{K}{1+c\nu(1-\beta)}, \quad \cdots \quad (4)$$

* Joh. Müller's *Lehrbuch d. kosmischen Physik*, 5te Aufl. p. 539 (Braunschweig, 1894).

† According to the measurements of Ekholm and Hagström, *Bihang till K. Sv. Vet-Ak. Handlingar*, Bd. xii. Afd. 1, No. 10, p. 11 (1886).

where c is a constant with the values 1·88, 1·58, and 1·37 respectively for the three cases *. In this way we find the following corrected values which represent the variation of temperature, if the solid ground changes its temperature 1° C. in consequence of a variation of β as calculated by means of formula (3).

TABLE V.—*Correction Factors for the Radiation.*

$\beta =$	Solid ground, $\nu=1$.	Water, $\nu=0{\cdot}925$.	Snow, $\nu=0{\cdot}5$.	Clouds ($\nu=0{\cdot}22$) at a height of		
				0 m.	2000 m.	4000 m.
0·65	1·53	1·46	0·95	0·49	0·42	0·37
0·75	1·60	1·52	0·95	0·47	0·40	0·35
0·85	1·69	1·59	0·95	0·46	0·38	0·33
0·95	1·81	1·68	0·94	0·43	0·36	0·31
1·00	1·88	1·74	0·94	0·41	0·35	0·30

If we now assume as a mean for the whole earth $K=1$ and $W=1$, we get $\beta=0{\cdot}785$, and taking the clouded part to be 52·5 p. c. and the clouds to have a height of 2000 metres, further assuming the unclouded remainder of the earth's surface to consist equally of land and water, we find as average variation of temperature

$$1{\cdot}63\times 0{\cdot}2385+1{\cdot}54\times 0{\cdot}2385+0{\cdot}39\times 0{\cdot}525=0{\cdot}979,$$

or very nearly the same effect as we may calculate directly from the formula (3). On this ground I have used the simpler formula.

In the foregoing I have remarked that according to my estimation the air is less transparent for dark heat than on Langley's estimate and nearly in the proportion 37·2 : 44. How great an influence this difference may exercise is very easily calculated with the help of formula (3) or (4). According to Langley's valuation, the effect should be nearly 15 p. c. greater than according to mine. Now I think that my estimate agrees better with the great absorption that Langley has found for heat from terrestrial radiating bodies (see p. 260), and in all circumstances I have preferred to slightly underestimate than to overrate the effect in question.

* $1{\cdot}88=\left(\frac{288}{246}\right)^4$, $1{\cdot}58=\left(\frac{276}{246}\right)^4$, and $1{\cdot}37=\left(\frac{266}{246}\right)^4$. 246° is the mean absolute temperature of the higher radiating layer of the air.

IV. *Calculation of the Variation of Temperature that would ensue in consequence of a given Variation of the Carbonic Acid in the Air.*

We now possess all the necessary data for an estimation of the effect on the earth's temperature which would be the result of a given variation of the aërial carbonic acid. We only need to determine the absorption-coefficient for a certain place with the help of Table III. if we know the quantity of carbonic acid (K=1 now) and water-vapour (W) of this place. By the aid of Table IV. we at first determine the factor ρ that gives the mean path of the radiation from the earth through the air and multiply the given K- and W-values by this factor. Then we determine the value of β which corresponds to ρK and ρW. Suppose now that the carbonic acid had another concentration K_1 (*e.g.* $K_1 = 1{\cdot}5$). Then we at first suppose W unaltered and seek the new value of ρ, say ρ_1, that is valid on this supposition. Next we have to seek β, which corresponds to $\rho_1 K_1$ ($1{\cdot}5\rho_1$) and $\rho_1 W$. From formula (3) we can then easily calculate the alteration (t) (here increase) in the temperature at the given place which will accompany the variation of β from β to β_1. In consequence of the variation (t) in the temperature, W must also undergo a variation. As the relative humidity does not vary much, unless the distribution of land and water changes (see table 8 of my original memoir), I have supposed that this quantity remains constant, and thereby determined the new value W_1 of W. A fresh approximation gives in most cases values of W_1 and β_1 which may be regarded as definitive. In this way, therefore, we get the variation of temperature as soon as we know the actual temperature and humidity at the given place.

In order to obtain values for the temperature for the whole earth, I have calculated from Dr. Buchan's charts of the mean temperature at different places in every month * the mean temperature in every district that is contained between two parallels differing by 10 and two meridians differing by 20 degrees, (*e. g.*, between 0° and 10° N. and 160° and 180° W.). The humidity has not as yet been sufficiently examined for the whole earth; and I have therefore collected a great many measurements of the relative humidity at different places (about 780) on the earth and marked them down in maps of the world, and thereafter estimated the mean values for every district. These quantities I have tabulated for the four seasons, Dec.-Feb., March–May, June–Aug., and Sept.–Nov. The detailed table and the observations used are to be found in my original memoir: here I reproduce only the mean values for every tenth parallel (Table VI.).

* Buchan: Report on the Scientific Results of the Voyage of H.M.S. 'Challenger,' Physics and Chemistry, vol. ii., 1889.

TABLE VI.—*Mean Temperature, Rela*

Latitude.	Mean Temperature.					Mean Re	
	Dec.–Feb.	March–May.	June–Aug.	Sept.–Nov.	Mean of the year.	Dec.–Feb.	March–May.
70	−21·1	− 8·3	+ 7·5	− 6·0	− 7·0	86	81
60	−11·2	+ 0·2	+13·5	+ 2·2	+ 1·2	83	74
50	− 1·4	+ 7·8	+18·7	+ 9·7	+ 8·7	78	73
40	+ 8·4	+14·5	+21·8	+16·6	+15·3	73	68
30	+17·0	+21·5	+26·0	+23·0	+21·9	71	68
20	+23·2	+25·5	+26·8	+25·9	+25·4	74	73
10	+25·5	+25·8	+25·4	+25·5	+25·5	77	78
0	+25·7	+25·5	+24·0	+25·0	+25·1	81	81
−10	+24·9	+24·0	+20·8	+23·1	+23·2	79	78
−20	+22·4	+20·5	+16·4	+19·3	+19·7	75	79
−30	+17·5	+15·2	+11·3	+14·2	+14·5	75	80
−40	+11·6	+ 9·5	+ 5·9	+ 8·2	+ 8·7	81	81
−50	+ 5·3	+ 2·0	− 0·4	+ 1·6	+ 2·1	83	79
−60							

* From the figures for temperature and relative humidity I have

tive and Absolute Humidity.*

elative Humidity.			Mean Absolute Humidity.				
June–Aug.	Sept.–Nov.	Mean of the year.	Dec.–Feb.	March–May.	June–Aug.	Sept.–Nov.	Mean of the year.
77	84	82	1·15	2·14	6·22	2·84	3·09
76	80	78·2	2·22	3·82	8·82	4·7	4·9
69	76	74	3·86	5·98	10·8	7·16	6·95
67	71	69·7	6·53	8·63	13·4	10·13	9·7
70	73	70·5	10·36	12·63	17·1	15·0	13·8
78	77	75·5	15·3	17·0	19·6	16·8	17·2
82	81	79·5	17·7	18·9	19·9	19·3	18·9
82	80	81	19·4	19·0	17·9	18·3	18·7
80	77	78·5	18·0	17·1	14·6	16·0	16·4
80	75	77·2	14·8	14·0	11·1	13·0	13·2
80	79	78·5	11·1	10·4	8·1	9·6	9·8
83	79	81	8·34	7·08	5·94	6·63	6·99
—	—	—	5·74	4·46	—	—	—

calculated the absolute humidity in grams per cubic metre.

TABLE VII.—*Variation of Temperature cause*

Latitude.	Carbonic Acid = 0·67.					Carbonic Acid = 1·5.					Car				
	Dec.–Feb.	March–May.	June–Aug.	Sept.–Nov.	Mean of the year.	Dec.–Feb.	March–May.	June–Aug.	Sept.–Nov.	Mean of the year.	Dec.–Feb.				
70	−2·9	−3·0	−3·4	−3·1	−3·1	3·3	3·4	3·8	3·6	3·52	6·0				
60	−3·0	−3·2	−3·4	−3·3	−3·22	3·4	3·7	3·6	3·8	3·62	6·1				
50	−3·2	−3·3	−3·3	−3·4	−3·3	3·7	3·8	3·4	3·7	3·65	6·1				
40	−3·4	−3·4	−3·2	−3·3	−3·32	3·7	3·6	3·3	3·5	3·52	6·0				
30	−3·3	−3·2	−3·1	−3·1	−3·17	3·5	3·3	3·2	3·5	3·47	5·6				
20	−3·1	−3·1	−3·0	−3·1	−3·07	3·5	3·2	3·1	3·2	3·25	5·2				
10	−3·1	−3·0	−3·0	−3·0	−3·02	3·2	3·2	3·1	3·1	3·15	5·0				
0	−3·0	−3·0	−3·1	−3·0	−3·02	3·1	3·1	3·2	3·2	3·15	4·9				
−10	−3·1	−3·1	−3·2	−3·1	−3·12	3·2	3·2	3·2	3·2	3·2	5·0				
−20	−3·1	−3·2	−3·3	−3·2	−3·2	3·2	3·2	3·4	3·3	3·27	5·2				
−30	−3·3	−3·3	−3·4	−3·4	−3·35	3·4	3·5	3·7	3·5	3·52	5·5				
−40	−3·4	−3·4	−3·3	−3·4	−3·37	3·6	3·7	3·8	3·7	3·7	5·8				
−50	−3·2	−3·3	—	—	—	3·8	3·7	—	—	—	6·0				
−60															

d by a given Variation of Carbonic Acid.

bonic Acid = 2·0.				Carbonic Acid = 2·5.					Carbonic Acid = 3·0.				
May.	June–Aug.	Sept.–Nov.	Mean of the year.	Dec.–Feb.	March–May.	June–Aug.	Sept.–Nov.	Mean of the year.	Dec.–Feb.	March–May.	June–Aug.	Sept.–Nov.	Mean of the year.
6·1	6·0	6·1	6·05	7·9	8·0	7·9	8·0	7·95	9·1	9·3	9·4	9·4	9·3
6·1	5·8	6·1	6·02	8·0	8·0	7·6	7·9	7·87	9·3	9·5	8·9	9·5	9·3
6·1	5·5	6·0	5·92	8·0	7·9	7·0	7·9	7·7	9·5	9·4	8·6	9·2	9·17
5·8	5·4	5·6	5·7	7·9	7·6	6·9	7·3	7·42	9·3	9·0	8·2	8·8	8·82
5·4	5·0	5·2	5·3	7·2	7·0	6·6	6·7	6·87	8·7	8·3	7·5	7·9	8·1
5·0	4·9	5·0	5·02	6·7	6·6	6·3	6·6	6·52	7·9	7·5	7·2	7·5	7·52
5·0	4·9	4·9	4·95	6·6	6·4	6·3	6·4	6·42	7·4	7·3	7·2	7·3	7·3
4·9	5·0	5·0	4·95	6·4	6·4	6·6	6·6	6·5	7·3	7·3	7·4	7·4	7·35
5·0	5·2	5·1	5·07	6·6	6·6	6·7	6·7	6·65	7·4	7·5	8·0	7·6	7·62
5·3	5·5	5·4	5·35	6·7	6·8	7·0	7·0	6·87	7·9	8·1	8·6	8·3	8·22
5·6	5·8	5·6	5·62	7·0	7·2	7·7	7·4	7·32	8·6	8·7	9·1	8·8	8·8
6·0	6·0	6·0	5·95	7·7	7·9	7·9	7·9	7·85	9·1	9·2	9·4	9·3	9·25
6·1	—	—	—	7·9	8·0	—	—	—	9·4	9·5	—	—	—

By means of these values, I have calculated the mean alteration of temperature that would follow if the quantity of carbonic acid varied from its present mean value (K = 1) to another, viz. to K = 0·67, 1·5, 2, 2·5, and 3 respectively. This calculation is made for every tenth parallel, and separately for the four seasons of the year. The variation is given in Table VII.

A glance at this Table shows that the influence is nearly the same over the whole earth. The influence has a minimum near the equator, and increases from this to a flat maximum that lies the further from the equator the higher the quantity of carbonic acid in the air. For K = 0·67 the maximum effect lies about the 40th parallel, for K = 1·5 on the 50th, for K = 2 on the 60th, and for higher K-values above the 70th parallel. The influence is in general greater in the winter than in the summer, except in the case of the parts that lie between the maximum and the pole. The influence will also be greater the higher the value of ν, that is in general somewhat greater for land than for ocean. On account of the nebulosity of the Southern hemisphere, the effect will be less there than in the Northern hemisphere. An increase in the quantity of carbonic acid will of course diminish the difference in temperature between day and night. A very important secondary elevation of the effect will be produced in those places that alter their albedo by the extension or regression of the snow-covering (see p. 257), and this secondary effect will probably remove the maximum effect from lower parallels to the neighbourhood of the poles *.

It must be remembered that the above calculations are found by interpolation from Langley's numbers for the values K = 0·67 and K = 1·5, and that the other numbers must be regarded as extrapolated. The use of Pouillet's formula makes the values for K = 0·67 probably a little too small, those for K = 1·5 a little too great. This is also without doubt the case for the extrapolated values, which correspond to higher values of K.

We may now inquire how great must the variation of the carbonic acid in the atmosphere be to cause a given change of the temperature. The answer may be found by interpolation in Table VII. To facilitate such an inquiry, we may make a simple observation. If the quantity of carbonic acid decreases from 1 to 0·67, the fall of temperature is nearly the same as the increase of temperature if this quantity augments to 1·5. And to get a new increase of this order of magnitude (3°·4), it will be necessary to alter the quantity of carbonic acid till it reaches a value nearly midway between 2 and 2·5.

* See Addendum, p. 275.

Thus if the quantity of carbonic acid increases in geometric progression, the augmentation of the temperature will increase nearly in arithmetic progression. This rule—which naturally holds good only in the part investigated—will be useful for the following summary estimations.

V. 5. *Geological Consequences.*

I should certainly not have undertaken these tedious calculations if an extraordinary interest had not been connected with them. In the Physical Society of Stockholm there have been occasionally very lively discussions on the probable causes of the Ice Age; and these discussions have, in my opinion, led to the conclusion that there exists as yet no satisfactory hypothesis that could explain how the climatic conditions for an ice age could be realized in so short a time as that which has elapsed from the days of the glacial epoch. The common view hitherto has been that the earth has cooled in the lapse of time; and if one did not know that the reverse has been the case, one would certainly assert that this cooling must go on continuously. Conversations with my friend and colleague Professor Högbom, together with the discussions above referred to, led me to make a preliminary estimate of the probable effect of a variation of the atmospheric carbonic acid on the temperature of the earth. As this estimation led to the belief that one might in this way probably find an explanation for temperature variations of 5°–10° C., I worked out the calculation more in detail, and lay it now before the public and the critics.

From geological researches the fact is well established that in Tertiary times there existed a vegetation and an animal life in the temperate and arctic zones that must have been conditioned by a much higher temperature than the present in the same regions *. The temperature in the arctic zones appears to have exceeded the present temperature by about 8 or 9 degrees. To this genial time the ice age succeeded, and this was one or more times interrupted by interglacial periods with a climate of about the same character as the present, sometimes even milder. When the ice age had its greatest extent, the countries that now enjoy the highest civilization were covered with ice. This was the case with Ireland, Britain (except a small part in the south), Holland, Denmark, Sweden and Norway, Russia (to Kiev,

* For details *cf.* Neumayr, *Erdgeschichte*, Bd. 2, Leipzig, 1887; and Geikie, 'The Great Ice-Age,' 3rd ed. London, 1894; Nathorst, *Jordens historia*, p. 989, Stockholm, 1894.

Annex 4

T. C. Chamberlin, “An Attempt to Frame a Working Hypothesis of the Cause of Glacial Periods on an Atmospheric Basis”, *The Journal of Geology,* 1899, pp. 545-556, pages 545, 550-556

AN ATTEMPT TO FRAME A WORKING HYPOTHESIS OF THE CAUSE OF GLACIAL PERIODS ON AN ATMOSPHERIC BASIS [1]

THERE are hypotheses and working hypotheses. The suggestion that the last glacial period was caused by the passage of the solar system through a cold region of space may be styled a hypothesis, but scarcely a working hypothesis in the geological sense, for it does not form the groundwork or incentive of geological inquiry. An astronomer might be moved to hunt for the cold spot, but it has no inspiration for the geologist. General suggestions of a possible cause do not reach the dignity of working hypotheses until they are given concrete form, are fitted in detail to the specific phenomena, and are made the agents of calling into play effective lines of research. The construction of a concrete working hypothesis suited to stimulate and guide investigation in a wholesome manner, and to take its place in competition with other hypotheses of like working potentialities, thereby inducing a more searching scrutiny of the phenomena and a more varied application of interpretations, represents the higher limit of present reasonable aspiration. It is much too ambitious to hope for a demonstrative solution of the origin of the earth's glacial periods by first intention in the present state of knowledge.

The hypothesis here offered is not worked out into satisfactory detail at all points, but it is hoped that it is sufficiently matured to justify a preliminary statement. In forming it, which has been the work of several years, I have found, or seemed to find, the phenomena of past glaciation intimately associated with a long chain of other phenomena to which at

[1] A brief statement of the salient features of this hypothesis was given in a paper entitled A Group of Hypotheses Bearing on Climatic Changes, JOUR. GEOL., Vol. V, pp. 653–683, Oct.–Nov. 1897. For earlier history see footnotes on pp. 654 and 681 of that paper.

when the great saline deposits of New York, Ontario, Ohio, Michigan and adjacent regions were laid down.

Primary assumptions.— (1) It is therefore assumed as the working basis of the hypothesis that the carbon dioxide of the Paleozoic atmosphere was at certain stages not essentially greater than it is today, that at the specific epochs of great saliferous deposition and of glaciation it was reduced to a quantity notably less than the present content, while at other and intervening stages its amount exceeded the present content by some multiple —these latter periods being those in which the wide extension of marine epicontinental life took place. For myself, I am disposed to extend the assumption of a measurably limited atmosphere back to the very beginning. To this I am led in part by the conviction that the gravitation of the earth is incompetent to hold an atmosphere very greatly beyond the amount so assumed, and by the much more speculative consideration that the earth may have grown up by slow accretion rather than rapid concentration, and that hence the early development of the atmosphere was controlled by limitations much like those that have affected it in its later history. But, as already remarked, this assumption is not regarded as vital to the hypothesis. (2) Wrapped up in the foregoing postulate is an assumption of the essential correctness of the doctrine of Arrhenius that variations of the atmospheric carbon dioxide falling within limits compatible with life and with other geological phenomena, are competent to effectively change the thermal state of the atmosphere. This needs further statement.

The functions of carbon dioxide.— By the investigations of Tyndall,[1] Lecher and Pretner,[2] Keller,[3] Rœntgen,[4] and Arrhenius,[5] it

[1] Heat as a Mode of Motion, 6th ed., pp. 345–349, 1892. Contrib. to Mol. Physics, pp. 38. 117, 421, 1888.

[2] Sitzungsberichte des Akad. der Wissenschaften d. Wien (2). Vol. LXXXII, p. 851 (2), Vol. LXXXVI, p. 52.

[3] Am. Jour. Sci. (3), Vol. XXVIII, p. 190.

[4] Poggendorfs Annalen (2), Vol. XXIII, p. 1259.

[5] Phil. Mag., Vol. XLI, pp. 237–279.

A brief statement of the conclusions of these authors is given in the article of Mr. Tolman in this number, p. 586. See also his review of Dr. Arrhenius, p. 623.

has been shown that the carbon dioxide and water vapor of the atmosphere have remarkable power of absorbing and temporarily retaining heat rays, while the oxygen, nitrogen, and argon of the atmosphere possess this power in a feeble degree only. It follows that the effect of the carbon dioxide and water vapor is to blanket the earth with a thermally absorbent envelope. Their absence would leave the surface of the earth essentially exposed to the free impact and free radiation of the solar rays, measurably, though of course not entirely, as if the earth were devoid of atmosphere. A reduction or an increase in these constituents would produce corresponding partial effects. The general results assignable to a greatly increased or a greatly reduced quantity of atmospheric carbon dioxide and water may be summarized as follows:[1]

a. An increase, by causing a larger absorption of the sun's radiant energy, raises the average temperature, while a reduction lowers it. The estimate of Dr. Arrhenius, based upon an elaborate mathematical discussion of the observations of Professor Langley, is that an increase of the carbon dioxide to the amount of two or three times the present content would elevate the average temperature 8° or 9° C. and would bring on a mild climate analagous to that which prevailed in the Middle Tertiary age.[2] On the other hand, a reduction of the quantity of carbon dioxide in the atmosphere to an amount ranging from 55 to 62 per cent. of the present content, would reduce the average temperature 4° or 5° C., which would bring on a glaciation comparable to that of the Pleistocene period.

The amount of moisture in the atmosphere, other things being equal, is directly dependent upon the temperature, and the temperature in turn is dependent upon the amount of moisture in the atmosphere. This reciprocal dependence renders the aqueous

[1] The action has two phases that in an exhaustive exposition would need separate statement, (1) the absorption of solar rays before they reach the earth, and (2) the absorption of the rays radiated by the earth. The latter have longer wave-lengths on the average and are relatively much more affected by the constitution of the atmosphere.

[2] Dr. Arrhenius, loc. cit.

vapor a vacillating factor subject to the control of any other agency which increases or decreases the atmospheric temperature. Whenever therefore an increase of carbon dioxide raises the temperature, it increases the quantity of water vapor and this by its thermal absorption further increases the temperature and calls forth more vapor and this action and reaction continue in diminishing force until an equilibrium is established. A decrease in carbon dioxide decreases the temperature and thus lessens the water vapor, and this further lowers the temperature and inaugurates a reversed series of actions and reactions. Fluctuation in the quantity of carbon dioxide therefore is attended not simply by its own individual effects, but by these auxiliary effects also. The carbon dioxide becomes therefore the determinative factor, and the question of the thermal absorption of the atmosphere may be discussed for convenience as though it were solely dependent upon the fluctuations in the content of this constituent, although this will not be strictly exhaustive.

b. A second effect of increase and decrease in the amount of atmospheric carbon dioxide is the equalization, on the one hand, of surface temperatures, or their differentiation on the other. The temperature of the surface of the earth varies with latitude, altitude, the distribution of land and water, day and night, the seasons, and some other elements that may here be neglected. It is postulated that an increase in the thermal absorption of the atmosphere *equalizes* the temperature, and tends to eliminate the variations attendant on these contingencies. Conversely, a reduction of thermal atmospheric absorption tends to *intensify* all of these variations. A secondary effect of intensification of differences of temperature is an increase of atmospheric movements in the effort to restore equilibrium. Increased atmospheric movements, which are necessarily convectional, carry the warmer air to the surface of the atmosphere, and facilitate the discharge of the heat and thus intensify the primary effect. In the case of a naked earth, the radiant energy of the sun falling directly upon the tropical belt is concentrated in space, and subject to the minimum reflection; in high latitudes, the rays

are spread over greater space, and are subject to greater relative reflection because of the low angle of incidence. In the case of an earth swathed in a thermally absorptive mantle, the direct equatorial ray is absorbed in traversing the atmosphere to a less extent than the ray of higher latitudes because it penetrates a less depth of atmosphere, while the amount of reflection from the atmosphere is small in both cases, so far as the transparent elements are concerned. In so far therefore as the temperature effects are dependent upon the absorption of the incoming rays, the greater depth of atmosphere penetrated in the higher latitudes makes important compensation for obliquity of incidence.

In the case of a naked earth, or an earth clothed with a non-absorptive atmosphere, the solar rays which are tangential to the polar regions have no heating influence upon the earth, while in the case of an earth clothed with an absorbent atmosphere, similar rays are partially absorbed, and serve to warm the earth. In the polar regions, therefore there is a very radical difference between the effects of an absorbent and a non-absorbent atmosphere. The same holds true of the heating effects of the morning and evening sun. With a non-absorbent atmosphere, the tangential morning and evening rays pass through and are lost; in a thermally absorbent atmosphere, they are effectually retained.

In so far as the incoming rays are absorbed in the atmosphere their immediate effects are chiefly felt in its upper strata and their influence upon the surface of the earth is lessened. This is due to the fact that the upper regions are penetrated by rays of all the various wave-lengths that emanate from the sun, while the lower portions are penetrated only by such rays as are left after the selective absorption of the upper atmosphere. The degree of this absorption of the rays of long wave-lengths is such that comparatively little further absorption takes place in the basal portion of the atmosphere, according to the interpretations of Arrhenius. One effect of increasing the absorptive capacity of the upper air by increasing the amount of carbonic acid is an increase in the elevation of the strata chiefly heated by the

incoming rays and the consequent reduction of the thermal gradient of a vertical column of the atmosphere. As a result there is less effective tendency to convection and less discharge of heat from the atmosphere.

In high latitudes, besides this effect, it is also to be noted that with an increase of the absorptive capacity of the upper atmosphere, rays that previously passed through the higher strata with little absorption are arrested and contribute heat to the upper air. The same is true of morning and evening rays at high elevations.

In the case of the outgoing rays, which are absorbed in much larger proportions than the incoming rays because they are more largely long-wave rays, the tables of Arrhenius[1] show that the absorption is augmented by increase of carbonic acid in greater proportions in high latitudes than in low; for example, the increase of temperature for three times the present content of carbonic acid is 21.5 per cent. greater between 60° and 70° N. latitude than at the equator. The maximum thermal effects also lie in higher latitudes for the summer months than for the winter months. On the other hand, when the carbonic acid is reduced to 0.67 of the present content, the maximum winter variation is felt between 30° and 40° N. latitude. If the carbonic acid be further reduced, the maximum variation found by extrapolation falls at and below 30°, the latitude of the Carboniferous glaciation. It is not intended, however, to imply that this would be sufficient in itself to produce that glaciation.

An atmosphere having a relatively large percentage of carbon dioxide and water, *i. e.*, an absorptive atmosphere, has a higher heat content than a non-absorptive one, and its circulation in latitude more effectually equalizes the temperature with the same degree of movement.

Similar considerations are applicable to the effects of land and water areas. In so far as the atmosphere absorbs the incoming rays in passing through it, the amount that reaches the surface of the earth is reduced. To this extent the possibility of

[1] Loc. cit., p. 266.

differential effects between the sea and land is lessened. On the other hand, in the absence of absorptive and diffusive effects, the tropical rays fall with full intensity upon the surface. On the land they promptly heat the immediate surface, and the heat is as promptly radiated away. On the sea, neglecting reflection, they penetrate deeply into the water until they are absorbed. The upper layer of the sea is therefore heated to a notable depth, and radiates its heat away with relative slowness. The result is an intensification of the differences in average temperature of the land and the sea. This action is quite familiar, but perhaps not the point here urged—that this difference is dependent on the atmospheric effects upon the incoming as well as outgoing rays. If the atmosphere were so far robbed of its absorbent factors, carbon dioxide and water, as to give great intensity to this differential effect, the result might be an average temperature of the land below the freezing point, while that of the sea might be relatively warm. It seems clear that at some point short of an absolute thermal transparency a stage would be reached where the average temperature of the land would sink below zero, while yet the sea, barring convection in latitude, would retain a comparatively mild temperature. There would then apparently arise, even in low latitudes, the conditions of glaciation.

Without following out these lines into greater detail, the more pertinent deductions may be summed up in the following propositions: A reduction of the thermal absorption of the atmosphere would intensify the differences of temperatures between (1) the basal and the upper portions of the atmosphere; (2) low and high latitudes; (3) land and sea; (4) night and day; and (5) the seasons. In short, it would intensify temperature differences generally, and would lead to (1) greater local heat, as well as greater local cold; (2) to greater local dryness, as well as greater local moisture; (3) to more intense movements of the atmosphere in the endeavor to maintain equilibrium; and (4) to lower average temperature. The effect of reducing the absorbent factors is the intensification of differences.

On the other hand, an increase in the absorptive factors renders ineffectual, in a corresponding degree, the variations of altitude, of latitude, of land and sea, of day and night, and of the seasons, and conduces to an equable and mild temperature, to gentle and yet thermally effective circulation, and to higher average temperature. As Arrhenius has remarked, "The geographical, annual, and diurnal changes of temperature would be partly smoothed away if the quantity of carbonic acid was augmented. The reverse would be the case (at least to a latitude of 50° from the equator) if the carbonic acid diminished in amount."[1]

AGENCIES OF DEPLETION AND ENRICHMENT

It now becomes necessary to assign agencies capable of removing carbon dioxide from the atmosphere at a rate sufficiently above the normal rate of supply, at certain times, to produce glaciation; and on the other hand, capable of restoring it to the atmosphere at certain other times in sufficient amounts to produce mild climates.

These agencies on both sides belong to two classes, the permanent and the temporary, and the distinction has practical importance.

Sources of permanent loss.—Permanent depletion results from the consumption of carbon dioxide in the transformation of the silicates of the original earth, and of volcanic products into the carbonates of the secondary strata. It is fairly safe to assume that the original earth's surface was composed of material of the general class represented by the igneous rocks and the basement complex. These, it is needless to say, consist largely of silicates with which are associated certain quantities of certain gases to be considered more fully hereafter. These silicates, where exposed to the weathering action of the atmosphere, become decomposed and take the form of carbonates (with less quantities of sulphates, phosphates, etc.) and of residual silicates and oxides (kaolin, quartz, ferric oxides, etc.). Neglecting the minor transformations which do not concern us here, the operation may be

[1] Loc. cit., p. 268.

Annex 5

G. Callendar, "The artificial production of carbon dioxide and its influence on temperature", *Quarterly Journal of the Royal Meteorological Society,* 1938, pp. 223-240, pages 223-225

551.510.4 : 551.521.3 : 551.524.34

THE ARTIFICIAL PRODUCTION OF CARBON DIOXIDE AND ITS INFLUENCE ON TEMPERATURE

By G. S. CALLENDAR

(Steam technologist to the British Electrical and Allied Industries Research Association.)

(Communicated by Dr. G. M. B. DOBSON, F.R.S.)

[Manuscript received May 19, 1937—read February 16, 1938.]

SUMMARY

By fuel combustion man has added about 150,000 million tons of carbon dioxide to the air during the past half century. The author estimates from the best available data that approximately three quarters of this has remained in the atmosphere.

The radiation absorption coefficients of carbon dioxide and water vapour are used to show the effect of carbon dioxide on " sky radiation." From this the increase in mean temperature, due to the artificial production of carbon dioxide, is estimated to be at the rate of 0·003°C. per year at the present time.

The temperature observations at 200 meteorological stations are used to show that world temperatures have actually increased at an average rate of 0·005°C. per year during the past half century.

Few of those familiar with the natural heat exchanges of the atmosphere, which go into the making of our climates and weather, would be prepared to admit that the activities of man could have any influence upon phenomena of so vast a scale.

In the following paper I hope to show that such influence is not only possible, but is actually occurring at the present time.

It is well known that the gas carbon dioxide has certain strong absorption bands in the infra-red region of the spectrum, and when this fact was discovered some 70 years ago it soon led to speculation on the effect which changes in the amount of the gas in the air could have on the temperature of the earth's surface. In view of the much larger quantities and absorbing power of atmospheric water vapour it was concluded that the effect of carbon dioxide was probably negligible, although certain experts, notably Svante Arrhenius and T. C. Chamberlin, dissented from this view.

Of recent years much new knowledge has been accumulated which has a direct bearing upon this problem, and it is now possible to make a reasonable estimate of the effect of carbon dioxide on temperatures, and also of the rate at which the gas accumulates in the atmosphere. Amongst important factors in such calculations may be mentioned the temperature-pressure-alkalinity-CO_2 relation for sea water, determined by C. J. Fox (1909), the vapour pressure-atmospheric radiation relation, observed by A. Angstrom (1918) and others, the absorption spectrum of atmospheric water vapour, observed by Fowle (1918), and a full knowledge of the thermal structure of the atmosphere.

This new knowledge has been used in arriving at the conclusions stated in this paper, but for obvious reasons only those parts having a meteorological character will be referred to here.

1. THE RATE OF ACCUMULATION OF ATMOSPHERIC CARBON DIOXIDE

I have examined a very accurate set of observations (Brown and Escombe, 1905), taken about the year 1900, on the amount of carbon dioxide in the free air, in relation to the weather maps of the period. From them I concluded that the amount of carbon dioxide in the free air of the North Atlantic region, at the beginning of this century, was $2{\cdot}74 \pm 0{\cdot}05$ parts in 10,000 by volume of dry air.

A great many factors which influence the carbon cycle in nature have been examined in order to determine the quantitative relation between the natural movements of this gas and the amounts produced by the combustion of fossil fuel. Such factors included the organic deposit of carbon in swamps, etc., the average rate of fixation of the gas by the carbonisation of alkalies from igneous rocks, and so on. The general conclusion from a somewhat lengthy investigation on the natural movements of carbon dioxide was that there is no geological evidence to show that the *net* offtake of the gas is more than a small fraction of the quantity produced from fuel. (The artificial production at present is about 4,500 million tons per year.)

The effect of solution of the gas by the sea water was next considered, because the sea acts as a giant regulator of carbon dioxide and holds some sixty times as much as the atmosphere. The rate at which the sea water could correct an excess of atmospheric carbon dioxide depends mainly upon the fresh volume of water exposed to the air each year, because equilibrium with the atmospheric gases is only established to a depth of about 200 m. during such a period.

The vertical circulation of the oceans is not well understood, but several factors point to an equilibrium time, in which the whole sea volume is exposed to the atmosphere, of between two and five thousand years. Using Fox's solution coefficients for sea water of known total alkalinity and average surface temperature, it is possible to calculate the change in atmospheric CO_2 pressure over a given

TABLE I.—THE EFFECT OF THE ARTIFICIAL PRODUCTION OF CARBON DIOXIDE UPON ITS PRESSURE IN THE ATMOSPHERE.

Annual net addition of CO_2 to the air = 4,300 million tons.

Total pressure from CO_2 = 0·000274 atmospheres in the year 1900.
Sea surface at 15°C. and total alkalinity = 40 mg. of negative hydroxyl ions per litre; it is this quantity which is maintained neutral by the dissolved CO_2.
P (CO_2) stands for the pressure of CO_2 in the air at normal barometric pressure.

Sea equilibrium time, years	Date: 1936	2000	2100	2200
	P (CO_2) in atmos./10,000			
2000	2·89	3·14	3·46	3·73
5000	2·90	3·17	3·58	3·96
All CO_2 to the air	2·96	3·35	3·96	4·58

From 1900 to 1936 the increase should be close to 6 per cent.

period, when the rate of addition of the gas is known and the equilibrium time for the sea water is assumed. A few such figures are given in Table I, and it will be seen that when periods of a few centuries are considered the sea equilibrium time is less important.

Since calculating the figures in Table I, I have seen a report of a great number of observations on atmospheric CO_2, taken recently in the eastern U.S.A. The mean of 1,156 "free air" readings taken in the years 1930 to 1936 was 3·10 parts in 10,000 by volume. For the measurements at Kew in 1898 to 1901 the mean of 92 free air values was 2·92, including a number of rather high values effected by local combustion, etc.; and assuming that a similar proportion of the American readings are affected in the same way, the difference is equal to an increase of 6 per cent. Such close agreement with the calculated increase is, of course, partly accidental.

2. Infra-red absorption by carbon dioxide and water vapour

The loss of heat from the earth's surface and atmosphere is nearly all carried upon wave lengths greater than 4μ, the maximum intensity being at about 10μ.

There have been a great many careful and accurate measurements of the absorption and radiation by various gases in this part of the spectrum, but owing to the very great difficulties attending these observations most of the earlier values were highly conflicting. However, considerable accuracy has now been attained, and from a number of considerations, which cannot be detailed, the values observed by Rubens and Aschkinass (1898), of Germany, are used here for the absorption by carbon dioxide on the longer wave lengths.

For water vapour I have made many comparisons between the measurements of F. E. Fowle (1918), who observed the absorption by atmospheric water vapour, and those of Rubens and of Hettner (1918), who used steam at 1 atmos. pressure for their measurements. These comparisons fully support the conclusion arrived at by Fowle, that the absorption by water vapour as it occurs in the air is less than half as great as that found for steam under laboratory conditions. Perhaps the most powerful support for this conclusion comes from a comparison between the observed and calculated atmospheric radiation, which shows that, for dry and cold air conditions, the absorption exponents found for steam lead to much too high a value for atmospheric radiation.

To return to the absorption by carbon dioxide, the three primary bands given by this gas are at 2·4 to 3·0 μ, 4 to 4·6 μ, and 13 to 16 μ, the latter being much the most important for atmospheric conditions because very little low temperature radiation is carried on the small bands.

The relation between absorption and quantity of gas is usually expressed as

$$A_\lambda = 1 - e^{-kl} \quad . \quad . \quad . \quad . \quad (1)$$

where A_λ is the absorption by l units of gas in the path of radiation of wave length λ, k being the absorption exponent for the gas at

Annex 6

G. Callendar, “Variations of the amount of carbon dioxide in different air currents”, *Quarterly Journal of the Royal Meteorological Society,* 1940, pp. 395-400, pages 395, 398-400

551.510.4

VARIATIONS OF THE AMOUNT OF CARBON DIOXIDE IN DIFFERENT AIR CURRENTS

By G. S. CALLENDAR

SUMMARY

The first measurements to determine the composition of the atmosphere were made at least 180 years ago, but chemists worked more than a century before they obtained really accurate values for the amount of carbon dioxide in the air.

In the following a brief review is given of the present state of knowledge concerning the variations of atmospheric carbon dioxide, together with some observations which appear to show that the amount of this gas in the air has increased of late years.

CAUSES OF VARIATIONS OF CO_2 IN DIFFERENT AIR CURRENTS

The changes of the amount of CO_2 in the air which are often observed during quiet weather are generally of local origin, and are caused by organic or human activities; but the variations occurring in the great wind currents have a more fundamental basis which seems to be connected with the differences of CO_2 pressure in the surface waters of the oceans.

Theoretical considerations suggest that this gas should be more abundant in the air of equatorial regions than elsewhere, because:— (*a*) The CO_2 pressure in water varies directly with the temperature, so that warming water gives up the gas to the air, whilst cooling water withdraws it. (*b*) Owing to organic action CO_2 tends to accumulate in deep water; in equatorial regions, where this water rises to the surface, the excess gas is returned to the air. These considerations are supported both by observations in the water and in the air. For the water the extensive and well-spaced measurements taken by the "Meteor" expedition (Wattenberg, 1933) in the Atlantic Ocean, have been used to compute the average CO_2 pressure in the surface layers 0 to 50 metres depth; the following pressures were obtained:—

Equatorial region,	20N. to 20S.	Lat.,	from 291	observations,	3·27 atmos./10,000
Temperate ,,	40S. to 60S.	Lat., ,,	192	,,	2·99 ,, ,,

The amount of CO_2 in the air of these southern latitudes was measured by Muntz and Aubin (1886), whose observations are known to be amongst the most reliable which have been made; they obtained the following mean values, in volumes of CO_2 per million volumes of air, from readings taken over a period of several months in each region:—

West Indies region,	20N.	Lat.,	from 40	observations,	284 parts per million
S. American ,,	40S.	Lat., ,,	34	,,	272 ,, ,, ,,
At Cape Horn	56S.	Lat., ,,	39	,,	256 ,, ,, ,,

It will be seen that the amount of CO_2 in the air shows a marked falling off in high southern latitudes, the actual difference being

air supply came from far to the south, and the most consistently low values during periods of windy unsettled weather with numerous depressions moving in from the Atlantic. For long easterly winds the results were more variable, being generally high during winter and spring, but often below the average in summer and autumn. Long north-westerly and northerly winds present a difficulty owing to the restricted area of the early weather maps, and when these winds were associated with a large anticyclone to the west they often gave rather high CO_2 values. The relatively low value for marine air at Kew is partly caused by the consistently low readings obtained at this station during very strong winds, for neither of the other sets shows a marked deficiency of CO_2 during gales.

Seasonal variation of CO_2

All the observations mentioned under (1) to (5) above have been arranged on a monthly basis to see whether the average amount of CO_2 varies at different times of year. The seasonal means obtained from over 1,000 observing days, between 1872 and 1901, are as follows:—

Spring = 297·1, summer = 290·5, autumn = 294·4, winter = 296·5.

The fall in the amount of CO_2 between spring and summer is partly due to meteorological factors, prevailing winds, etc., and partly to the actual reduction of the amount in the air to supply the seasonal growth of plants.

Measurements in the twentieth century

The close agreement attained by the observers in the latter part of the nineteenth century was doubtless the cause of the scarcity of CO_2 measurements during the first thirty years of the present century. The only systematic observations in the free air during this period seem to have been those of the long series at the Nutrition Institution, Boston (Benedict, 1912). These readings were of the rapid type, made with a small volume of air, and were not accurate enough for correlation with wind direction, etc., but the basis seems to have been reliable and the mean value obtained is included in Table II.

K. Buch at Petsamo Fjord, 1934-35

The numerous observations by Professor Buch, of Abo, Finland, make a very welcome addition to the long series of CO_2 measurements, their accuracy appearing to equal that of the best nineteenth century observations.

Prof. Buch gives the following values for the amount of CO_2 in the air currents reaching Petsamo Fjord, North Finland, from a long series of measurements made in 1934 and 1935:—

Continental = 332, Marine = 329, Arctic = 310 p.p.m.

He attributes the deficiency of CO_2 in the arctic winds of this region to absorption of the gas by the cold waters between Greenland and Nova Zemla.

Buch also made a number of observations whilst crossing the north Atlantic Ocean in temperate latitudes; the mean of these

(Table II) was almost the same as at Petsamo, but, as would be expected, the variation for the different air masses was less.

A secular increase of carbon dioxide

It will have been noticed that the values obtained by Prof. Buch are somewhat larger than those recorded by the nineteenth century observers, the difference of the mean values being as much as 10 per cent. In order to see how far this increase is supported by other measurements a number of the most reliable mean values have been assembled in Table II to cover the whole period, of about seventy years, since accurate observations were first made.* Measurements which were not designed to give the highest precision have been omitted. In nearly all cases the mean values have been computed from the single readings given in the original papers.

TABLE II.—THE OBSERVED PROPORTION OF CARBON DIOXIDE IN THE AIR, 1866-1935. VOLUMES CO_2 PER MILLION VOLUMES OF AIR

Authority	Location	Date	No. obs.	Mean CO_2
T. Thorpe.	North Atlantic . . .	1866	51	295
F. Schulze.	Rostock.	1868-71	1034	292
J. Reiset	Near Dieppe . . .	1872-73	80*b*	292*a*
A. Levy	Montsouris, Observatory	1876-87	(1000)	292
G. Armstrong. . . .	Grasmere, England. .	1879	53*b*	296
J. Reiset	Near Dieppe . . .	1879-80	89*b*	291*a*
Muntz & Aubin . . .	France (country) . .	1881	64	287*a*
Petermann & Graftiau .	Near Gembloux. . .	1889-91	525	294
Letts & Blake. . . .	Near Belfast . . .	1897	64	289*a*
Brown & Escombe . .	Kew Gardens . . .	1898-01	92	294*a*
F. Benedict	Near Boston, Mass. .	1909-12	645	303
K. Buch	North Atlantic . . .	1932	28	318
K. Buch	Petsamo, Finland . .	1934-35	95	321*a*
K. Buch	North Atlantic . . .	1935	53	320
J. Haldane.	Near Perth, Scotland .	1935	152	324

a Thought to be the most accurate values; *b* excluding night values.

The modern measurements in Table II show an increase over those taken in the nineteenth century of approximately 30 p.p.m. of CO_2; if this increase is assumed to have occurred throughout the whole atmosphere, then the additional mass of CO_2 in the air would be 200,000 million tons. In the period between 1900 and 1935 the amount of coal and oil burnt has been very nearly 50,000 million tons, equal to the direct addition to the atmosphere of 150,000 million tons of CO_2. As by far the larger proportion of this has been produced in the North Temperate zone, where the observations were also made, the greater increase found in the air might be due to incomplete mixing of the whole atmosphere.

For the period from 1866 to 1900 the amount of CO_2 produced by the combustion of fossil carbon was relatively small, and the observations do not record a change in the air.

The importance of the sea water in regulating the amount of CO_2 in the air has already been mentioned, and one would expect to find that a considerable part of the gas produced from fuel had been absorbed by the sea; but the observations in Table II appear to

* In the early part of last century most of the values obtained were far too large, often by 200 or 300 per cent, because nearly all the common errors of the CO_2 measurement tend to increase the apparent value.

show that all this extra gas has remained in the air. The most probable reason for the failure of the sea to absorb the excess can be traced to the very slow vertical circulation in the oceans; for it is only the shallow contact surface, about 1·3 per cent of the whole volume, which quickly reaches equilibrium with the atmospheric gases, and the period required for the whole volume of water to pass through this surface zone has been estimated at several thousand years. Also the excess CO_2 pressure has only reached about 0·00002 atmos. at present, and this is not large enough to force much of the gas into the surface zone.

Thus, although the total capacity of the sea water to absorb CO_2 is immense, it is very slow in action, and will doubtless take many centuries to stabilise the great eruption of this gas, now about 300 million cubic metres per hour, which has resulted from human activities. There is, of course, no danger that the amount of CO_2 in the air will become uncomfortably large because as soon as the excess pressure in the air becomes appreciable, say about 0·0003 atmos., the sea will be able to absorb this gas as fast as it is likely to be produced.

References

Armstrong, G. F. 1880 *Proc. Roy. Soc.*, **30**, 343.

Benedict, F. G. 1912 *Pub. Carnegie Inst.*, No. 166.

Brown, H., and Escombe, F. 1905 *Proc. Roy. Soc.*, B, **76**, 118.

Buch, K. 1939 *Acta Acad. Abo*, Math. and Phys., **11**, No. 12.

Haldane, J. B. S. 1936 *Nature, Lond.*, **137**, 575.

Letts, E., and Blake, R. 1900 *Sci. Proc. R. Dublin Soc.*, **9**, N.S., Part 2, 107.

Levy, A. 1877, etc. *Annu. Obs. Montsouris.*

Muntz, A., and Aubin, E. 1886 *Recherches sur la constitution chimique de l'atmosphère*, **3**, Les Ministères de la Marine et de l'Instruction Publique, Paris.

Petermann, A., and Graftiau, J. 1892 *Mém. cour. Acad. R. Belg.*, **47**, 87.

Reiset, J. A. 1882 *Ann. Chim.*, **28**, 145.

Schulze, F. 1871 *Landw. Vers-Stationen*, **14**, 366.

Thorpe, T. E. 1867 *J. Chem. Soc. Lond.*, **5**, 189.

Wattenberg, H. 1933 *Wissen. Ergb. der Deutschen Atlantischen Expd. auf dem Forschungs- und Vermessungsschiff "Meteor.,"* 1925-1927, **8**.

Annex 7

G. Callendar, “Can carbon dioxide influence climate?”, *Weather,* 1949, pp. 310-314

CAN CARBON DIOXIDE INFLUENCE CLIMATE?

By G. S. Callendar

An interpretation of climatic change in terms of the variable carbon dioxide content of the atmosphere was first proposed some sixty years ago by the famous Swedish physicist, Sevante Arrhenius, who made some of the classic experiments on the absorption of heat radiation by gases. Since then the theory has had a chequered history; it was abandoned for many years when the preponderating influence of water vapour radiation in the lower atmosphere was first discovered, but was revived again a few years ago when more accurate measurements of the water vapour spectrum became available.

Reduced to its simplest terms this theory depends on the fact that, whereas carbon dioxide is almost completely transparent to solar radiation, it is partially opaque to the heat which is radiated back to space from the earth. In this way it acts as a heat trap, allowing the temperature near the earth's surface to rise above the level it would attain if there were no carbon dioxide in the air. Two other gases in the atmosphere, water vapour and ozone, also possess this property of returning back towards the surface some of the low-temperature radiation which would otherwise escape directly to space. The former is present in such large quantities over most of the earth's surface that it plays by far the most important part in the radiation of the lower atmosphere.

It is mainly owing to the predominance of water vapour and the extreme irregularity of its absorption that attempts to assess the effect of carbon dioxide on temperatures have so far met with little success. Even in the laboratory the absorption of radiation by water vapour has proved an exceedingly difficult measurement, and after eighty years of experiments agreement is by no means complete. Carbon dioxide, however, has a simpler and more restricted spectrum and fair agreement has been attained for this gas (*Quart. J.R.Met. Soc.*, Vol. 67, 1941, p. 263).

In the present state of knowledge it seems probable that the change in temperature as a result of variations in carbon dioxide can best be evaluated by comparing the earth to a body receiving a constant supply of heat which is dissipated by radiation through a surrounding medium. Then it can be shown that

$$\frac{dT}{dE} = \frac{T}{4-4E}$$

where T is the temperature of the surface, and E is the emissivity of the surrounding medium towards the surface.

Changes in the amount of carbon dioxide affect the emissivity of the atmosphere at all levels, including the downward component at the surface, and these effects can be calculated with some accuracy from the known absorption coefficients. For example it is found that, with a temperature of 280° A and a downward emissivity of 0·70, a change to double the present

amount of carbon dioxide in the atmosphere should increase E by 1·3 per cent, equal to a temperature rise of 2·1° C (3·8° F) so long as it caused no interference with the heat supply to the surface. Such calculations would occupy too much space to elaborate here.

WHERE THE EFFECT OF CARBON DIOXIDE IS GREATEST

In considering the regions where variations in the amount of carbon dioxide will have most effect on the balance of heat-exchange, one naturally turns to those where the temperature is very low and the importance of water-vapour radiation is reduced ; but there are many low-lying regions of intense cold in the northern winter where the surface heat-loss is small and unimportant because there is little heat-supply from the stagnant air. The active regions of heat-loss in very cold air generally occur at higher levels in the atmosphere, or on elevated land masses such as Central Asia and the Antarctic Continent.

As an example of the former, the heavy convectional rainfall of the tropics depends very much upon the speed at which the middle and upper troposphere can rid itself of the heat energy which is constantly being sent up from below, mainly as the latent heat of water condensation. This heat is radiated away through the thin cold air of the stratosphere, in these regions almost devoid of the protecting layers of water-vapour. It contains, however, the usual proportions of carbon dioxide, in optical densities such that small changes have a relatively large effect on its absorption of radiation from below. Thus an increase of carbon dioxide could reduce the rate of heat-loss from the upper troposphere, which in turn could reduce the vigour of the convection currents and the rainfall, or, alternatively, allow surface temperatures to rise until a new balance was reached. An increase in the aridity of marginal tropical regions and a recession of the glaciers on high tropical mountains might be one of the first indications of this.

Another area of active heat-loss where changes of carbon dioxide could be very important is the upper surface of clouds. This area is vast and its loss of heat often occurs through very dry layers of the atmosphere ; thus, increase of carbon dioxide would mean slower cooling of clouds, perhaps accompanied by less persistent cloud cover and more effective solar heating at low levels.

In the great polar ice caps, where temperatures are very low, and yet for dynamical reasons the rate of heat loss is quite high, the effect of changes of carbon dioxide is doubtless more complex, although we might expect some temperature adjustment to balance the change of emissivity. Whether this temperature adjustment had any effect on convectional processes would depend on its difference from changes elsewhere in the atmosphere. There are many other effects which might be attributed to changes in the amount of carbon dioxide, but enough has been said to indicate where they are most likely to have some influence on world temperatures. The next step is to examine the possibility of such changes being brought about by human agency.

Although those who have studied radiation in the atmosphere will agree that variations of carbon dioxide could have significant effects in the regions just mentioned, they may be doubtful of the possibility of such variations being caused by human activities. For instance, we know that the green parts of plants use this gas to build up their structure, that sea-water can absorb it, that limestone is partially composed of it, and so on. These are all factors in the natural carbon cycle which has been so ably treated by Lundegath (*Der Kreislauf der Kohlensaure in der Natur*, Jena, 1924), Quinn and Jones (*Carbon Dioxide*, Reinhold, 1945) and several others ; but it is not possible to examine these factors here, beyond stating that they are part of a balance maintaining a fairly constant amount of this gas in the air.

It is only during the present century that man has exerted his influence on a sufficient scale to disturb nature's slow-moving carbon-balance, but now his demand for heat and power has led to the transfer of large quantities of " fossil " carbon from the rocks to the air. As one ton of coal or oil produces about three tons of carbon dioxide it is a simple matter to estimate the quantity of the latter derived from the known output of these fuels. This is now about 5,000 million tons per year. One part per million by volume (p.p.m.) in the whole atmosphere is equal to 8,000 million tons of carbon dioxide, the change in the latter over the years may be obtained and compared with the most reliable measurements as in Table 1.

Table 1.—*Estimated effect of fuel combustion on atmospheric* CO_2

Date	CO_2 from fuel as p.p.m.	Total air CO_2 p.p.m.	Observed value		
			Date	Authority	p.p.m.
to 1900	Small	290	1870–1900	Numerous (*a*)	290
1901–10	3	293	1910	Benedict (*a*)	303
1911–20	5	298	1922	Lundegath (*b*)	305
1921–30	5·5	303	1931	Carpenter (*c*)	310
1931–40	6	310	1935	Buch (*a*)	320
1941–50	6·5	316	—	—	—

Refs. : (*a*) See Callendar, 1940 *Quart. J. R. Met. Soc.*, Vol. 66, p. 395.
(*b*) *loc. cit.*
(*c*) 1937 *J. Amer. Chem. Soc.*, Vol. 59, p. 323.

The observed values in Table 1 appear to indicate a more rapid increase of carbon dioxide than that from fuel alone, but there are several other ways in which man's activities release this gas to the atmosphere in amounts reckoned in thousands of millions of tons ; chief among these are the clearance of forests and the drainage and cultivation of land, by which immense quantities of organic residues are exposed to bacterial oxidation. There is, however, no need for alarm at the possibility of the air becoming contaminated by too much carbon dioxide, because the waters of the oceans provide a reservoir of almost infinite capacity to absorb excess. As the deep waters of the sea move slowly and only a shallow contact surface is involved in the carbon-

dioxide equilibrium, this reservoir does not immediately control a sudden eruption of the gas such as has occurred this century. It will be hundreds or perhaps thousands of years before the sea absorbs its fair share.

Similarly it is possible for the percentage of carbon dioxide to vary considerably in periods of only a few centuries when some exceptional event absorbs large quantities. An example of this is the recolonization of continental areas by forests and peat at the close of the last glaciation.

THE PRESENT TREND OF CLIMATE

It will be seen from the foregoing that the amount of carbon dioxide in the atmosphere may be increased significantly by human activities ; and that there are reasons to expect some slight amelioration in climate to follow from the increase. Hence we may now consider whether the thermometer already shows signs of rising in synchronization with the increasing thickness of the carbon-dioxide radiation blanket, remembering that only very small changes of temperature are expected to occur in periods of a few decades, and that the pitfalls which await the uncritical who venture into this field are numerous. There remain, however, a fair number of temperature records from different parts of the world, of over half a century's duration, which will stand critical analysis both as regards accuracy and the stability of surrounding conditions.

Examination of the trend of mean temperature given by these long records shows that it has been upward during the last half-century in nearly all cases. A few typical figures (Table 2) indicate the order of the temperature rise over this period, as deviations in successive twenty-year means. Some attempt at random selection has been made by taking half the stations under the letter B which have the necessary length of record, and also a wide distribution over the earth.

Table 2.—The trend of temperature in various regions.

20-year deviations from the mean for 1880–1899, in tenths of a degree Fahrenheit.

20 years ending	Britain	Bergen	Boise	Bombay	Batavia	Buenos Aires
1909	3	0	6	3	3	2
1919	3	1	11	5	5	3
1929	4	3	10	7	7	4
1939	7	10	17	7	11	9
1948	10	—	—	—	—	—

Naturally, one would have to go into the history of these observations, comparing them with neighbouring rural sites and so on, before accepting the figures at their face value ; but, without going into details, it may be said that any other half-dozen stations selected at random from widely-scattered regions would show much the same average change of temperature as those given. In marginal sub-arctic regions changes three or four times as great have occurred in the last few decades, but here advectional influences are of paramount importance.

The variations of glaciers, often located in regions where there are no reliable temperature records of long duration, are perhaps even more significant of climatic change than the instrumental readings with their possibility of human error. That they have lately been receding in most parts of the world is well known ; recent evidence of this from the southern Andes and New Zealand is specially valuable, because of the lack of old temperature records in the southern hemisphere which can be said to be free from urban influence.

Naturally one would expect any change of climate due to variations in the atmospheric radiation to be world wide in its effects, although there is much doubt as to their nature in a region such as the Antarctic continent, where temperatures are below freezing point at all seasons. In fact, an increase in the amount of ice here might be the ultimate result of higher world temperatures. But in a short article such as this it is only possible to consider the broad outlines of the probable effect of carbon dioxide on climates, and we must be content to leave many of the problems associated with it for future research.

In conclusion it may be said that the climates of the world are behaving in a manner which suggests that slightly more solar heat is being retained in the atmosphere. This could be due to its increasing opacity to terrestrial heat as a result of the additions of carbon dioxide. But the coincidence by itself is no proof, because we do not know if the solar heat has remained constant over the period ; it does, however, provide an intriguing example where the expected happens on the grand scale.

METEOROLOGY IN GRAMMAR SCHOOLS

By S. E. Ashmore, B.Sc., A. Inst. P.

Honorary Meteorologist to the Borough of Wrexham

The Royal Meteorological Society, keenly aware of the instructional needs of the science which it sponsors, has always encouraged the formulation of schemes and the publication of informed opinion on the teaching of meteorology. The last article on the subject in its publications having appeared in 1931, the time is now opportune to review the question again. The weather being one of the most profound influences on mankind, there is a good case for making the study of it an important part of a curriculum, or at any rate, giving it more prominence than it has enjoyed hitherto. With the widening of man's activity in earth and sea and sky, the influence of the weather becomes a correspondingly greater factor and hence a wider understanding of its principles is desirable ; in this connection it is worth noting that among the Ministry of Education vacation courses planned for 1949 the science course in Norway includes meteorology. The teaching of the subject in schools is easier nowadays than ever before ; there is an increase in the number of teachers in schools with training in meteorology, many being ex-service meteorological personnel ; again, synoptic data are now readily available. This article is an expression of the writer's personal opinion on the question of teaching meteorology in Grammar Schools, most of the

Annex 8

G. Plass, “The Carbon Dioxide Theory of Climatic Change”, *Tellus,* 1956, pp. 140-154, pages 140-146, 149-150

The Carbon Dioxide Theory of Climatic Change

By GILBERT N. PLASS

The Johns Hopkins University, Baltimore, Md.[1]

(Manuscript received August 9 1955)

Abstract

The most recent calculations of the infra-red flux in the region of the 15 micron CO_2 band show that the average surface temperature of the earth increases 3.6° C if the CO_2 concentration in the atmosphere is doubled and decreases 3.8° C if the CO_2 amount is halved, provided that no other factors change which influence the radiation balance. Variations in CO_2 amount of this magnitude must have occurred during geological history; the resulting temperature changes were sufficiently large to influence the climate. The CO_2 balance is discussed. The CO_2 equilibrium between atmosphere and oceans is calculated with and without $CaCO_3$ equilibrium, assuming that the average temperature changes with the CO_2 concentration by the amount predicted by the CO_2 theory. When the total CO_2 is reduced below a critical value, it is found that the climate continuously oscillates between a glacial and an inter-glacial stage with a period of tens of thousands of years; there is no possible stable state for the climate. Simple explanations are provided by the CO_2 theory for the increased precipitation at the onset of a glacial period, the time lag of millions of years between periods of mountain building and the ensuing glaciation, and the severe glaciation at the end of the Carboniferous. The extra CO_2 released into the atmosphere by industrial processes and other human activities may have caused the temperature rise during the present century. In contrast with other theories of climate, the CO_2 theory predicts that this warming trend will continue, at least for several centuries.

1. Introduction

In 1861, TYNDALL wrote that "if, as the above experiments indicated, the chief influence be exercised by the aqueous vapour, every variation of this constituent must produce a change of climate. Similar remarks would apply to the carbonic acid diffused through the air... It is not, therefore, necessary to assume alterations in the density and height of the atmosphere to account for different amounts of heat being preserved to the earth at different times; a slight change in its variable constituents would suffice for this. Such changes in fact may have produced all the mutations of climate which the researches of geologists reveal. However this may be, the facts above cited remain: they constitute true causes, the *extent* alone of the operation remaining doubtful." A century of scientific work has been necessary in order to calculate with any certainty the extent of the influence of carbon dioxide.

Although Tyndall was the first to attempt a calculation of the infrared flux in the atmosphere, FOURIER (1827) had compared the influence of the atmosphere to the heating of a closed space beneath a pane of glass. The calculation by ARRHENIUS (1896) of the influence of carbon dioxide on the temperature was the most extensive made during the nineteenth century. In a series of articles

[1] This work was sponsored by the U.S. Office of Naval Research. This article was completed while the author was on leave of absence at Michigan State University, East Lansing, Michigan. Present address: Systems Research Corporation, Van Nuys, California.

CHAMBERLIN (1897, 1898, 1899) presented in detail the geological implications of the carbon dioxide theory. As a result of these early articles, during that period the carbon dioxide theory was probably the most widely held explanation of climatic change.

In recent years the carbon dioxide theory has had relatively few adherents. Most authors have dismissed this theory with a remark similar to the following quotation from C. E. P. BROOKS (1951): the carbon dioxide theory was "abandoned when it was found that all the long-wave radiation absorbed by CO_2 is also absorbed by water vapour." This often quoted conclusion is based on early, approximate calculations of the radiation flux in the atmosphere. The results of more accurate calculations of the radiation flux have recently become available. Thus it seems worthwhile to reappraise the CO_2 theory of climatic change. A preliminary report of these results has been given by PLASS (1953).

Many authors believe that most of the world-wide climatic changes are caused primarily by variations of a single factor. In this article simple explanations are given in terms of the carbon dioxide content of the atmosphere for many of the known facts about climatic change. Although it seems significant that so many facts can be explained by the carbon dioxide theory, the possibility remains that variations in solar energy, volcanic dust in the atmosphere and the heights of the continents may have had an important influence on the climate at particular places and periods in the earth's history.

2. Calculation of the radiation flux

An extensive calculation of the radiation flux in the region of the 15 micron CO_2 band has recently been made by PLASS (1956 b). Recent accurate laboratory measurements of the absorption in the CO_2 band by CLOUD (1952) were used to calculate the radiation flux in the atmosphere with the aid of the MIDAC high speed digital computor. None of the many approximations were used that had necessarily been made in earlier attempts to solve this complex problem. Accurate laboratory absorption data, recent theoretical work and the availability of an electronic computer made it possible to obtain an accurate solution of this problem.

The method of calculation took into account the many properties of the line spectrum. In particular it was valid for: (1) any arbitrary variation from one spectral line to another of the spacing between lines and of the line intensity; (2) any degree of overlapping of the spectral lines; (3) the actual variation in the atmosphere of the half-width of the spectral lines with pressure. At the highest altitudes a correction for the Doppler line shape was introduced. Another correction took account of the variation of the line intensity and half-width with temperature. The reduction from beam to hemisphere radiation was made by a new, more accurate method. Certain restrictions on the path-length for this method of calculation were checked against the experimental data.

The accuracy of the results were checked at each stage of the calculation. The upward and downward flux in the atmosphere could be computed with the same accuracy as the original laboratory measurements. It is estimated that the calculated upward and downward atmospheric radiation flux is accurate to within 4 per cent; this figure includes an allowance for the additional corrections that must be introduced into the atmospheric calculation. Further details are given by PLASS (1956 b).

3. Temperature variations caused by changes in CO_2 concentration

The upward and downward radiation flux was calculated by PLASS (1956 b) for intervals of 1 km from the surface of the earth to 75 km and for three different CO_2 concentrations. From these results the change in temperature at any level can be calculated for a given change in the CO_2 concentration. It is assumed that nothing else changes that affects the radiation balance when the CO_2 amount varies. In order to obtain the temperature change it was assumed that an additional amount of heat energy equal to 0.0033 cal/cm^2 min would be radiated to space from the surface of the earth, if the average temperature increased by 1° C. Unfortunately this number cannot be calculated accurately until a detailed study of the H_2O spectrum has been made. When a more accurate value for this number is obtained in the future, all the temperature

changes given here should be multiplied by the ratio of the new to the old values.

With this assumption, PLASS (1956 b) finds that, in order to restore equilibrium, the surface temperature must rise 3.6° C if the CO_2 concentration is doubled and the surface temperature must fall 3.8° C if the CO_2 concentration is halved. It is also assumed here that no other factors change at the same time which can influence the radiation balance.

If the CO_2 amount is doubled, ARRHENIUS (1896) calculated that the temperature increased about 6° C, while CALLENDAR (1938) obtained a 2° C increase. The values quoted here are larger than other recent calculated values primarily because: (1) the weaker lines far from the band center have an important influence and the entire frequency interval from 12 to 18 microns was included in the calculation; (2) the pressure broadening of the spectral lines was taken into account, which results in the radiation varying approximately as the square root of the CO_2 concentration (PLASS and FIVEL, 1955 a) over a considerable portion of the frequency interval.

The actual temperature change due to CO_2 variations is slightly smaller than the results given above for clear sky conditions. When clouds are present, the CO_2 is less effective in changing the net amount of radiation from the surface. In order to estimate the magnitude of this effect, PLASS (1956 b) also calculated the temperature change at the earth's surface for variations in the CO_2 amount when the lower cloud surfaces are at 4 and 9 km. When these values are averaged over a reasonable average cloud distribution for the earth, the result is obtained that the average surface temperature must increase by 2.5° C or decrease by 2.7° C when the CO_2 amount in the atmosphere is doubled or halved.

The usual objection to the CO_2 theory of climatic change has been that, since the H_2O absorbs so strongly in the same spectral region as CO_2, the CO_2 can have little influence on the infrared flux. Until a more detailed study is made of the H_2O spectrum and its influence on the atmosphere, it is not possible to investigate this matter quantitatively. However, several considerations suggest that H_2O has a much smaller effect than has generally been believed in recent years. In the first place, the mixing ratio of H_2O decreases very rapidly with height whereas the mixing ratio of CO_2 is nearly constant with height. Even if the H_2O absorption were greater than that of CO_2 near the surface of the earth in certain frequency intervals, the H_2O absorption would decrease with height very much more rapidly than the CO_2 absorption. Calculations by PLASS and FIVEL (1955 b, Figs. 1 and 2) have shown the magnitude of this effect. Thus, even a relatively short distance above the earth's surface, the CO_2 controls the radiative flux in the frequency interval from 12 to 18 microns.

In the second place, it is important to take account of the structure of the individual spectral lines. The various lines in the spectrum of H_2O and CO_2 occur at random with respect to each other. When this happens there are theoretical calculations and experimental measurements which indicate that the combined transmission is nearly the product of the individual transmissions of the two gases. Thus, changes in the CO_2 amount still cause appreciable changes in the transmission of the atmosphere. In order to obtain a more accurate estimate of this effect, a numerical calculation was made with the average line strength for H_2O given by ELSASSER (1942, Fig. 19) and with the assumption that the H_2O lines occur at random with respect to the CO_2 lines. The results of this calculation show that the temperature changes at the surface of the earth already given would not be decreased by more than 20 per cent because of absorption by H_2O. Since the temperature change due to CO_2 variations would be further increased by 10 to 20 per cent from the additional spectral lines outside the 12 to 18 micron region included in Plass' calculation, this factor would at least partly cancel the H_2O effect just discussed. Thus the values for the temperature change already given are probably as accurate as can be calculated at the present time and take into account all known effects of the structure of the spectral lines.

The radiation calculations predict a definite temperature change for every variation in CO_2 amount in the atmosphere. These temperature changes are sufficiently large to have an appreciable influence on the climate. A relatively small change in the average temperature can have a large effect on the climate;

Table 1. Major factors in the CO_2 balance at the present time

	tons/year	
Photosynthesis	-60×10^9	organic world
Decay, respiration	$+60 \times 10^9$	organic world
Formation of new coal beds and other organic deposits	-0.01×10^9	organic world
Weathering of igneous rocks	-0.1×10^9	inorganic world
Released from interior of earth by hot springs, volcanoes, etc.	$+0.1 \times 10^9$	inorganic world
Combustion of fossil fuels; clearance of forests; cultivation of land	$+6.0 \times 10^9$	man's activities

some geologists estimate that another period of glaciation would result from a drop of 3 or 4° C in the average temperature. In order to explain climatic changes, it is necessary to understand the role of the various factors that control the CO_2 content of the atmosphere. In the next sections these factors are investigated together with the CO_2 equilibrium between the atmosphere and the oceans.

4. The CO_2 balance

Many authors have discussed the CO_2 balance in recent years. The fascinating book about climatic changes edited by SHAPLEY (1953) gives many of their results together with numerous references to the literature. RUBEY (1951) has made one of the most extensive studies of the CO_2 equilibrium. UREY (1952) and KUIPER (1952) have givena discussion of the many factors that influence the amounts of various gases in the atmosphere.

Estimates of the magnitude of some of the principal factors that influence the atmospheric CO_2 concentration at the present time are given in Table I. Most of these figures are known only to an order of magnitude; naturally, the estimates of different authors vary widely. An attempt has been made to average some of the more careful estimates for each factor.

Estimates made by reliable scientists of the amount of CO_2 used in photosynthesis vary from 7 to 200×10^9 tons per year. Regardless of the exact value, in a steady state precisely the same amount of CO_2 must be returned to the atmosphere each year by all the processes of respiration and decay of plants and animals, provided none of this CO_2 is permanently lost in forming new coal, oil and other organic deposits. At the present time, at least, the amount lost in this manner is very small compared to the CO_2 used in photosynthesis and can be neglected in a discussion of the balance of factors from the organic world. Let us suppose that the steady state absorption and emission of CO_2 by the organic world is disturbed, for example, by a sudden increase in the amount of CO_2 in the atmosphere. The amount of CO_2 used in photosynthesis would increase, but in a very short time interval the processes of decay and respiration would also have increased. Since an average carbon atom that has been used in photosynthesis returns to the atmosphere from the biosphere in about 10 years and virtually all the carbon atoms return in 250 years, it follows that the factors from the organic world would again be in balance in a relatively few years following a change in the CO_2 concentration in the atmosphere.

During geological history the amount of CO_2 lost from the atmosphere by the formation of new coal beds and other organic deposits and by the weathering of igneous rocks and deposition of carbonates has varied widely, as has the CO_2 added to the atmosphere by such factors as the evolution of CO_2 from hot springs, volcanic vents, gas wells, and other sources. Since the variations in these factors occur independently of each other, the net gain or loss of CO_2 by the atmosphere from these factors must have changed frequently on a geological time scale. Although it is not always easy to deduce the net result of these many independent variations for a given epoch, the mere knowledge that these factors have changed many times in the past has important implications for studies of the climate.

In recent years industrial and other activities of man are adding considerably more CO_2 to the atmosphere than any of the above factors from the inorganic world (Table I). The combustion of fossil fuels is adding 6×10^9 tons per year of CO_2 to the atmosphere at the present time. In addition such activities as the clearance of forests, the drainage and cultivation of lands, and industrial processes such as lime burning and fermentation release addi-

tional amounts of CO_2 that are not included in the above estimate. This is a large enough contribution to upset the carbon dioxide balance and to increase the amount in the atmosphere appreciably. Some of this additional CO_2 is used in photosynthesis, but as already discussed, very little of the extra CO_2 is permanently lost to the atmosphere since there is a corresponding increase in the rates of decay and respiration. Another part of this additional CO_2 is absorbed by the oceans; this factor is discussed in detail in the following sections. However, it seems probable that these losses are small at the present time. If this is true, then a major portion of the extra CO_2 from man's activities will remain in the atmosphere and the CO_2 concentration will increase for at least several centuries to come. If this extra CO_2 is remaining in the atmosphere, the concentration is increasing from this source at the rate of 30 per cent a century.

5. CO_2 exchange between oceans and atmosphere

Recent radiocarbon determinations (KULP, 1952) have shown that deep ocean water at the latitude of Newfoundland was at the surface about 1700 years ago. Kulp states in SHAPLEY (1953) that "if this sample water started near the surface in the Arctic, then the rate of turnover of the oceans must be on a scale of at least 10,000 years." Thus, the amount of CO_2 in the ocean and atmosphere must come to equilibrium after a change in the CO_2 balance in a period of time of this order of magnitude.

Several excellent studies have been made in recent years of the equilibrium between the oceans and the atmosphere (SVERDRUP, JOHNSON and FLEMING, 1942; RUBEY, 1951; DINGLE, 1954). We have recalculated this equilibrium with the additional assumption that the average temperature of the oceans is determined by the CO_2 concentration in the atmosphere. The average temperature of the oceans at the present time was taken as 8° C; for half the present amount of atmospheric CO_2, it was assumed that the average temperature of the oceans was lowered to 4.2° C. This is the same change in average temperature that a similar CO_2 variation causes on land. Similar changes in the ocean temperatures were assumed for other CO_2 concentrations.

The following equations were used to calculate the equilibrium between the gaseous CO_2 and the carbonates in the sea water:

$$[A] = [HCO_3^-] + 2[CO_3^=] + [H_2BO_3^-] + \\ + [OH^-] - [H^+], \qquad (1)$$

$$[A_{CO_2}] = [A] - \frac{2.2(10)^{-5}\, Cl^0/_{00}\, K_B'}{[H^+] + K_B'} + [H^+] - \\ - [OH^-] \qquad (2)$$

$$[H_2CO_3] = \frac{[A_{CO_2}]}{1 + \frac{2K_2'}{[H^+]}} \cdot \frac{[H^+]}{K_1'} \qquad (3)$$

$$[HCO_3^-] = \frac{[A_{CO_2}]}{1 + \frac{2K_2'}{[H^+]}} \qquad (4)$$

$$[CO_3^=] = \frac{[A_{CO_2}]}{1 + \frac{2K_2'}{[H^+]}} \cdot \frac{K_2'}{[H^+]} \qquad (5)$$

$$P_{CO_2} = \frac{[A_{CO_2}]}{K_1'\, \alpha_0\, a_{H_2O} \left(1 + \frac{2K_2'}{[H^+]}\right)} \cdot \frac{[H^+]}{} \qquad (6)$$

where $[A]$ is the excess base, $[A_{CO_2}]$ is the carbonate alkalinity, K_B' is the apparent first dissociation constant of boric acid in sea water, K_1' and K_2' are the first and second apparent dissociation constants of H_2CO_3, a_{H_2O} is the activity of water in sea water, and P_{CO_2} is the atmospheric CO_2 pressure. The remaining symbols have their usual meaning. The values of the constants were taken from the tables in HARVEY (1945).

It was assumed that the average ocean temperature is 8° C, the pH is 8.17 and the chlorinity is 19.5 ‰ at the present time. With $K_1' = 0.76 \times 10^{-6}$, $K_2' = 0.73 \times 10^{-9}$, $a_{H_2O} = 0.981$, $\alpha_0 = 0.0576$ moles/l, it follows from (1—6) that $P_{CO_2} = 3.0 \times 10^{-4}$ atm. Since this value for P_{CO_2} agrees with the average carbon dioxide concentration that was measured in the atmosphere at the end of the nineteenth century, the usual values for the above constants lead to the conclusion that the atmosphere-ocean system is nearly in equilibrium today. From (1—6) it also follows that at the

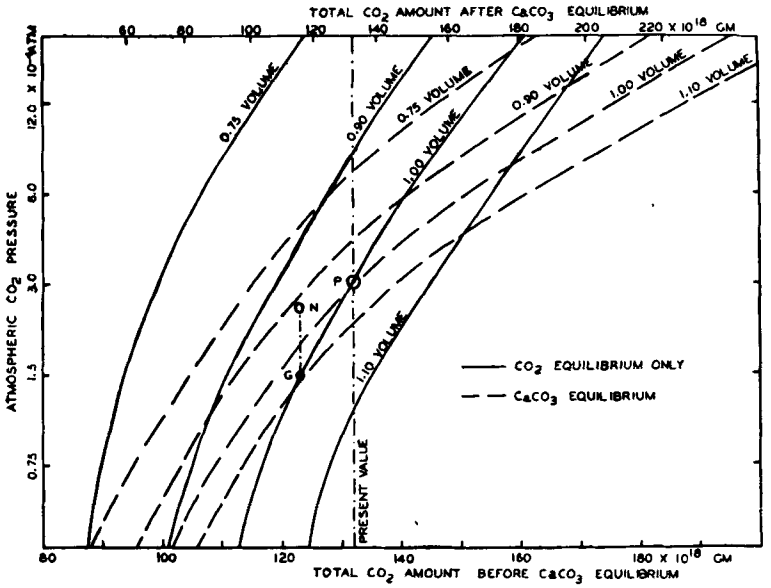


Fig. 1. Equilibrium amounts of CO_2 for the atmosphere-ocean system. The ordinate is the logarithm of the CO_2 pressure in the atmosphere; the abscissa is the corresponding total CO_2 amount present in both the oceans and atmosphere at equilibrium. The solid curves are for the CO_2 equilibrium only; the dashed curves assume in addition that $CaCO_3$ equilibrium has been established in the oceans. Each set of curves is given when the oceans have a volume equal to 0.75, 0.90, 1.00 and 1.10 times their present volume. For the curves that assume $CaCO_3$ equilibrium, the abscissa marked in the lower and upper margins give the total CO_2 amount before and after $CaCO_3$ equilibrium respectively. The CO_2 pressure today is marked by the point "P". The points "G" and "N" represent possible conditions when glaciers are forming and melting respectively. The dashed line between "G" and "N" represents the typical oscillations in the climate during a glacial epoch.

present time $[CO_2] = 1.41 \times 10^{-5}$ moles/l; $[HCO_3^-] = 1.89 \times 10^{-3}$ moles/l; and $[CO_3^=] = 0.204 \times 10^{-3}$ moles/l.

From the known volume of the oceans and the atmosphere it is found that there are 130×10^{18} gm of CO_2 (in the form of carbonates and dissolved gas) in the oceans and 2.33×10^{18} gm of CO_2 in the atmosphere or a total of 132×10^{18} gm of CO_2 in the atmosphere-ocean system. In Fig. 1 the present value for the atmospheric CO_2 pressure and the total CO_2 amount is marked "P".

Next, the equilibrium value of P_{CO_2} was calculated for a number of different values of the total CO_2 amount. It was assumed in agreement with the carbon dioxide theory of climatic change that the average temperature of the oceans was 15.0°C when $P_{CO_2} = 12 \times 10^{-4}$ atm; 11.6° C when $P_{CO_2} = 6 \times 10^{-4}$; 8.0° C when $P_{CO_2} = 3 \times 10^{-4}$; 4.2° C when $P_{CO_2} = 1.5 \times 10^{-4}$; 0.5° C when $P_{CO_2} = 0.75 \times 10^{-4}$. Although the constants in (1—6) are functions of the temperature, the curves shown in Fig. 1 are insensitive to the particular assumption that is made about their temperature variation. The equilibrium values of P_{CO_2} for various total CO_2 amounts in the atmosphere-ocean are shown in Fig. 1 as the solid curve marked "1.00 Vol."

These same calculations were repeated assuming that the oceans had 0.75, 0.90 and 1.10 times their present volumes. The other solid curves in Fig. 1 show the results for these cases.

RUBEY (1951) has emphasized that the oceans must reach equilibrium with $CaCO_3$ after a sufficient period of time following a change in the total amount of CO_2 in the atmosphere-ocean system. If there is an excess amount of $CaCO_3$, it precipitates; if there is

too little $CaCO_3$, it dissolves and at the same time accumulates from the rivers that flow into the oceans until the solubility product is reached. The equilibrium CO_2 pressure can be obtained when there is $CaCO_3$ equilibrium by solving equations (1—6) with the additional requirement that

$$[Ca^{++}]\ [CO_3^{=}] = K'_{CaCO_3} \qquad (7)$$

The results of this calculation are shown as the dashed lines in Fig. 1 for oceans with 0.75, 0.90, 1.00 and 1.10 times the present volume. The curves in Fig. 1 for the $CaCO_3$ equilibrium have abscissa marked at the bottom of the figure for the total amount of CO_2 in the atmosphere-ocean system before the $CaCO_3$ dissolves or precipitates to bring about equilibrium; the corresponding final amounts of CO_2 in the atmosphere-ocean system are marked on the top margin of Fig. 1. The following values were used for K'_{CaCO_3}: 1.3×10^{-6} at 30° C; 1.8×10^{-6} at 20° C; 2.1×10^{-6} at 10° C; 2.3×10^{-6} at 0° C. These values agree with the measurements of SMITH (1940) when they are corrected for temperature dependence. With these values of the constants, (1—7) show that the oceans are very nearly in equilibrium at the present time with $CaCO_3$ for an average temperature of 8° C and $P_{CO_2} = 3 \times 10^{-4}$ atm. Apparently the $CaCO_3$ dissociation constant is not known accurately. A change in its value would move the curves in Fig. 1 to the right or left, but would not change their qualitative features.

Curves are given in Fig. 1 for different volumes of the oceans, since the ocean volume decreases during a period of glaciation and would increase still further, if all the glacial ice present today should melt. Estimates show that water having a volume from 5 to 10 per cent of that of the oceans was frozen in the glaciers at the period of the last advance of the ice sheets (FLINT, 1947; SHAPLEY, 1953). This number may have been even larger during earlier great epochs of glaciation. Further, the volume of the oceans has probably changed during the recorded geological history of the earth by the addition of juvenile water from the interior of the earth.

The pH of the oceans does not change by more than one-half a unit as P_{CO_2} varies from one-fourth to four times its present value. For example, the pH range is 7.67 to 8.62 for this range of values of P_{CO_2} without $CaCO_3$ equilibrium and is 7.81 to 8.51 with $CaCO_3$ equilibrium. With $CaCO_3$ equilibrium, P_{CO_2} can vary from 0.38×10^{-4} to 20×10^{-4} atm without the pH changing by more than one-half unit. It is interesting to note that higher marine animals (herring, for example) can not tolerate pH changes of more than $\pm$ 0.5 and that lower marine animals are less sensitive, but many species (sea urchins, diatoms, algae) can not tolerate pH changes of more than $\pm$1.0 (RUBEY, 1951). This suggests that during the geological periods in which these animals have lived that the pH of the sea has either stayed constant within these limits or at most has changed very slowly so that the animals had a chance to adapt to their new environment. Thus the amount of CO_2 in the atmosphere can change relatively rapidly by a factor of fifty-three without influencing marine life appreciably and even more over long periods of time. Such variations in CO_2 amount are more than enough to cause appreciable climatic changes.

6. Explanation of climatic change in terms of the CO_2 theory

According to Bell (SHAPLEY, 1953), Willett believes "that the similarity in the change of the circulation pattern, whether the change in climate be of the order of hundreds or thousands or tens of thousands of years constitutes a powerful argument in favor of a single variable factor underlying all changes". From this point of view, it seems significant that the CO_2 theory can provide simple, straight-forward explanations for many of the known facts about climatic change. These explanations are discussed in this and the following section.

a. *Periodic oscillations from glacial to interglacial climate*

Recent analysis of the sediments of the deep ocean floor by WISEMAN (1954) show 10 distinct temperature minima within the last 620,000 years. Four distinct periods of advance and retreat of the ice sheets have long been recognized by geologists. These fluctuations in the climate, which seem to be a characteristic of a glacial period, can be explained by the CO_2 theory. If the total amount of CO_2 in the atmosphere-ocean system is reduced by a small amount from its present value, the CO_2

able degree, the extra CO_2 that is added to the atmosphere counteracts the CO_2 used up in weathering and the onset of glaciation is postponed. In fact, some major periods of mountain building have not been followed by extensive ice sheets. A possible explanation would be that more CO_2 had been added to the atmosphere from the interior of the earth than could later be removed by rock weathering. In any case, when a glacial epoch does follow a period of mountain building, the CO_2 theory clearly predicts an appreciable time delay between the two events.

d. *Influence of man's activities on climate*

At the present time the burning of fossil fuels is adding more than 6×10^9 tons per year of CO_2 to the atmosphere. Other activities of man such as the clearance of forests and the drainage and cultivation of land add additional amounts of CO_2 to the atmosphere each year. The total amount added each year from these sources is several orders of magnitude larger than any factor that contributes to the CO_2 balance from the inorganic world at the present time (see Table I). Therefore, this additional factor has greatly disturbed the CO_2 balance. If all this additional CO_2 remains in the atmosphere, there will be 30 per cent more CO_2 in the atmosphere at the end of the twentieth century than at the beginning. If no other factors change, man's activities are increasing the average temperature by 1.1° C per century. This argument was first presented by CALLENDAR (1938, 1949).

There appear to be only two ways in which the excess CO_2 could be removed from the atmosphere. More CO_2 is used in photosynthesis when the CO_2 concentration increases. However, as already discussed, in a relatively short period of time increased rates of respiration and decay bring the factors from the organic world into balance once again. Except for a small initial loss, no appreciable part of the extra CO_2 can be used up in this manner.

Some of the extra CO_2 will also be absorbed by the oceans. Because of the slow circulation of the oceans it would probably take at least 10,000 years for the atmosphere-ocean system to come to equilibrium after a change in the atmospheric CO_2 amount. The surface layers of the ocean start absorbing some of the extra CO_2 from the atmosphere as soon as the P_{CO_2} is greater than the equilibrium amount. The rate at which this absorption takes place is not known accurately, but it is probably true that the surface layers can absorb only a small fraction of the extra CO_2 in a period of several hundred years. Thus it appears that most of the additional CO_2 that is released into the atmosphere will stay there for at least several centuries. Even if the oceans absorb CO_2 much more rapidly than has been assumed here, the accumulation of CO_2 in the atmosphere will become an increasingly important problem through the centuries.

The known reserves of coal and oil amount to about 13×10^{18} gm. After making allowance for the growth of industrial activity it is expected that this amount of fuel will be used up in less than one thousand years. If this occurs, nearly 40×10^{18} gm of CO_2 will have been added to the atmosphere. This is seventeen times the present amount of CO_2 in the atmosphere. Even if it is assumed that the atmosphere-ocean system will be near equilibrium at the end of this period, the total CO_2 amount will increase from 132×10^{18} gm to 172×10^{18} gm. From an extension of Fig. 1 the equilibrium value of P_{CO_2} is found to be 30×10^{-4} atm corresponding to a temperature rise of 12.2° C. Even if there were sufficient time for $CaCO_3$ equilibrium to set in, Fig. 1 shows that P_{CO_2} is 11×10^{-4} atm (nearly four times the present value) and the corresponding temperature rise is 7.0° C. Since complete equilibrium between the atmosphere and oceans cannot be maintained when the atmospheric CO_2 amount is constantly increasing, the actual temperature rise will be considerably greater than 7° C.

It is tempting to give an explanation of the recent rise in average temperature over the entire globe in terms of the increased CO_2 amount in the atmosphere (CALLENDAR, 1938, 1949). A great deal more data in the form of accurate CO_2 measurements over a period of time and temperature records for the remainder of the century will be needed to prove or disprove this explanation. Many local variations, such as the extremely rapid rise in temperature in Scandinavia cannot be explained by the CO_2 theory and are probably due to changes in the general circulation. However, it is entirely possible that the general

temperature rise over the entire earth is due to the CO_2 effect. Furthermore, the influence of the extra CO_2 on the climate will become increasingly important in the near future as continuously greater amounts of CO_2 are released into the atmosphere by man's activities.

e. *Carboniferous period; glaciation in phase in both hemispheres*

A change in any of the other factors that influence the CO_2 balance can also influence the climate according to the CO_2 theory. Unfortunately it is often difficult to estimate the relative importance of the various factors at specific times in the past. Nevertheless it is certain that all of these factors have changed by large amounts during the earth's history.

The amount of organic material being trapped in new coal and oil deposits and other sediments may have been much greater at certain periods of the earth's history than it is today. This was presumably the case during the Carboniferous period when the relatively level land and many marshes created the proper conditions for the formation of large amounts of organic sediments. After a long period of time this had the effect of reducing the amount of CO_2 in the atmosphere-ocean system. It is perhaps significant that the glaciation at the end of the Carboniferous appears to have been the most severe in the earth's history.

Any large scale climatic variations due to changes in the CO_2 amount in the atmosphere must occur simultaneously (on a geological time scale) in both hemispheres. Presumably a few centuries or less would be sufficient time to equalize the atmospheric CO_2 amount in both hemispheres following a disturbance in one. An exception might occur if one hemisphere were considerably more mountainous than the other. The temperature drop would be the same in both hemispheres following a decrease in the CO_2 amount. Nevertheless the mountainous land of one hemisphere could provide a favorable source for the glaciers, whereas they would be unable to form on the relatively flat land of the other hemisphere.

7. Unsolved problems for the CO_2 theory

In this section various problems are discussed for which either more study is required in order to understand the various factors that are involved or more time is needed to accumulate additional data. The answers to these questions can only be suggested at this time.

The temperature trend during the remainder of this century should provide a definitive test of the relative importance of such factors as CO_2, variations in the solar energy and volcanic dust in determining the climate at the present time. The predictions based on these theories are entirely different. The CO_2 theory states that the average temperature of the earth will continue to increase for many centuries, as the atmospheric CO_2 content increases due to the burning of fossil fuels and other activities of man. The solar theory predicts that the average temperature will decrease for some decades to come. The maximum of the eighty year period in the sunspot cycle probably occurred in 1947. The average energy that the earth receives from the sun including the ultraviolet should decrease for a number of years, thus causing the average temperature to decrease. A continual temperature rise could not be explained by the solar theory unless measurements at the same time should show an appreciable increase in the solar constant. The volcanic dust theory predicts a lower average temperature for several years after a major volcanic explosion that sends large amounts of dust into the atmosphere. There has been no such explosion since 1912 when Katmai erupted in the Aleutian Islands. Further attempts at verification of this theory must await new volcanic action.

There have not been sufficient measurements of the CO_2 content of the atmosphere in recent years to establish beyond doubt that the CO_2 amount has actually risen since 1900. In view of the importance of the problem, further measurements over a period of years should be undertaken. The predicted rise of 3 per cent in 10 years could be detected with measurements of moderate accuracy. At the same time more data could be accumulated on the variation in CO_2 amount with different types of air masses. Simultaneous measurements in both hemispheres could obtain in addition information on the rate of exchange of gases between the hemispheres. The level of industrial activity is so much less in the Southern Hemisphere than in the Northern at the present time that most of the increase for the Southern Hemisphere would be due

Annex 9

R. Revelle & H. Suess, “Carbon Dioxide Exchange Between Atmosphere and Ocean and the Question of an Increase of Atmospheric CO2 during the Past Decades”, *Tellus,* 1957, pp. 18-27, pages 18-20, 24-26

Carbon Dioxide Exchange Between Atmosphere and Ocean and the Question of an Increase of Atmospheric CO_2 during the Past Decades

By ROGER REVELLE and HANS E. SUESS, Scripps Institution of Oceanography, University of California, La Jolla, California

(Manuscript received September 4, 1956)

Abstract

From a comparison of C^{14}/C^{12} and C^{13}/C^{12} ratios in wood and in marine material and from a slight decrease of the C^{14} concentration in terrestrial plants over the past 50 years it can be concluded that the average lifetime of a CO_2 molecule in the atmosphere before it is dissolved into the sea is of the order of 10 years. This means that most of the CO_2 released by artificial fuel combustion since the beginning of the industrial revolution must have been absorbed by the oceans. The increase of atmospheric CO_2 from this cause is at present small but may become significant during future decades if industrial fuel combustion continues to rise exponentially.

Present data on the total amount of CO_2 in the atmosphere, on the rates and mechanisms of exchange, and on possible fluctuations in terrestrial and marine organic carbon, are inadequate for accurate measurement of future changes in atmospheric CO_2. An opportunity exists during the International Geophysical Year to obtain much of the necessary information.

Introduction

In the middle of the 19th century appreciable amounts of carbon dioxide began to be added to the atmosphere through the combustion of fossil fuels. The rate of combustion has continually increased so that at the present time the annual increment from this source is nearly 0.4 % of the total atmospheric carbon dioxide. By 1960 the amount added during the past century will be more than 15 %.

CALLENDAR (1938, 1940, 1949) believed that nearly all the carbon dioxide produced by fossil fuel combustion has remained in the atmosphere, and he suggested that the increase in atmospheric carbon dioxide may account for the observed slight rise of average temperature in northern latitudes during recent decades. He thus revived the hypothesis of T. C. CHAMBERLIN (1899) and S. ARRHENIUS (1903) that climatic changes may be related to fluctuations in the carbon dioxide content of the air. These authors supposed that an increase of carbon dioxide in the upper atmosphere would lower the mean level of back radiation in the infrared and thereby increase the average temperature near the earth's surface.

Subsequently, other authors have questioned Callendar's conclusions on two grounds. First, comparison of measurements made in the 19th century and in recent years do not demonstrate that there has been a significant increase in

Contribution from the Scripps Institution of Oceanography, New Series, No. 900. This paper represents in part results of research carried out by the University of California under contract with the Office of Naval Research.

Table 1. CO_2 added to atmosphere by consumption of fossil fuels

Decade	Average amount added per decade Measured		Cumulative total added			
	10^{18} gms	% Atm CO_2	10^{18} gms	% Atm CO_2	10^{18} gms	% Atm CO_2
1860—69	0.0054	0.23	0.0054	0.23		
1870—79	0.0085	0.36	0.0139	0.59		
1880—89	0.0128	0.54	0.0267	1.13		
1890—99	0.0185	0.79	0.0452	1.92		
1900—09	0.0299	1.27	0.0751	3.19		
1910—19	0.0405	1.72	0.1156	4.91		
1920—29	0.0470	2.00	0.1626	6.91		
1930—39	0.0497	2.11	0.2123	9.02		
1940—49	0.0636	2.71	0.2759	11.73		
	Forecast					
	Assuming fossil fuels are used to meet future requirements of fuel and power as estimated by UN (1955)				Assuming fossil fuel consumption remains constant at estimated 1955 rate	
1950—59	0.091	3.9	0.367	15.6	0.367	15.6
1960—69	0.128	5.4	0.495	21.0	0.458	19.5
1970—79	0.176	7.5	0.671	28.5	0.549	23.4
1980—89	0.247	10.5	0.918	39.0	0.640	27.2
1990—99	0.340	14.5	1.258	53.5	0.731	31.1
2000—09	0.472	20.0	1.730	73.5	0.822	35.0

atmospheric CO_2 (SLOCUM, 1955; FONSELIUS *et al.* 1956). Most of the excess CO_2 from fuel combustion may have been transferred to the ocean, a possibility suggested by S. ARRHENIUS (1903). Second, a few percent increase in the CO_2 content of the air, even if it has occurred, might not produce an observable increase in average air temperature near the ground in the face of fluctuations due to other causes. So little is known about the thermodynamics of the atmosphere that it is not certain whether or how a change in infrared back radiation from the upper air would affect the temperature near the surface. Calculations by PLASS (1956) indicate that a 10 % increase in atmospheric carbon dioxide would increase the average temperature by 0.36° C. But, amplifying or feed-back processes may exist such that a slight change in the character of the back radiation might have a more pronounced effect. Possible examples are a decrease in albedo of the earth due to melting of ice caps or a rise in water vapor content of the atmosphere (with accompanying increased infrared absorption near the surface) due to increased evaporation with rising temperature.

During the next few decades the rate of combustion of fossil fuels will continue to increase, if the fuel and power requirements of our world-wide industrial civilization continue to rise exponentially, and if these needs are met only to a limited degree by development of atomic power. Estimates by the UN (1955) indicate that during the first decade of the 21st century fossil fuel combustion could produce an amount of carbon dioxide equal to 20 % of that now in the atmosphere (Table 1).[1] This is probably two orders of magnitude greater than the usual rate of carbon dioxide production from volcanoes, which on the average must be equal to the rate at which silicates are weathered to carbonates (Table 2). Thus human beings are now carrying out a large scale geophysical experiment of a kind that could not have happened in the past nor be reproduced in the future. Within a few centuries we are returning to the atmosphere and oceans the concentrated organic carbon stored in sedimentary rocks over hundreds of millions of years. This experiment, if adequately

[1] World production of CO_2 from the use of limestone for cement, fluxing stone and in other ways was about 1 % of the total from fossil fuel combustion in 1950.

documented, may yield a far-reaching insight into the processes determining weather and climate. It therefore becomes of prime importance to attempt to determine the way in which carbon dioxide is partitioned between the atmosphere, the oceans, the biosphere and the lithosphere.

The carbon dioxide content of the atmosphere and ocean is presumably regulated over geologic times by the tendency toward thermodynamic equilibrium between silicates and carbonates and their respective free acids, silica and carbon dioxide (UREY, 1952). The atmosphere contains and probably has contained during geologic times considerably more CO_2 than the equilibrium concentration (HUTCHINSON, 1954), although uncertainties in the thermodynamic data are too great for an accurate quantitative comparison. Equilibrium is approached through rock weathering and marine sedimentation. Estimated rates of these processes give a very long time constant of the order of magnitude of 100,000 years. Rapid changes in the amount of carbon dioxide produced by volcanoes, in the state of the biosphere, or as in our case, in the rate of combustion of fossil fuels, may therefore cause considerable departures from average conditions.

Table 2. Estimated present annual rates of some processes involving atmospheric and oceanic carbon dioxide, in part after HUTCHINSON (1954)

	10^{18} gms	In units of atm $CO_2(A_0)$
Consumption of fossil fuels—CO_2 produced.	0.0091	0.0039
Bicarbonate and carbonate added to ocean by rivers (as CO_2)[1] ..	0.00103	0.0004
Photosynthesis on land —CO_2 consumed	0.073±0.018	0.031
Photosynthesis in ocean —CO_2 consumed	0.46±0.3	0.20

[1] According to CONWAY (1942) and HUTCHINSON (1954) 87 % of the river borne bicarbonate and carbonate comes from weathering of carbonate rocks, the remainder from weathering of silicates.

The answer to the question whether or not the combustion of coal, petroleum and natural gas has increased the carbon dioxide concentration in the atmosphere depends in part upon the rate at which an excess amount of CO_2 in the atmosphere is absorbed by the oceans. The exchange rate of isotopically labeled CO_2 between atmosphere and ocean, which, in principle, could be deduced from C^{14} measurements, is not identical with the rate of absorption, but is related to it.

Notations and geochemical constants

In our discussion of exchange and absorption rates we shall use the following notations:

S_0: Total carbon of the marine carbon reservoir at equilibrium condition, at time zero.

A_0: Atmospheric CO_2 carbon at time zero.

i: Annual amount of industrial CO_2 added to the atmosphere.

t: Time in years.

$s = S_t - S_0$: Amount of CO_2 derived from industrial fuel combustion in the sea at time t.

$r = it - s$: Amount of CO_2 derived from industrial fuel combustion in the atmosphere at time t.

r^*: Observed decrease in C^{14} activity.

τ(atm): Average lifetime of a CO_2 molecule in the atmosphere, before it becomes dissolved in the sea.

τ(sea): Average lifetime of carbon in the sea, before it becomes atmospheric CO_2.

$k_1 = 1/\tau$(atm): Rate of CO_2 transfer per year from the atmosphere to the sea.

$k_2 = 1/\tau$(sea): Rate of CO_2 transfer per year from the sea to the atmosphere.

P_{CO_2}: Partial CO_2 pressure in the atmosphere.

Table 3 gives the amount of carbon, expressed in CO_2 equivalents, in the various geochemical reservoirs on the surface of the Earth.

The symbols S^* and A^* shall be used for denoting respective "effective" reservoirs.

Rate of CO_2 exchange between sea and atmosphere

Two types of C^{14} measurements independently allow calculation of the exchange rate

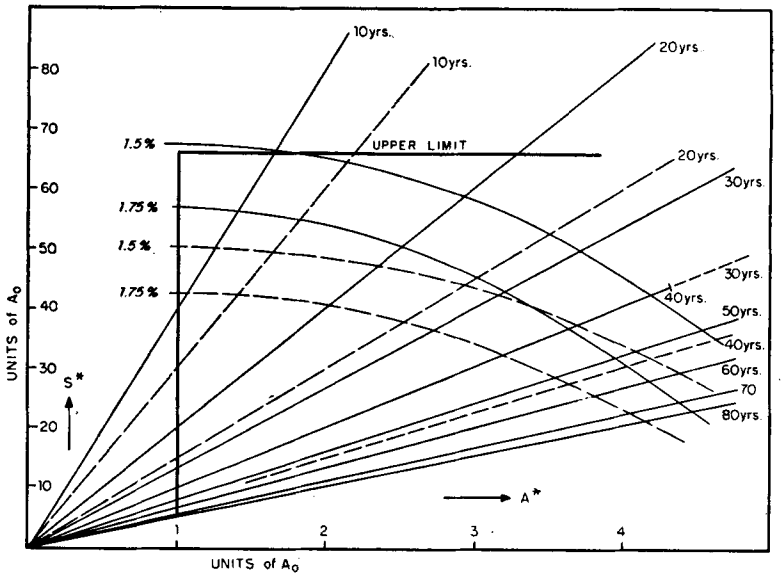


Fig. 1. Graphic solutions of Eq. (1 a) for values $1/k_1$ ranging from 10 to 80 years (straight lines), and of Eq. (5 a) for $r^* = 1.5$ % and 1.75 % (curved lines), for average apparent C^{14} age of sea water $1/k_2 = 400$ years (solid lines) and 300 years (broken lines). Points of intersection of straight lines and curves are possible solutions of the two equations for effective reservoirs A^* and S^*.

effect from industrial fuel combustion needs further experimental investigation.

We conclude that the exchange time τ (atm) = $= 1/k_1$, defined as the time it takes on the average for a CO_2 molecule as a member of the atmospheric carbon reservoir to be absorbed by the sea, is of the order of magnitude of 10 years. This corresponds to a net exchange rate of the order of 10^{-7} mol CO_2 per second and square meter of the ocean surface, larger by a factor of 100 than that postulated by PLASS (1956) and smaller by a factor of 10,000 than that deduced by DINGLE (1954) as a lower limit from numerical values of the various rate controlling constants. These are, as HUTCHINSON (1954) has forcefully pointed out, too uncertain to allow any definite conclusions. On the other hand, our exchange data give a value for the "invasion coefficient" of carbon dioxide close to that determined experimentally by BOHR (1899) for a stirred liquid surface.

Secular variation of CO_2 in the atmosphere

In the preceding section of this paper, two simplifying assumptions were made when estimating the exchange rate of CO_2 between the atmosphere and the oceans: (1) that the rate constants k_1 and k_2 were not affected by a small increase of the exchangeable carbon reservoir such as that from industrial fuel combustion, and (2) that, except for that increase, no other changes in the sizes of the oceanic and atmospheric carbon reservoirs have taken place. If these assumptions were rigorously correct, the increase in atmospheric CO_2 due to an addition of C^{14} free CO_2 would be nearly equal to r, as given by Eq. (5) and in table 4, and equal to the decrease in the specific C^{14} activity r^*, multiplied by a factor A^*/A.

Because of the peculiar buffer mechanism of sea water, however, the increase in the partial CO_2 pressure is about 10 times higher than the increase in the total CO_2 concentration of sea water when CO_2 is added and the alkalinity remains constant (BUCH, 1933, see also HARVEY, 1955), so that under equilibrium conditions at a given alkalinity

$$\frac{r}{A_0} = \frac{\gamma s}{S_0} \text{ or } \frac{A_0}{S_0} = \frac{k_1}{k_2} = \frac{r}{\gamma s},$$

γ being a numerical factor of the order of 10

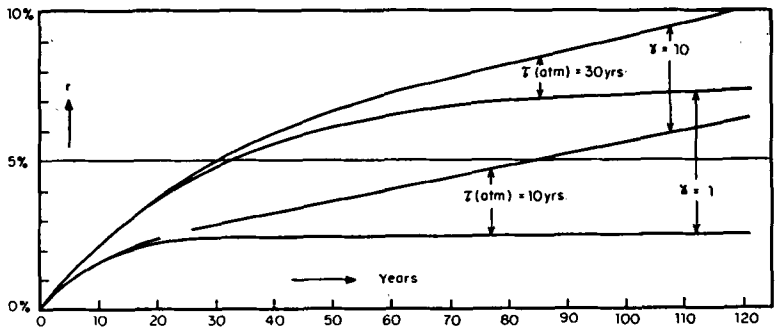


Fig. 2. Expected secular increase in the CO_2 concentration of air (r) according to Eq. (7), for average lifetimes of CO_2 in the atmosphere τ(atm) = 10 years and 30 years, with and without correction for the increase in the partial CO_2 pressure with total CO_2 concentration of sea water (curves for $\gamma = 10$ and $\gamma = 1$ respectively), for a constant rate of addition of industrial CO_2 of $i = 2.5 \cdot 10^{-3} \times A_0$.

for r and s small compared to A_0 and S_0 respectively.

As a reasonable approximation we may write instead of Eq. (3):

$$s = it\frac{k_1}{k_1+\gamma k_2} - i\frac{k_1}{(k_1+\gamma k_2)^2}\left(1 - e^{-(k_1+\gamma k_2)t}\right) \quad (6)$$

or

$$r = it\frac{\gamma k_2}{k_1+\gamma k_2} + i\frac{k_1}{(k_1+\gamma k_2)^2}\left(1 - e^{-(k_1+\gamma k_2)t}\right) \quad (7)$$

Figure 2 shows r as a function of time calculated from Eq. (7) for two values of k_1 corresponding to an exchange time of 10 and 30 years respectively, assuming constant addition of industrial CO_2 equal to 0.25 % of the CO_2 in the atmosphere per year. At present the integrated amount of industrial CO_2 corresponds to about 40 to 50 years of addition at this constant rate. The increase in CO_2 in the atmosphere plus biosphere and soil due to industrial fuel combustion should therefore at present amount to 3 to 6 %, depending on the assumptions made with respect to the size of the "effective" atmospheric carbon reservoir that exchanges with the ocean.

Eq. (7) and figure 2 show that addition of industrial CO_2 at a constant rate should eventually lead to a situation in which the secular increase in CO_2 in the atmosphere plus biosphere and soil equals $\frac{i\gamma k_2/k_1}{1+\gamma k_2/k_1}$ per year. With $S_0/A_0 = k_1/k_2 \approx 60$ and $i = 0.25$ an increase of 3.6 % per century is obtained. We have neglected the present rate of increase in alkalinity, which is small compared to the rate of CO_2 production from fossil fuels. However, over a sufficiently long period of time the alkalinity of the ocean must be expected to rise more rapidly as a consequence of the higher total CO_2 concentration in the atmosphere and ocean which will tend to increase the rate of rock weathering and to decrease the rate of deposition of $CaCO_3$. The secular increase in r should therefore be less than that calculated from Eq. (7) with $\gamma = 10$ and somewhere between the curves shown in figure 2 for $\gamma = 10$ and $\gamma = 1$.

It seems therefore quite improbable that an increase in the atmospheric CO_2 concentration of as much as 10 % could have been caused by industrial fuel combustion during the past century, as Callendar's statistical analyses indicate. It is possible, however, that such an increase could have taken place as the result of a combination with various other causes. The most obvious ones are the following:

1) Increase of the average ocean temperature of 1° C increases P_{CO_2} by about 7 %. However, such increase would also raise the sea level by about 60 cm, due to thermal expansion of the ocean water. Actually, according to MUNK and REVELLE (1952), although the sea level has risen about 10 cm during the last century, this rise can be accounted for almost quantitatively by addition of melt water from retreating glaciers and ice caps. The increase in the average ocean temperature is probably not more than 0.05° C, which corresponds to an increase in P_{CO_2} of 0.35 %. In the case of slow oceanic mixing, the increase could be somewhat larger, if only

the top layers of the sea were affected by a rise in temperature.

2) Decrease in the carbon content of soils: HUTCHINSON (1954) considers this the most probable additional cause of the Callendar effect. The increase in arable lands of about 4×10^{16} cm^2 since the middle of the 19th century has resulted in a corresponding decrease of forest land of about 10 %. Assuming that 70 % of all the soil carbon is in forests (probably a considerable over-estimate), and that cultivation reduced this by 50 %, the total decrease in soil carbon would correspond to 9×10^{16} gms of CO_2 which is 4 % of that in the atmosphere. At least four-fifths of this amount should have been transferred to the ocean.

3) Change in the amount of organic matter in the oceans. About 7 % of the marine carbon reservoir consists of organic material. The amount of organic matter must depend on the balance between the rates of reduction of CO_2 by photosynthesis and of production of CO_2 by oxidation. As pointed out previously, a change in the CO_2 content of sea water by a certain factor without a corresponding change in alkalinity changes P_{CO_2} by about 10 times this factor. Therefore a 1 % change in the concentration of organic material in the sea will change the partial CO_2 pressure and hence the atmospheric CO_2 by roughly 1 %. During the past 50 years, the increase in marine carbon from absorption of industrial CO_2 of about 0.2 % might have increased the rate of photosynthesis without a corresponding change in the rate of oxidation per unit mass of organic matter, and thus decreased P_{CO_2}. An increase in the temperature of surface water might have increased the rate of oxidation per unit mass of organic matter, and hence increased P_{CO_2}. We suspect that fluctuations in the amount of organic marine carbon might be an important cause for changes in the atmospheric CO_2 concentration.

ERIKSON and WELANDER (1956) have discussed a mathematical model of the carbon cycle between the atmosphere, the land biosphere and dead organic matter, and the ocean, in which it is assumed that the rate of input of carbon to the biosphere is directly proportional, not only to the total size of the biosphere but also to the amount of CO_2 in the atmosphere. Their estimate of the land biosphere is 7 times larger than that given in Table 3. They conclude that most of that part of the CO_2 added by fossil fuel consumption, which has not been absorbed by the ocean, has probably gone into the biosphere. Erikson and Welander's basic assumption that the amount of atmospheric carbon dioxide limits the growth of the terrestrial biosphere seems highly unlikely, in view of the fact that the principal photosynthetic production on land is in forests, where a deficiency of plant nutrients might be expected. In any case as HUTCHINSON (1954) has shown, the amount of carbon in the biosphere and soil humus has probably decreased, rather than increased, during the past century, because of the clearing of forests.

In contemplating the probably large increase in CO_2 production by fossil fuel combustion in coming decades we conclude that a total increase of 20 to 40 % in atmospheric CO_2 can be anticipated. This should certainly be adequate to allow a determination of the effects, if any, of changes in atmospheric carbon dioxide on weather and climate throughout the earth.

Present data on the total amount of CO_2 in the atmosphere, on the rates and mechanisms of CO_2 exchange between the sea and the air and between the air and the soils, and on possible fluctuations in marine organic carbon, are insufficient to give an accurate base line for measurement of future changes in atmospheric CO_2. An opportunity exists during the International Geophysical Year to obtain much of the necessary information.

Acknowledgements

A paper on the same subject by James R. Arnold and Ernest C. Anderson appears in this issue of this journal; we are grateful to Drs. Arnold and Anderson for the opportunity of discussing the problem before publication. We are happy to note that these authors have simultaneously and independently derived essentially the same conclusions as presented in this paper. We hope that the somewhat different approach will make both contributions equally valuable to the reader. We also wish to thank Dr. Carl Eckart for valuable discussions and Dr. Harmon Craig for much constructive criticism. Dr. Craig's own careful analysis of the subject appears in a separate paper in this issue.

Annex 10

H. R. Brannon et al., “Radiocarbon evidence on the dilution of atmospheric and oceanic carbon by carbon from fossil fuels”, *Transactions, American Geophysical Union,* 1957, pp. 643-650, pages 643-644

Transactions
American Geophysical Union

VOLUME 38 OCTOBER 1957 NUMBER 5

Radiocarbon Evidence on the Dilution of Atmospheric and Oceanic Carbon by Carbon from Fossil Fuels

H. R. BRANNON, JR., A. C. DAUGHTRY, D. PERRY, W. W. WHITAKER, AND M. WILLIAMS

Abstract—The dilution of atmospheric carbon dioxide by carbon dioxide from fossil fuels is estimated to be about 3½ pct, on the basis of radiocarbon assays of tree rings of known ages from several trees of different genera, after allowance has been made for effects attributable to ecological differences. The cumulative mass of fossil carbon dioxide released to the atmosphere is 3.3 x 10^{17} gm, equivalent to about 14 pct of the carbon dioxide in the atmosphere. Based on these data, the fractional part of the atmospheric carbon dioxide which enters the ocean each year is estimated to be 0.062. Radiocarbon assays of several nineteenth-century marine shells and of their modern counterparts indicate a one to two per cent dilution of shallow oceanic carbonates by carbon dioxide from fossil fuels. Use of these data in a simplified mathematical model of atmosphere-ocean yields information on mixing times of the ocean.

Introduction—The effects of addition to the carbon cycle in nature of carbon dioxide from industrial activities have been the subject of speculation in several fields of science. Of particular interest is the fate of the enormous quantity of carbon dioxide which has been introduced into the atmosphere since the beginning of the industrial revolution in the 19th century, and the manner in which the added carbon dioxide has been distributed in the carbon cycle. Although appreciable amounts of carbon dioxide have undoubtedly been added from soils by tilling of land, apparently a much greater amount has resulted from the combustion of fossil fuels.

Callendar [1940] pointed out that direct measurements of the carbon dioxide concentration in air, made over a number of years by various investigators, indicate a significant increase in concentration over the period 1866–1935. From this he concluded that most of the carbon dioxide from the industrial revolution has remained in the air and, consequently, that the rate of absorption of carbon dioxide by the oceans is very slow. *Hutchinson* [1954] suggested that the radiocarbon content of woods from trees which have lived during the industrial revolution might throw light on the dilution of atmospheric carbon dioxide by carbon dioxide from the combustion of fossil fuels. *Suess* [1954] at about the same time determined the radiocarbon content of tree rings of known ages from several trees. These results indicated a dilution of about 3½ pct. In later work *Suess* [1955], on the basis of results on additional samples, revised the probable dilution downward to less than one per cent and ascribed the former higher indicated dilution to localized effects of industrial activity.

Within the last several years there have been rapid advances in the methodology of radiocarbon assay, particularly as it pertains to radiocarbon dating. As a result, it is possible today to make routine radiocarbon assays in which the statistical uncertainty is less than one per cent for contemporary concentrations of natural radiocarbon. In view of such precision, a knowledge of the dilution effect becomes important in the precise radiocarbon dating of carbon-containing materials. It was to gain knowledge of the dilution effect in both plant material and shallow oceanic carbonates that the investigation described in the following sections was undertaken. In all of the experimental work, radiocarbon assays were made by proportional counting of the sample as carbon dioxide gas, contained in the counter under a pressure of five atmospheres absolute [*Brannon, Taggart,* and *Williams,* 1955]. The same counter was used for all assays. In the preparation of each sample the conversion to carbon dioxide and the recovery of the carbon dioxide were virtually complete, assuring an absence of effects due to isotopic fractionation. The results in all cases have been expressed in terms of net counts per minute for the particular counter employed. No attempt has been made to convert the results to a form which would reflect the absolute disintegration rate per unit mass of carbon.

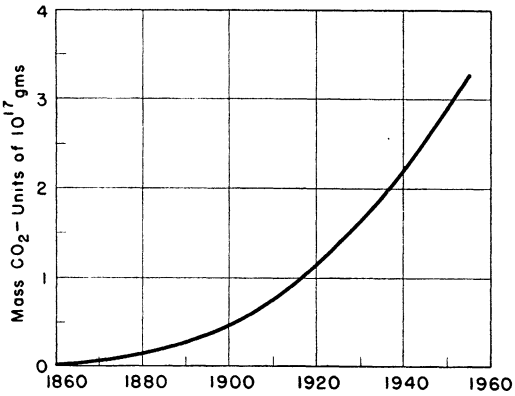


FIG. 1 — Cumulative carbon dioxide released to atmosphere by combustion of fossil fuels

Appraisal of carbon dioxide production from fossil fuels—Although various estimates have been made of the cumulative amount of carbon dioxide released to the atmosphere since the beginning of the industrial revolution by the combustion of fossil fuels, it was deemed desirable to reappraise both the total amount and the rate at which it has been introduced into the atmosphere.

The greater part of this carbon dioxide, by far, has been attributable to the burning of coal. Perhaps the best data suitable for the estimation of the contribution from coal are given by *Putnam* [1953] for world-wide consumption since the year 1860. His values are expressed in terms of heat content of coal consumed, so that proper weight may be considered to have been given to the rank of the coal. The conversion of Putnam's figures for coal consumption to mass of carbon dioxide produced may be accomplished by means of a factor relating carbon content to heat content of coal. Perhaps the most reliable data for the consumption of liquid petroleum are those given in a publication of *DeGolyer* and *MacNaughton* [1955]. The carbon dioxide produced by combustion of petroleum may be estimated by use of an average value for the carbon content of liquid petroleum. Although the mass of carbon dioxide produced by the combustion of natural gas is relatively minor, this may be approximated by use of an average carbon content of natural gas and of a ratio of gas to oil produced. This ratio may be assumed to have increased continuously from about 1910 to the present.

Figure 1 shows an estimate of the cumulative amount of carbon dioxide released to the atmosphere by the burning of fossil fuels made by use of the foregoing data and assumptions. The cumulative production to date, approximately 3.3×10^{17} grams of carbon dioxide, is equivalent to about 14 pct of the total amount of carbon dioxide in the atmosphere. This is somewhat less than an estimate made by *Putnam* [1953], and is slightly higher than an unpublished estimate made by Harrison Brown (private communication). Although no values of carbon dioxide equivalency are contained in a paper on total fossil fuel production by *Hubbert* [1956], application of reasonable carbon contents of coal and of petroleum to Hubbert's estimates of production would likely result in an estimate of total carbon dioxide production which would be slightly higher than that of Figure 1. It may also be noted that the estimate made by *Callendar* [1940] for carbon dioxide production between 1900 and 1935 is somewhat higher than that shown by Figure 1.

The curve of Figure 1 is not of simple exponential form. The portion from 1860 to about 1910 approximates an exponential form, but the part of the curve from 1910 onward deviates progressively from the exponential. The deviation is such that less carbon dioxide has been produced than would be expected from an exponential relation fitted to the early part of the curve. Application to the curve of combustion efficiency factors given by Putnam, however, yields a curve which follows closely an exponential form. From this it may be inferred that improvements in efficiency of utilization of fuels achieved during the last several decades have resulted in appreciably less consumption of fuels than would have been the case otherwise.

Evidence on dilution of atmospheric carbon dioxide—In investigating the dilution of atmospheric carbon dioxide and, consequently, of the carbon contained in vegetation by carbon from fossil fuels, the method of attack was essentially that followed by *Suess* [1954, 1955]. Radiocarbon assays were made of tree rings of known age, including rings of very recent age.

The selection of the woods for investigation posed a problem. Obviously, if an attempt were made to include all types of woody plants from all possible environments in which they are found, the number of samples would be prohibitively large. The decision was made, therefore, to choose only a very limited number of woods, but, in the selection, to attempt to choose samples which might yield definitive results. In particular, the samples were selected to represent extremes in environment and ecology.

The woods investigated were oak, gum, 'cypress' (*Taxodium*), and Douglas fir. The oak and gum samples were obtained from locations in eastern Texas approximately 75 miles north of Houston.

Annex 11

B. Bolin & E. Eriksson, “Changes in the carbon dioxide content of the atmosphere and sea due to fossil fuel combustion”, in THE ATMOSPHERE AND THE SEA IN MOTION: SCIENTIFIC CONTRIBUTIONS TO THE ROSSBY MEMORIAL VOLUME, ed. B. Bolin (Rockefeller Institute Press, 1959), pages 130-132

DISTRIBUTION OF MATTER IN THE SEA AND ATMOSPHERE

Changes in the Carbon Dioxide Content of the Atmosphere and Sea due to Fossil Fuel Combustion[1]

By BERT BOLIN and ERIK ERIKSSON

International Meteorological Institute in Stockholm

Abstract

The dissociation equilibrium of carbon dioxide in the sea is discussed with particular emphasis on the buffering effect of sea water, when changes of the partial pressure of CO_2 in the gas phase take place. The results are used in a study of the changes of the carbon dioxide content of the atmosphere and the sea that occur as a result of release of CO_2 to the atmosphere by fossil fuel combustion. It is shown that the steady state considerations given by previous authors hereby are considerably modified. Thus an increase of the CO_2 content of the atmosphere of about 10% as reported by Callendar may be compatible with a Süess effect of only a few percent. Because of the small buffering effect of the sea it seems likely that the biosphere on land may play a more important role for the changes actually occurring in the atmosphere due to release of CO_2 by combustion than previously believed. This problem warrants further investigation, but already the present treatment indicates that an appreciable increase of the amount of CO_2 in the atmosphere may have occurred since last century. This increase will continue and should be detectable with present techniques for measuring CO_2 in the atmosphere within a few years in areas with little or no local pollution due to fossil fuel combustion as in the Antarctica or on Hawaii.

1. Introduction

Fossil fuel combustion has added considerable amounts of carbon dioxide to the atmosphere during the last 100 years. In view of the great importance of CO_2 in the atmosphere for maintaining a radiational balance between the earth and space it is of great interest to know whether this output of CO_2 has caused a significant increase of the total content of carbon dioxide in the atmosphere or whether most of it has been transferred into the oceans. Some twenty years ago CALLENDAR (1938) could show that most likely a noticeable increase of the CO_2 in the atmosphere had occurred and he has recently (CALLENDAR, 1958) indicated that this increase in 1955—56 amounted to about 10 % as compared with an output due to combustion of about 14 % of the total amount of CO_2 present in the atmosphere (cf. REVELLE and SÜESS, 1957). His conclusions have recently been supported by BRAY (1959) in a detailed statistical investigation. However, by studying the C^{14} distribution in the atmosphere and the sea and its variation in the atmosphere during the last 100 years as revealed by the ratio C^{14}/C^{12} in wood one has been able to show that the exchange time between the atmosphere and the ocean is about 5 years (CRAIG, 1957, 1958; REVELLE and SÜESS, 1957; ARNOLD and ANDERSON, 1957; RAFTER and FERGUSSON, 1958). It has then been concluded (REVELLE and SÜESS, l.c.) that most of the CO_2 due to combustion has been transferred into the ocean and that a net increase of CO_2 in the atmosphere of only

[1] The research reported in this paper was partly sponsored by the Office of Naval Research through the Woods Hole Oceanographic Institution. Contribution No. 1025 from the Woods Hole Oceanographic Institution.

a few percent has actually occurred. Callendar's deduction has therefore been rejected particularly since the CO_2 measurements from the 19th century are indeed very uncertain.

Towards the end of their paper Revelle and Süess point out, however, that the sea has a buffer mechanism acting in such a way that a 10 % increase of the CO_2-content of the atmosphere need merely be balanced by an increase of about 1 % of the total CO_2 content in sea water to reach a new equilibrium. The crude model of the sea they used assuming it to be one well-mixed reservoir of CO_2, did not permit them to study the effect of this process more in detail.

The low buffering capacity of the sea mentioned by Revelle and Süess is due to a change in the dissociation equilibrium between CO_2 and H_2CO_3 on one hand and HCO_3 and CO_3 ions on the other. An addition of CO_2 to the water will change the pH and thereby decrease the dissociation resulting in a larger portion of CO_2 and H_2CO_3 molecules. Since the pressure of CO_2 in the gas phase being in equilibrium with CO_2 dissolved in water is proportional to the number of CO_2 and H_2CO_3 molecules in the water, an increase of the partial pressure occurs which is much larger (about 12.5 times) than the increase of the *total content* of CO_2 in the water. The change of this equilibrium in the sea is almost instantaneous. However, in course of its circulation the ocean water gets in contact with solid $CaCO_3$ on the bottom of the sea whereby a change towards another equilibrium takes place. This latter process is extremely slow and may be disregarded when discussing changes due to fossil fuel combustion. It will, however, be indicated in section 2 how this equilibrium is of major interest when being concerned with processes with a time scale of several thousand years.

In discussing the consequences of such a shift in the dissociation equilibrium with respect to the exchange of CO_2 between the atmosphere and the sea and within the sea it is not sufficient to treat the ocean as one well-mixed reservoir. We shall instead first follow a suggestion by CRAIG (1957) and divide the ocean in two layers. The upper reservoir, in direct contact with the atmosphere, is the part of the ocean located above the thermocline and constitutes about 1/50 of the total sea. This part of the ocean is well mixed due to wind action and convection. The remaining part of the ocean, the deep sea, is also taken as a well-mixed water body in direct exchange with the mixed layer above. Certainly this latter assumption is a poor approximation to actual conditions but will, as we shall see, give internally consistant results. In the first instance we shall neglect the effect of living matter on the earth but some general remarks about the exchange of CO_2 between vegetation and the atmosphere will be given towards the end of the paper.

It is obvious that an addition of CO_2 to the atmosphere will only slightly change the CO_2 content of the sea but appreciably effect the CO_2 content of the atmosphere. It is possible to deduce a relation between the exchange coefficient for transfer from the atmosphere to the sea and the corresponding coefficient for the exchange between the deep sea and the mixed layer. It turns out that a 10 % increase of the CO_2 content of the atmosphere as a result of a total output due to combustion amounting to 13 % of the total CO_2 content of the atmosphere would result for a residence time of water in the deep sea of around 500 years. Only a considerably more rapid turn over of the ocean model yield appreciably lower values, while the rate of exchange between the atmosphere and the sea is much less important.

The change in the dissociation equilibrium in water resulting from a transfer of CO_2 to the sea also effects the C^{14} distribution in the three reservoirs and REVELLE'S and SÜESS' (1957) considerations in this matter are thereby appreciably changed. It is clear that a large percentage change of the CO_2 in the atmosphere and a comparatively small percentage change in the sea will yield a C^{14}/C^{12} ratio in the sea which is considerably greater than that of the atmosphere. The distribution of C^{14} between these two reservoirs is therefore not in equilibrium any longer. A transfer of C^{14} from the sea to the atmosphere will result. A more detailed study of this secondary effect reveals that

a) the steady state considerations of CO_2 exchange between the atmosphere and the sea as given by CRAIG (1957, 1958) are somewhat modified and a likely residence time for CO_2 in the atmosphere is 5 years.

b) the Süess effect would be 3—5 % depending on the rate of overturning of the sea.

In view of the observed values of the Süess-effect being around 3 % in 1954 (before the hydrogen bomb tests) (cf. BROECKER and WALTON, 1959; DE VRIES, 1958) the values obtained in this

analysis are somewhat too large if using a value for the residence of water in the deep sea of 500 years. One possible explanation of this discrepancy would be the neglect of the exchange of CO_2 between the atmosphere and the biosphere. The main difficulty met when trying to incorporate this effect is, that we actually do not know whether a net increase of the amount of CO_2 present in vegetation may have occurred due to a transfer from the atmosphere or whether the direct influences from man's activities have had an effect in the opposite direction. It is clear, however, that even if no net transfer of CO_2 from the atmosphere into living or dead matter on land has occurred these exchange processes will modify the estimate of the "Süess effect" obtained by merely considering the atmosphere and the sea.

2. The CO_2-system in the sea

The different components of CO_2 present in the sea are CO_2, H_2CO_3, HCO_3^- and CO_3^{-2}. As CO_2 is difficult to distinguish from H_2CO_3 it is customary to express the sum of these species as CO_2. The sea is also in contact with ample amounts of solid $CaCO_3$ which should be considered in equilibrium being attained over several "turnover times" of the sea itself. Another important item in the system is the carbonate alkalinity, denoted here by A which is the sum of those cations which balance the charges of HCO_3^- and CO_3^{-2}. The following average values for the concentrations of the different components will be used here:

$C_{CO_2} = 0.0133$ mmol $\times 1^{-1}$ (sum of CO_2 and H_2CO_3)
$C_{HCO_3^-} = 1.90$ mmol $\times 1^{-1}$
$C_{CO_3^{-2}} = 0.235$ mmol $\times 1^{-1}$

The sum of all these species is denoted by ΣC_{CO_2} and becomes 2.148 mmol $\times 1^{-1}$. A is given in mval $\times 1^{-1}$ and becomes, $A = C_{HCO_3^-} + 2\ C_{CO_3^{-2}} = 2.37$ mval $\times 1^{-1}$. Now the following relationships can be derived, namely

$$\sum C_{CO_2} = \left(1 + \frac{K_1}{C_{H^+}} + \frac{K_1 K_2}{C_{H^+}^2}\right) C_{CO_2} \qquad (1)$$

$$A = \left(\frac{K_1}{C_{H^+}} + \frac{2K_1K_2}{C_{H^+}^2}\right) C_{CO_2} \qquad (2)$$

where K_1 and K_2 are the first and second dissociation constants of H_2CO_3 in sea water and C_{H^+} is the hydrogen ion concentration. It is convenient to have the average values of the fractions within the brackets. They are

$$\frac{K_1}{C_{H^+}} = 143 \qquad \frac{K_1 K_2}{C_{H^+}^2} = 18$$

As to calcium carbonate, its solubility product L_p can be written

$$C_{Ca^{+2}} \cdot C_{CO_3^{-2}} = L_p$$

or more conveniently

$$C_{Ca^{+2}} = L_p \frac{C_{H^+}^2}{K_1 K_2} \frac{1}{C_{CO_2}} \qquad (3)$$

and in sea water $C_{Ca^{2+}} = 10$ mmol $\times 1^{-1}$.

Finally we have for the equilibrium between the atmospheric CO_2 and that in sea water

$$P_{CO_2} = \frac{1}{\alpha} C_{CO_2} \qquad (4)$$

where α is a proportionality constant and P_{CO_2} is the partial pressure of CO_2 in the atmosphere.

The constants K_1, K_2, L_p and α are only functions of temperature and salinity and will be regarded as constants in the following. We may therefore consider relations between small variations in P_{CO_2}, C_{CO_2}, ΣC_{CO_2}, A, C_{H^+} and $C_{Ca^{2+}}$. Using the variational method applied on equations (1) to (4) one obtains

$$\frac{\delta \Sigma C_{CO_2}}{\Sigma C_{CO_2}} = \frac{\delta C_{CO_2}}{C_{CO_2}} + \frac{\dfrac{\partial}{\partial C_{H^+}}\left(1 + \dfrac{K_1}{C_{H^+}} + \dfrac{K_1K_2}{C_{H^+}^2}\right)}{1 + \dfrac{K_1}{C_{H^+}} + \dfrac{K_1K_2}{C_{H^+}^2}} \delta C_{H^+} \qquad (5)$$

$$\frac{\delta A}{A} = \frac{\delta C_{CO_2}}{C_{CO_2}} + \frac{\dfrac{\partial}{\partial C_{H^+}}\left(\dfrac{K_1}{C_{H^+}} + \dfrac{2K_1K_2}{C_{H^+}^2}\right)}{\dfrac{K_1}{C_{H^+}} + \dfrac{2K_1K_2}{C_{H^+}^2}} \delta C_{H^+} \qquad (6)$$

$$\frac{\delta C_{Ca^{+2}}}{C_{Ca^{+2}}} = \frac{2\,\delta C_{H^+}}{C_{H^+}} - \frac{\delta C_{CO_2}}{C_{CO_2}} \qquad (7)$$

$$\frac{\delta P_{CO_2}}{P_{CO_2}} = \frac{\delta C_{CO_2}}{C_{CO_2}} \qquad (8)$$

Annex 12

L. D. Kaplan, “The Influence of Carbon Dioxide Variations on the Atmospheric Heat Balance”, Letter to the Editor, *Tellus,* 1961, pp. 296-300

LETTERS TO THE EDITOR

"*The Influence of Carbon Dioxide Variations on the Atmospheric Heat Balance*", by L. D. Kaplan, Tellus **12**, pp. 204—208 (1960).

Dear Sir,

In a recent article with the above title, Kaplan (1960) describes the results of his carbon dioxide calculations, which according to his own evaluation can "be accepted as definitive". On the other hand his article criticizes my earlier treatment of this problem which Kaplan describes as "inadequate", "approximate", and "too subjective to be reproducible". In addition in his abstract Kaplan writes that "Plass' estimate of a temperature drop of 3.8° C due to a halving of the carbon dioxide concentration appears to be too high by a factor of two or three." This statement would seem to be somewhat misleading since Kaplan compares two entirely different quantities: my result for clear skies with his result for cloudy skies! Actually, when our results for the temperature drop are compared under approximately the same conditions, there is only a 22 % difference between them. This question is discussed in more detail later in this letter.

Kaplan has made a number of approximations in his calculations, none of which are adequately discussed in his article in Tellus nor in the Rossby Memorial Volume (KAPLAN, 1959). Some of these approximations introduce significant errors in his final results which are tabulated to five significant figures. Thus the reader naturally presumes that these results are also accurate to five significant figures. Unfortunately this is not the case since errors in the first two significant figures have been introduced into his calculations by the truncation of the atmosphere at 100 millibars. Somewhat smaller errors have been introduced by the use of the Curtis-Godson approximation. Furthermore the absolute accuracy of theoretical calculations is limited by the experimental errors in the determination of the integrated band intensities which are at least of the order of 5 percent.

Before I discuss the differences between our calculations, I should like to emphasize that climatic changes which occur over time intervals of geological significance can be explained by the carbon dioxide theory regardless of whether the temperature decreases by 3.8° C (PLASS, 1956b) or by 1.8° C (KAPLAN, 1960) when the CO_2 amount is halved. Our present knowledge of the relative importance and the magnitude of the various factors which have entered into the carbon dioxide cycle during past geologic eras is very limited. Many of the climatic changes which have occurred over the past several billion years of the earth's history can readily be explained by variations of the atmospheric CO_2 amount. Sufficiently large variations are entirely consistent with the known facts even if Kaplan's value is adopted for the temperature change. On the other hand, the difference between our two values for the temperature change is significant for the explanation of the world-wide temperature increase which has occurred in the twentieth century. If Kaplan's value is correct, this recent temperature increase cannot be explained entirely by the CO_2 theory. If my value is correct, the CO_2 theory offers a possible explanation.

I would like to discuss the following points about Kaplan's calculation and his comparison of our results:

(1) In my opinion the most serious defect of Kaplan's calculations is the truncation of the atmosphere at 100 mb. Kaplan must have assumed (although he does not state this) that the downward flux is zero at 100 mb since the flux above this level cannot be obtained by the method as described.

KAPLAN (1959) correctly states that the equation for the net upward flux at a given height must be integrated to some

arbitrary level chosen so that virtually no radiation from above this arbitrary level can reach the level at which the flux is being evaluated. In the present article Kaplan takes this arbitrary level to be at 100 millibars. This is equivalent to the assumption that the downward flux is zero at 100 millibars. A glance at Fig. 7 of my article (PLASS, 1956b) shows that the value of the downward flux over the entire band at the 100 millibar level is already 14 percent of its value at the ground. Since this emission from the stratosphere is entirely omitted from Kaplan's calculations, this downward flux should be added to his results which are given in Table 1 for the net radiation at 100 millibars. This correction becomes relatively more and more important the nearer the cloud top is to the 100 millibar level. A smaller error is introduced into the results of Table 2 for the net radiation at the ground since his results do not include the fraction of the radiation emitted above 100 mb which reaches the ground.

The emission by the molecules in the stratosphere in the wavelength band from 12 to 14 microns and from 16 to 18 microns has an important influence on the change in the infrared flux with carbon dioxide concentration. The physical explanation of this fact is that the emission in a given frequency interval of this radiation by the molecules in the stratosphere increases more rapidly with the carbon dioxide concentration than does the absorption of this same radiation by the lower atmospheric layers. In order to check this point quantitatively I have repeated my calculation (PLASS, 1956b), but with Kaplan's boundary condition that the downward flux is zero at 100 millibars. Consider *the difference* ΔI between the downward flux when the CO_2 has its present value and when it is 50 percent of this value. The result is that this approximative boundary condition reduces the value of ΔI by 8.1 percent. Thus Kaplan's values for ΔI the change in flux with carbon dioxide amount should be increased by approximately 8.1 percent of this amount because of his incorrect boundary condition at 100 millibars.

(2) Some of the temperature distributions used by Kaplan are quite unrealistic. He assumes a constant lapse rate from the ground to the 100 mb level. Consider first the case when $\varkappa = \frac{1}{3}$. If this corresponds to a lapse rate of 11.2° C per km as stated in his text (however 11.4° C per km is used in his tables!), then, when the surface temperatures are 273° K and 313° K, the 100 millibar level is at 13.0 and 14.7 km respectively and the temperatures at this level are 127° K and 146° K respectively. These values clearly do not correspond to any temperatures that have ever been observed in our atmosphere. The values are somewhat more reasonable when $\varkappa = \frac{1}{6}$. When the surface temperatures are 273° K and 313° K, the 100 millibar level is at 15.5 and 17.9 km respectively and the temperatures at that level are 186° K and 213° K. However, neither of these distributions represents the average temperature variation with height in our actual atmosphere with much accuracy. In contrast to these unrealistic temperature distributions my calculations were made with a distribution which is very close to the actual observed values. In these calculations the temperature decreased with a constant lapse rate of 6° K/km up to 13 km, had the constant value of 210° K from 13 to 22 km, and then increased again.

(3) In his calculation Kaplan uses the Curtis-Godson approximation. For η near unity this can cause errors as large as 5.8 percent in the absorption between surfaces at one and zero atmospheres (KAPLAN, 1959). This error decreases as η becomes either very small or very large compared to unity. Thus it is not easy to estimate the error introduced by this approximation for the total flux from an actual band which contains a wide range of values of η. Nevertheless, the fact remains that the spectral lines with η near unity are the most important for the effects under discussion here. When η is very small the lines may be too weak to contribute to the total unless they are quite numerous. There are only a few spectral lines with large η. There is little change in the absorption from these strong lines as the CO_2 concentration changes because they overlap the neighboring lines. When all of these effects are taken into account, I estimate that the Curtis-Godson approximation introduces an error of several percent in the total absorption of this band.

(4) It would seem that Kaplan should have presented sufficient details of his calculations so that the interested reader could recalculate any of his results. However, he has not given

us the most fundamental data which enters into his calculation: the total band intensities. In a private communication, he has stated that they are nearly the same as those given by YAMAMOTO and SASAMORI (1958). But exactly what values did Kaplan use?

Kaplan states that he used "better laboratory data" than was available when my calculation was performed. The reader must presume that this is the data referred to by KAPLAN (1959, p. 176). He does not tell us what criteria were used to decide that this data is better than the careful measurements of Cloud. Furthermore, the measurements which he uses were not made for the primary purpose of obtaining band intensities. Actually the most comprehensive and possibly the most accurate CO_2 measurements have just been completed at Ohio State and have not been used by either of us. How well do Kaplan's calculations actually agree with laboratory data over a range of path lengths and pressures? It would seem that he should give us some detailed comparisons or sufficient data so that the interested reader can make his own comparisons.

(5) Kaplan does not state what isotopes of CO_2 were included in his calculation. Even some of the rarer isotopes can make an appreciable contribution over a path length through the entire atmosphere. For example, even though only 0.2 percent of the molecules are $C^{12}O^{16}O^{18}$, the contribution of this molecule to the total absorption can be appreciably more than this amount in a frequency interval where a maximum of one of its absorption bands corresponds with a region of small absorption for the most common isotope. If the isotopes were taken into account in the calculation, how were the intensities and frequencies of their spectral lines obtained?

(6) Kaplan's method uses the random Elsasser model to represent the absorption of the band. In each frequency interval a small number of sub-bands are found such that the spectral lines of each sub-band have approximately equal spacing and equal intensity. How many sub-bands did Kaplan use in typical frequency intervals? What intensity did Kaplan choose for each of these sub-bands? The reader can only guess that the actual intensities of all the spectral lines of this sub-band for the given frequency interval were averaged and that this average intensity was used in the calculation. This is probably a good approximation although the intensities of a single sub-band may vary by a considerable amount in an interval of 10 cm^{-1}.

(7) The effect of the wings of strong spectral lines which are one or more frequency intervals away from the one under consideration may contribute appreciably to the absorption in some spectral regions. This effect may materially increase the variation of the absorption with CO_2 concentration in some of the regions of weaker absorption since the wing absorption increases at first in direct proportion to the CO_2 concentration. In order to calculate this effect a wing line shape must be assumed. Unfortunately the line shape far from the line center is not well known so that some particular shape must be assumed. The effect of the wings of strong spectral lines whose center is outside of the spectral interval being considered does not seem to have been included in Kaplan's calculation since he does not mention it.

(8) The half-width of the spectral lines varies with the rotational quantum number. Kaplan apparently uses an average value in his calculation. This is probably necessary for this type of calculation, since it would be very difficult to take account of the actual variation.

(9) What were the weakest lines which Kaplan included in his calculation? He does not tell us the criterion which was used to terminate the calculation of the rotational lines which belong to a given vibrational transition. The numerous weak lines may be important in some spectral intervals over the long path lengths which occur in the atmosphere.

(10) Kaplan's method is only valid for a constant lapse rate. Thus the flux cannot be calculated for the actual temperature variation obtained from a given sounding.

(11) I cannot agree with Kaplan's comparison of our results since he uses the wrong lapse rate for my calculation. The result of Kaplan's calculation is two values for the change in the downward flux when the carbon dioxide concentration is halved: 8,020 and 4,890 c.g.s. units for surface temperatures of 40° C and 0° C respectively. In order to compare his results with mine (surface temperature of 15° C), he makes a linear interpolation. Now a linear interpolation is certainly not justified between two values that differ as widely as

these when the quantity is known to vary non-linearly with the surface temperature. However, since only these two values are available, let us for the moment allow him to make a comparison in this manner. The value obtained by linear interpolation of Kaplan's results is 6,060 c.g.s. units. This is calculated for a lapse rate of 5.6° C per km. My calculation assumed a lapse rate of 6.0° per km (PLASS, 1956b, p. 311) rather than 5.5° C per km which Kaplan states that I used. The quantity 220 c.g.s. units must be added to Kaplan's result to correct it to a lapse rate of 6.0° per km. Furthermore, as discussed above, 490 c.g.s. units must be added to his value because of the incorrect boundary condition at 100 millibars.

Thus, as nearly as can be estimated, Kaplan's result is 6,770 c.g.s. units for somewhat similar conditions to those which I assumed. My result is 8,720 c.g.s. units. Thus Kaplan's result is 22 % lower than mine by this rather approximate method of comparison. Actually this would seem to be excellent agreement when it is considered that: (1) entirely different methods of calculation are used; (2) different laboratory data is used; (3) the distribution of temperature with height is not the same in the two calculations; (4) approximations were made in both methods of calculation. The comparison of these results certainly offers no basis for Kaplan's claim that this shows that my method is "inadequate for the problem of determining radiative temperature changes in the atmosphere".

(12) In his abstract Kaplan compares his result for the temperature change when the average cloud amount is taken into consideration (1.8° C) with my result for clear skies (3.8° C). This seems rather misleading to the reader, especially since the question of cloudy skies was thoroughly discussed in my papers (PLASS, 1956b, p. 320; PLASS, 1956c, p. 148). The argument given there showed that increased precipitation and cloud amount were likely to occur when the CO_2 amount was decreased. This in turn increases the earth's albedo and further decreases the surface temperature. As the temperature drops the maximum possible water vapor content of the atmosphere decreases very rapidly. The infrared bands of H_2O are thus less effective in holding the heat energy near the surface of the earth and the temperature further decreases. In addition the infrared energy loss from the cloud tops to space increases. This in turn increases the convection currents in the cloud and allows it to grow. An increased cloud amount causes more sunlight to be reflected to space and further reduces the temperature. Thus the effect of water vapor is to amplify the initial temperature changes caused by CO_2. Because of the many complicated interactions this effect cannot be calculated quantitatively. However, I believe that the actual temperature change for the earth with an average cloud distribution when the CO_2 amount is halved is at least 3.8° C and probably considerably more. Even in the tropics H_2O cannot effectively shield the CO_2, but merely slightly raises the height at which the CO_2 begins to influence the radiation. This occurs because the variation of the H_2O and CO_2 concentrations with height is very different. Kaplan implies on the contrary that H_2O will reduce the temperature changes due to CO_2 rather than reinforcing them. He offers no arguments to support this view.

There are several different ways to calculate the radiative flux in the atmosphere. The method based on the direct use of laboratory data (PLASS, 1952, 1956a, 1956b, 1958, 1960) is limited by the accuracy of the original experiments. The absolute accuracy of Kaplan's method is also limited by the same factor. The advantages of the method which is based directly on the laboratory data are: (1) even the weakest spectral lines are included which can contribute to the absorption for the range of variables measured in the laboratory; (2) all isotopes are included in the correct proportion; (3) the variable half-width of the spectral lines is automatically taken into account; (4) all of the spectral lines are included with their correct line intensities and frequencies; (5) the correct wing absorption for distant strong lines is included for not only the Lorentz line shape, but for any line shape whose absorption coefficient is proportional to the pressure in the wings of the line; (6) the effect of the overlapping is correctly taken into account; (7) the method can be used with any arbitrary variation of pressure and temperature with height. The disadvantages include: (1) a discontinuity in the slope (but not in the value) occurs where any two of the three different approximations for the absorption curve are joined together; (2) until laboratory measure-

ments are available at lower temperatures the results must be corrected theoretically (PLASS, 1956b) for their variation with temperature; (3) in order to extrapolate the results over a wide range of pressures and path lengths the laboratory measurements must have been made over a sufficiently wide range of the variables in order to define the "strong line", "weak line", and "nonoverlapping line" regions. The effect of variations in the absorption curve chosen to represent the laboratory data has been considered in detail in one case (PLASS, 1956a). The absorption curves are closely defined by the laboratory data. The total band intensities can only be determined in Kaplan's method from curves which are obtained from experimental results. The line intensities calculated by Kaplan are directly proportional to the band intensity obtained by experiment.

The method which involves the theoretical calculation of the intensities and positions of all the spectral lines is certainly another valid approach to this problem. However, numerous approximations which have been outlined above have been made by Kaplan in applying this method in practice. The accuracy of the final results depends on how judiciously the investigator has approximated the actual physical situation. Kaplan should have pointed out some of these limitations in his article.

Sincerely yours

GILBERT N. PLASS

Aeronutronic, a Division of
Ford Motor Company
Newport Beach, Calif.

REFERENCES

KAPLAN, L. D., 1959: A method for calculation of infrared flux for use in numerical models of atmospheric motion, *Rossby Memorial Volume*, pp. 170—177.

— 1960: The influence of carbon dioxide variations on the atmospheric heat balance, *Tellus* **12**, pp. 204—208.

PLASS, G. N., 1952: A method for the determination of atmospheric transmission functions from laboratory absorption measurements, *J. Opt. Soc. Amer.* **42**, pp. 677—683.

— 1956a: The influence of the 9.6 micron ozone band on the atmospheric infrared cooling rate, *Quart. J. Roy. Meteor. Soc.* **82**, pp. 30—44.

— 1956b: The influence of the 15 micron carbon dioxide band on the atmospheric infrared cooling rate, *Quart. J. Roy Meteor. Soc.* **82**, pp. 310—324.

PLASS, G. N., 1956c: The carbon dioxide theory of climatic change, *Tellus* **8**, pp. 140—153.

— 1958: Models for spectral band absorption, *J. Opt. Soc. Amer.* **48**, pp. 690—703.

— 1960: Useful representations for measurements of spectral band absorption, *J. Opt. Soc. Amer.* **50**, pp. 868—875.

YAMAMOTO, G. and SASAMORI, T., 1958: Calculation of the absorption of the 15 micron carbon dioxide band, *Science Reports of Tohoku University*, Ser. 5, Geophysics, **10**, pp. 37—57.

Annex 13

G. Callendar, "Temperature fluctuations and trends over the earth", *Quarterly Journal of The Royal Meteorological Society,* 1961, pp. 1-12, pages 1, 8-10

QUARTERLY JOURNAL
OF THE
ROYAL METEOROLOGICAL SOCIETY

Vol. 87 JANUARY 1961 No. 371

551.524.34 : 551.583.1

Temperature fluctuations and trends over the earth

By G. S. CALLENDAR
A.R.D.E., Ministry of Supply, London

(Manuscript received 13 June 1960)

SUMMARY

The annual temperature deviations at over 400 meteorological stations are combined on a regional basis to give the integrated fluctuations over large areas and zones. These are shown in graphical form, and it is concluded that a solar or atmospheric dust hypothesis is necessary to explain the world-wide fluctuations of a few years duration. An important change in the relationships of the zonal fluctuations has occurred since 1920. The overall temperature trends found from the data are considered in relation to the homogeneity of recording, and also to the evidence of glacial recession in different zones. It is concluded that the rising trend, shown by the instruments during recent decades, is significant from the Arctic to about 45°S lat., but quite small in most regions below 35°N. and not yet apparent in some. It is thought that the regional and zonal distribution of recent climatic trends is incompatible with the hypothesis of increased solar heating as the cause. On the other hand, the major features of this distribution are not incompatible with the hypothesis of increased carbon dioxide radiation, if the rate of atmospheric mixing between the hemispheres is a matter of decades rather than years.

1. INTRODUCTION

The many books and articles published during the past century or more on the subject of climatic change testify to its unflagging interest, and, no doubt, also to the number and variety of the theories which have been advanced to account for such changes. Some of these theories, and much evidence of change, are discussed in *Climatic change* (Shapley 1953), and also by Lysgaard (1949) who has assembled a bibliography of no less than 500 items on this subject. Another source of much useful data and discussion of recent events in this field will be found in Ahlmann (1953). Recently Kraus (1960) has suggested that both ancient and modern climatic fluctuations are most readily explained on the basis of changes in the atmospheric cooling rate by long-wave radiation.

The present paper is intended to illustrate the fluctuations and trends of temperature which have occurred in various parts of the world during recent decades, and to suggest possible conclusions which may be drawn from them. This subject, however, is a vast one, and only too easily submerged in an ocean of repelling statistics, unless firm measures are taken to reduce the mass of data into a form which eliminates distracting or irrelevant detail, whilst emphasizing the large-scale features. With this object in view an attempt is made to illustrate the data in a manner which is not too uninviting for the ordinary reader's attention.

As regards the longer-period fluctuations, or trends of climate, which are, no doubt, of the most general interest outside the specialist field, it may be said that the extension of the data for another 10 to 20 years lends support to the conclusions reached in earlier studies of this nature by Lysgaard (1949) and Willett (1950); namely, that a gradual rise in the temperature climate has been in progress for several decades, with a maximum rate in higher latitudes of the Northern Hemisphere, and relatively small rates in most other regions. Temperatures, however, still appear to be quite stable in a few limited areas, amongst which the Black sea – Caspian region, most of Australia, and the far south Atlantic Ocean, are the most notable.

TABLE 1. 30-YR CHANGE 1921-1950 MINUS 1891-1920 INTEGRATED FOR THE ZONES

Zone	Latitude range of zone	Zone area per cent Earth	Approx. station cover per cent zone	Average for zone °C 1921-1950 minus 1891-1920
Sub-arctic	73-60 N	4½	80	0·83°
North temperate	60-25 N	23	72	0·39°
Tropical	25 N-25 S	42	75	0·17°
South temperate	25-50 S	17	25	0·14°
N – T – S	60 N-50 S	82	63	0·23°

(c) *Seasonal trends*

Although only annual temperature trends are illustrated here, a word should be said about those for the seasons, because there appears to be a widespread impression that it is only the winter which has advanced. Although true for certain ice-infested districts of the sub-Arctic, this is far from being the case in several major regions of the north temperate zone, where the summer (June to August) temperature has risen more than the annual. In Table 2 the summer and annual 30-yr changes are shown for a few reliable stations, which have an annual trend quite typical of the region in which they are situated. Out of 40 stations in the north temperate zone, for which the summer temperatures were examined, only Valentia, Father Point, Tomsk and Irkutsk, showed rather less rise in summer than for the year.

TABLE 2. 30-YR CHANGE 1921-1950 MINUS 1891-1920 FOR SUMMER AND YEAR (°C)

Station	Region	Summer	Year	Station	Region	Summer	Year
Oxford	England	0·52	0·34	Suttsu	N. Japan	0·60*	0·21
Neuchatel	Switzerland	0·55	0·41	Hikone	S. Japan	0·71	0·12
Sonnblick	High Alps	0·75	0·49	Blue Hill	NE. U.S.A.	0·72	0·63
Irkutsk	Central Siberia	0·33	0·40	Alpina	Great Lakes	0·68	0·46
Tomsk	West Siberia	0·29	0·35	Concordia	Mid-west	0·69	0·56
Tashkent	Central Asia	0·29	0·08	Winnemucca	Plateau	0·91	0·59

* July to September

5. CAUSE OF THE RISING TEMPERATURE TREND

The cause of climate fluctuations and trends is speculative in the present state of knowledge, but a few brief remarks on this subject seem called for here. These are confined to certain radiative effects in the atmosphere, because limitation of space does not allow the discussion of several other theories which have been proposed from time to time.

(a) *Atmospheric dust as a cause*

It has been suggested by Wexler (1953) that the rising temperature trend could be due to increased atmospheric transparency for solar heat, owing to a reduced number of dust-producing volcanic eruptions in recent decades. There is no doubt that the short-period fluctuations in the zones (Fig. 3) lend some support to this view, for they strongly suggest disturbances to the radiation balance affecting all three zones in the same way rather than the transport of heat from one zone to another. For example, the high-altitude dust from Krakatoa 1883, and Pelée 1902, could have caused the sharp falls in all three zones about those dates, and the absence of concurrent fluctuations since 1920 might be attributed to a lack of explosive eruptions of sufficient size to affect the whole earth. But the problem is very complex, and it would be difficult to explain the big oscillations about 1912-20 on the basis of the Katmai eruption in 1912, or the fact that the many eruptions since 1920 do not appear to have had a significant effect on the zonal fluctuations. Evidently there are other factors at work besides volcanic dust.

If the upward temperature trend shown by the zonal averages (Fig. 4) were due to an increase of solar heat reaching the earth's surface, either because of greater atmospheric transparency, as proposed by Wexler, or a rise in the energy output of the sun itself, one would expect to find a greater rising trend in sunny sub-tropic countries than in the cloudy north Atlantic region. But the reverse is observed, in fact some of the sub-tropic and desert regions are notable for their absence of any temperature trend in the last 60 or more years – particularly sunny Australia and the Lake Balkhash-Caspian region of Central Asia. Also there would be reason to expect increased precipitation in the tropical rain belt if the solar heating grew stronger. In fact a decrease has been reported in some parts of this region (Kraus 1955).

The alternative theory that a warmer and drier trend has been caused by decreased solar heating is very hypothetical. It would require a decrease in the vigour of the general circulation, with reduced polar temperatures, both of which are contrary to observation as far as the North Atlantic sector is concerned (Lamb and Johnson 1959).

To summarize this brief discussion it could be said that, although a solar or dust hypothesis is applicable, or even necessary, to explain the short-period fluctuations found in the zones, it fails as an explanation of the pattern of recent climatic trends observed in various parts of the world.

(b) *Increased carbon-dioxide radiation as a cause*

Some years ago the writer suggested that rising temperature trends, already observed in certain regions, could be due to back radiation from the extra CO_2 produced by fossil-fuel combustion. (Callendar 1938, 1949). Since then calculations on atmospheric radiation by Plass* (1953) have supported this view, and he considers that variations of atmospheric carbon dioxide are an important factor in climatic change (Plass 1956). Here it will be assumed that the essential features of this hypothesis are well known, and also that a rise in the amount of atmospheric carbon dioxide has actually occurred since the turn of the century* (Callendar 1958). But if these factors are taken for granted an attempt

* For very small changes of CO_2 in the atmosphere Plass finds a surface temperature derivative, $dt/d\ CO_2$, of 12, in °C and gm cm^{-2}. From this a rise of 0·4° (North temperate zone, Table 1) would require 33 mg cm^{-2} more CO_2 in the atmosphere, equal to an average increase of 7 per cent between 1891-1920 and 1921-1950. This compares with an observed increase of CO_2 over these periods of approximately 6 per cent in the European region, (Callendar 1958). It should be remembered, however, that this matter of atmospheric CO_2 increase is highly controversial at the present time, and several authors (Revell and Suess 1957; Flohn 1958, and others) have expressed doubt as to the possibility of a CO_2 increase approaching the amount, (40 mg cm^{-2} by 1950) added by fossil-fuel combustion.

must be made to show that the observed distribution of recent climatic trends over the earth is not incompatible with the CO_2 hypothesis, and that in certain cases the latter can supply a reasonable explanation. It must be emphasized, however, that this hypothesis can only explain general trends, for the short-dated fluctuations are clearly due to quite other factors.

There are many features of the recent climatic fluctuations and trends which cannot be explained in the present state of knowledge, but it is possible that the CO_2 hypothesis can supply the answer to more than one of them. Examples of this explanation follow :

(1). It is observed that the rising temperature trend is very small in the south temperate zone as compared with that in the north (Table 1). Apart from the natural time lag due to the thermal inertia of the great southern oceans, with their constant supply of melting icebergs, there is also a large, but unknown, time lag in the transport of excess CO_2 from where it is nearly all produced, in middle northern latitudes, across the equator into the southern westerlies. Thus a considerable fraction of the extra CO_2, and the warming effect which goes with it, may still remain in the northern westerly circulation to give the greater temperature rise there than in other latitudes. This argument appears to be supported by radio-carbon measurements showing a much smaller proportion of fossil carbon (i.e., from coal and oil) in living vegetation taken from the Southern Hemisphere than in samples from the north temperate zone (Arnold and Anderson 1957).

(2). The tendency for precipitation to decrease in many warm regions, and remain sub-normal during the first three or four decades of this century (Kraus 1955). In this case the following explanation, although plausible in a general sense, does not presume to cover the details of this fluctuation in either time or space. As the quantity of precipitation is a measure of the latent heat released at the cloud level, anything which retards the loss of this heat will tend to slow down the convection currents and precipitation. Increased CO_2 in the atmosphere would be effective in reducing the loss of heat by radiation from the upper surface of clouds, the more so because there is seldom enough water vapour above the cloud level to interfere with radiation in the CO_2 wave bands. Thus more CO_2 should tend to depress the convective precipitation in the tropics, at least for a time while temperatures rise to restore the overall balance between heat supply and loss. In this connexion it has been pointed out by Kraus (1956) that the rainfall has apparently not decreased in the area of the SE Asia monsoon, where land heating drives the system. Therefore it may be that the thermal inertia of the oceans has delayed the re-establishment of radiative equilibrium in other tropical regions, with consequences as suggested.

(*c*) *Trends in the Arctic region*

There is no doubt that the most spectacular climatic event, of which we have reliable instrumental record, has been the big rise of temperature in most parts of the sub-arctic zone during the 1920's and 1930's (Fig. 3). This rise, however, has been quite local in relation to the major zones, and it cannot have a direct connexion with variations of atmospheric radiation, whether caused by CO_2 or any other factor. On the other hand, an indirect connexion is quite feasible because warming in lower latitudes could cause the polar vortex to contract and bring the westerly circulation, with its storms and clouds, more often into this marginal zone.

The significance of the latest developments in the sub-arctic zone, which include a marked temperature recession in some sectors, 1948-1956, cannot be judged as yet, but there is little sign of this recession spreading to temperate latitudes, where 1957-1959 have been warm years in many parts.

Annex 14

"Energy Resources: A Report to the Committee on Natural Resources of the National Academy of Sciences", *United States National Academy of Sciences – National Research Council,* 1962, pages 95-97

The complete book can be accessed through the British Library (*see* British Library catalogue, available at: https://bll01.primo.exlibrisgroup.com/discovery/fulldisplay?docid=alma990053613610100000&context=L&vid=44BL_INST:BLL01&lang=en&search_scope=Not_BL_Suppress&adaptor=Local%20Search%20Engine&tab=LibraryCatalog&query=any,contains,Energy%20Resources%20hubbert (last accessed on 12 March 2024). The British Library can be contacted for assistance by phone (at +44 (0)1937 546060) or email (at bl_ref_services@bl.uk)

This is one of seven special reports supporting a research study of natural resources conducted by the National Academy of Sciences—National Research Council at the request of the President of the United States. Each of these seven supporting documents was prepared under the supervision of a member of the Academy-Research Council Committee on Natural Resources, who called upon the expert advice of a number of consultants to assist in identifying the research needs and opportunities relating to the particular resource area or problem under consideration.

The seven reports of supporting studies are as follows:

A. Renewable Resources
B. Water Resources
C. Mineral Resources
D. Energy Resources
E. Marine Resources
F. Environmental Resources
G. Social and Economic Aspects of Natural Resources

The general conclusions and recommendations of the Committee as a whole are presented in a summary report which has been forwarded to President Kennedy, together with the supporting studies.

The grateful thanks of the Committee on Natural Resources and of the Federal Government, for which these special reports were prepared, are due those whose experience and ideas are reflected in this report.

Committee on Natural Resources

DETLEV W. BRONK
The Rockefeller Institute

DEAN F. FRASCHÉ
Union Carbide Ore Company

EDWIN R. GILLILAND
Massachusetts Institute of Technology

M. KING HUBBERT
Shell Development Company

PHILIP M. MORSE
Massachusetts Institute of Technology

FRANK W. NOTESTEIN
Population Council, New York City

SUMNER T. PIKE
Lubec, Maine

ROGER REVELLE
Department of the Interior

ATHELSTAN SPILHAUS
University of Minnesota

PAUL WEISS
The Rockefeller Institute

GILBERT F. WHITE
University of Chicago

ABEL WOLMAN
Johns Hopkins University

December, 1962

ENERGY RESOURCES

A Report to the
Committee on Natural Resources
of the
National Academy of Sciences—National Research Council

by
M. King Hubbert
Chairman of the Energy Resources Study

Publication 1000-D
National Academy of Sciences—National Research Council
Washington, D. C.
1962

Library of Congress

Catalog Card Number 63-60011

Requests for permission to reproduce or quote from the contents of this publication should be directed to the National Academy of Sciences. Such permission is not required of agencies of the United States Government.

CONTENTS

	Page
CHAPTER I. INTRODUCTION	1
Flux of Energy on the Earth	2
Summary	7
CHAPTER II. EVOLUTION OF MAN'S ABILITY TO CONTROL ENERGY	9
Growth of Human Population	15
CHAPTER III. ENERGY FROM FOSSIL FUELS	22
Production Data and Coal Reserves	22
World Production of Coal and Crude Oil	22
United States Production of Energy from Coal, Oil and Natural Gas	26
Future Production of Fossil Fuels	32
CHAPTER IV. ENERGY FROM FOSSIL FUELS (Continued)	41
Future Production of Petroleum and Natural Gas	41
Estimation of the Crude Oil Reserves of the United States	42
New Method for Estimating the Ultimate Crude-Oil Production of the United States	50
Verification by Means of Data on Large and Small Fields	64
Ultimate Potential Crude-Oil Reserves of the World	73
United States Production and Ultimate Reserves of Natural Gas	75
United States Production and Ultimate Reserves of Natural-Gas Liquids	82
United States Production and Ultimate Reserves of Liquid Hydrocarbons	85
Ultimate World Reserves of Natural Gas and Natural-Gas Liquids	86

Page

CHAPTER IV. (Continued)
Oil Shales and Tar Sands 87
Total Energy of the Fossil Fuels 88
Summary of Energy from the Fossil Fuels 90

CHAPTER V. CONTINUOUS SOURCES OF POWER 95
Solar Energy..... 95
Tidal Power 101
Geothermal Energy 103

CHAPTER VI. NUCLEAR ENERGY 106
Energy from the Fissioning of Heavy Isotopes 106
Waste Disposal of Fission Products 115
Energy from Fusion 120

CHAPTER VII. OUTLOOK AND RECOMMENDATIONS.. 124
Recapitulation..... 124
Time Perspective 134
Recommendations 136

CHAPTER V

CONTINUOUS SOURCES OF POWER

We now direct our attention to continuous sources of power, or sources which, if exhaustible, represent so great a reserve of energy that, for time periods of a few thousand years, they may be treated as if they were inexhaustible.

Solar Energy

The first of these is solar energy. As we have already pointed out in Chapter I, solar energy is intercepted by the earth at a mean rate of about 17.2×10^{16} watts, which is about a million times greater than the installed electrical-generating capacity of the United States in 1959.

At present only two channels of the flux of solar energy are available as large-scale sources of energy for human utilization. The first is the biological channel, beginning with photosynthesis; the second is the heat-engine channel, which produces the atmospheric and oceanic circulations and the hydrologic cycle, leading to wind power and water power.

Biologic Channel

At the Committee's conference on energy held in New York on July 19-20, 1961, the energy flux of the biologic channel was reviewed briefly by G. Evelyn Hutchinson of Yale University.

Professor Hutchinson pointed out that the rates of the photosynthetic process in terms of the fixation of carbon per year are presently estimated to be as follows:

	Grams/yr of fixed carbon
Forests	12×10^{15}
Agricultural lands	5.1×10^{15}
Grass lands	4.6×10^{15}
Total for land areas	21.7×10^{15}

The total amount of fixed carbon involved is about 1 to 3×10^{17} grams. The energetic efficiency of the process is only about 0.2 per cent.

Thus, while the biological efficiency in the capture of solar energy is low, the aggregate quantity is very large, the annual fixation of carbon on land by this process being about 7 times the fixed carbon in the fuels consumed per year.

The oceanic fixation of carbon per year is not accurately known, but could be as high as 35×10^{15} grams/year.

There is evidence that the greatly increasing use of the fossil fuels, whose material contents after combustion are principally H_2O and CO_2, is seriously contaminating the earth's atmosphere with CO_2. Analyses indicate that the CO_2 content of the atmosphere since 1900 has increased 10 per cent. Since CO_2 absorbs long-wavelength radiation, it is possible that this is already producing a secular climatic change in the direction of higher average temperatures. This could have profound effects both on the weather and on the ecological balances.

In view of the dangers of atmospheric contamination by both the waste gases of the fossil fuels and the radioactive contaminates from nuclear power plants, Professor Hutchinson urges serious consideration of the maximum utilization of solar energy.

Wind Power

The historical background on the development of power from both water and wind has been reviewed in Chapter II. Wind power is essentially limited to comparatively small units and is suitable for such special uses as pumping well water and charging batteries for local household electrical uses, but it does not offer much

promise of competing with other prime movers in producing large-scale electric power. Even for the traditional uses such as the propulsion of sailing ships and the Dutch windmills for pumping water from the Dutch polders and for grinding grain, the use of power from the fossil fuels and water power has almost completely displaced wind power.

Water Power

The only channel of solar energy which lends itself to large-scale power production is water power, which is made possible only by the fact that natural streams are a means of concentrating very large amounts of power in small areas. Yet it was not possible to utilize power in such quantities at a single locality before the development of the means for generating power electrically and transmitting it over large areas for utilization. Thus, while water power is one of the oldest and most important sources of industrial power, individual water-power units rarely exceeded a few tens of kilowatts in size prior to the introduction of electrical generation and distribution. Now sites are being developed in which individual installations have power capacities measurable in hundreds of megawatts.

Unlike the fossil fuels, water power is a rate of production rather than a quantity of energy. The long-term history of the development of water power accordingly should be represented by a logistic type of growth. The installed capacity must start at a very low level, increase with time, at first slowly and then more rapidly, and finally level off to a maximum when all available water power is being utilized.

When all available power is thus being used, power can be generated at this maximum rate more or less indefinitely, provided the climate does not change significantly, and also provided that a steady-state method of desilting the reservoirs can be devised. At present rates of deposition of silt, most of the large reservoirs will require only the order of a few centuries to become filled with sediment. Unless this sediment eventually is removed from the reservoir at the same rate as it is added, the power capabilities of the reservoirs will be greatly diminished.

The significant quantities pertaining to water power in any given area are the maximum potential water power available and the amount of this that has been utilized up to any given time.

Annex 15

"Implications of Rising Carbon Dioxide of the Atmosphere", *The Conservation Foundation,* 1963, page 1

IMPLICATIONS

of

RISING CARBON DIOXIDE CONTENT OF THE ATMOSPHERE

A statement of trends and implications of carbon dioxide research reviewed at a conference of scientists . . . . . .

Sponsored
by
THE CONSERVATION FOUNDATION
30 East 40th Street
New York 16, N. Y.

FOREWORD

On March 12, 1963, The Conservation Foundation assembled a conference of scholars to discuss the problem of rising carbon dioxide content of the atmosphere. The conferees were ecologists, chemists, physicists and others with particular experience and interest in the problem. The structure of the conference was formulated with the help of Professor G. Evelyn Hutchinson who serves on the Foundation's advisory council. Unfortunately, illness prevented Professor Hutchinson from attending the conference and participating in the discussions.

It is known that the carbon dioxide situation, as it has been observed within the last century, is one which might have considerable biological, geographical and economic consequences within the not too distant future. What is important is that with the rise of carbon dioxide, by way of exhaust gases from engines and other sources, there is a rise in the temperature of the atmosphere and oceans. It is estimated that a doubling of the carbon dioxide content of the atmosphere would produce an average atmospheric temperature rise of 3.8 degrees Fahrenheit. This could be enough to bring about an immense flooding of the lower portions of the world's land surface, resulting from increased melting of glaciers. So far, the increase of carbon dioxide has been of the order of 10 percent, and the oceans are already experiencing some rise of temperature.

A principal purpose of the meeting was to discuss the subject with a view to clarifying the minds of a small interdisciplinary group and crystallizing some ideas for future scientific research. It is hoped that the publication of this summary of conference discussions may contribute to further examination of the carbon dioxide situation. The subject should be one of considerable concern and controversy.

This paper is a statement of the consensus of the conference. It was prepared by Noel Eichhorn of The Foundation's research staff. Although the conclusions were those reached by the conferees as a group, the wording of this paper cannot be attributed to any conferee, but is the responsibility of The Conservation Foundation.

PARTICIPANTS IN THE CONFERENCE

F. FRASER DARLING	CHAIRMAN - Vice President, The Conservation Foundation, New York, New York
EDWARD S. DEEVEY.....	Department of Biology, Yale University, New Haven, Connecticut
ERIK ERIKSSON.....	International Meteorological Institute, Stockholm, Sweden
CHARLES D. KEELING	Scripps Institution of Oceanography, La Jolla, California
GILBERT N. PLASS	Aeronutronic Division of Ford Motor Company, Newport Beach, California
LIONEL WALFORD.....	Atlantic Marine Laboratory, U.S. Fish & Wildlife Service, Highlands, New Jersey
WILLIAM A. GARNETT.....	Photographer - Napa, California

OBSERVERS:

SAMUEL H. ORDWAY, JR....	President, The Conservation Foundation, New York, New York
GEORGE E. BREWER, JR....	Vice President, The Conservation Foundation, New York, New York
WALLACE D. BOWMAN.....	Executive Assistant, The Conservation Foundation, New York, New York
NOEL D. EICHHORN	Associate, The Conservation Foundation, New York, New York
JOHN P. MILTON	Associate, The Conservation Foundation, New York, New York

INTRODUCTION and SUMMARY

Carbon dioxide is not a pollutant in the ordinary sense. It is colorless and odorless. It has no immediate nasty effects. Even the largest amount likely to accumulate in the atmosphere, if the entire reserve of fossil fuels were burned, would not be detrimental to the existence of life; in fact, plant life would be more luxuriant. It is an inevitable product of combustion and cannot be filtered out or precipitated out. Ordinary pollutants are washed out of the atmosphere after a month or so; carbon dioxide will continue to accumulate as long as fossil fuels continue to be burned at present rates.

There is a lack of exact knowledge of the carbon cycle which is part of the general lack of quantitative knowledge of the biogeochemistry of the earth. The increasing funds available for general research and the improving coordination of research effort should help to reduce the uncertainties about the implications of the rise in atmospheric carbon dioxide.

It seems quite certain that a continuing rise in the amount of atmospheric carbon dioxide is likely to be accompanied by a significant warming of the surface of the earth which by melting the polar ice caps would raise sea level and by warming the oceans would change considerably the distributions of marine species including commercial fisheries.

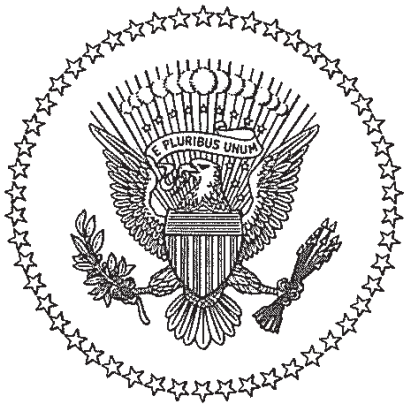
The biogeochemical system of the surface of the earth is, in general, very stable and has persisted with little change over geologically long periods of time. However, the buffering mechanisms which have been adequate in the past seem unlikely to be able to compensate fully for changes of the magnitude of those now being effected by man.

The effects of a rise in atmospheric carbon dioxide are world-wide. They are significant not to us but to the generations to follow. The consumption of fossil fuel has increased to such a pitch within the last half century that the total atmospheric consequences are matters of concern for the planet as a whole. Although there is the possibility of capturing the CO_2 formed by the burning of fossil fuels and storing it in the form of carbonates, relief is most likely through the development of new sources of power.

Annex 16

"Report of the Environmental Pollution Panel for the President's Science Advisory Committee", *The White House,* November 1965, pages 1-2, 111-114, 123-127

RESTORING THE QUALITY OF OUR ENVIRONMENT



Report of The
Environmental Pollution Panel
President's Science Advisory Committee

THE WHITE HOUSE

NOVEMBER 1965

THE WHITE HOUSE

WASHINGTON

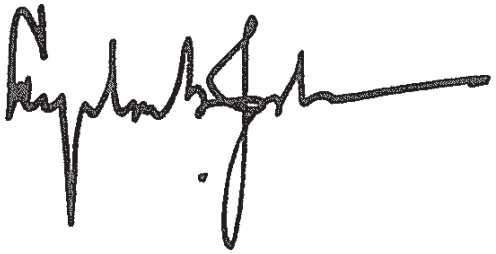
November 5, 1965

Ours is a nation of affluence. But the technology that has permitted our affluence spews out vast quantities of wastes and spent products that pollute our air, poison our waters, and even impair our ability to feed ourselves. At the same time, we have crowded together into dense metropolitan areas where concentration of wastes intensifies the problem.

Pollution now is one of the most pervasive problems of our society. With our numbers increasing, and with our increasing urbanization and industrialization, the flow of pollutants to our air, soils and waters is increasing. This increase is so rapid that our present efforts in managing pollution are barely enough to stay even, surely not enough to make the improvements that are needed.

Looking ahead to the increasing challenges of pollution as our population grows and our lives become more urbanized and industrialized, we will need increased basic research in a variety of specific areas, including soil pollution and the effects of air pollutants on man. We must give highest priority of all to increasing the numbers and quality of the scientists and engineers working on problems related to the control and management of pollution.

I am asking the appropriate Departments and Agencies to consider the recommendations and report to me on the ways in which we can move to cope with the problems cited in the Report. Because of its general interest, I am releasing the report for publication.



PRESIDENT'S SCIENCE ADVISORY COMMITTEE

DONALD F. HORNIG, *Chairman,* Special Assistant to the President for Science and Technology

HERBERT F. YORK, Jr., *Vice Chairman,* Professor of Physics, University of California, San Diego

Lewis M. Branscomb, Chairman, Joint Institute for Laboratory Astrophysics, Boulder

Melvin Calvin, Professor of Chemistry, University of California, Berkeley

Richard L. Garwin, Thomas J. Watson Research Center, International Business Machines Corporation, Yorktown Heights

Marvin L. Goldberger, Professor of Physics, Princeton University

Philip Handler, Chairman, Department of Biochemistry, Duke University Medical Center

Franklin A. Long, Vice President for Research and Advanced Studies, Cornell University, Ithaca

Gordon J. F. MacDonald, Chairman, Department of Planetary and Space Physics, Institute of Geophysics and Planetary Physics, University of California, Los Angeles

William D. McElroy, Chairman, Department of Biology, The Johns Hopkins University

George E. Pake, Provost, Washington University, St. Louis

John R. Pierce, Executive Director, Research—Communications Sciences Division, Bell Telephone Laboratories

Kenneth S. Pitzer, President, Rice University

Edward M. Purcell, Professor of Physics, Harvard University

Frederick Seitz, President, National Academy of Sciences

ENVIRONMENTAL POLLUTION PANEL

JOHN W. TUKEY, *Chairman,* Professor of Mathematics, Princeton University, and Associate Executive Director, Research—Communications Sciences Division, Bell Telephone Laboratories

Martin Alexander, Associate Professor of Soil Science, New York State College of Agriculture, Cornell University, Ithaca

H. Stanley Bennett, Dean, Division of Biological Sciences, University of Chicago

Nyle C. Brady, Director of Office of Science and Education, U.S. Department of Agriculture (until August 31, 1965), Director of the Cornell University Experiment Station, Director of Research, New York State College of Agriculture, Cornell University, Ithaca

John C. Calhoun, Jr., Science Advisor to the Secretary of the Interior (until February 5, 1965), Vice President for Programs, Texas A & M University System, College Station

John C. Geyer, Chairman, Department of Sanitary Engineering and Water Resources, The Johns Hopkins University, Baltimore

Aarie J. Haagen-Smit, Professor of Biochemistry, California Institute of Technology, Pasadena

Norman Hackerman, Vice Chancellor for Academic Affairs, University of Texas, Austin

James B. Hartgering, Director of Research and Education, American Hospital Association, Chicago

David Pimentel, Head, Department of Entomology and Limnology, New York State College of Agriculture, Cornell University, Ithaca

Roger Revelle, Director, Center for Population Studies, Harvard University

Louis H. Roddis, President, Pennsylvania Electric Company, Johnstown

William H. Stewart, (member until June, 1965) Office of the Secretary, U.S. Department of Health, Education, and Welfare, Washington

James L. Whittenberger, Professor of Public Health, Harvard School of Public Health

John L. Buckley, *Staff,* Technical Assistant, Office of Science and Technology, Washington

Contents

	Page
Acknowledgements	IX
Introduction	1
The Effects of Pollution	3
Health Effects	3
Excessive air pollution for short periods	3
Prolonged exposure to ordinary urban air pollution	3
Water-borne pollutants and health	4
Pesticides and human health	4
Effects on Other Living Organisms	5
Why do we care?	5
Kinds of effects on organisms other than man	5
Impairment of Water and Soil Resources	7
Excess fertility in waters	7
Soil pollution	7
Polluting Effects of Detergents	8
Deterioration of Materials and Urban Environments	9
Climatic Effects of Pollution	9
The Sources of Pollution	10
Municipal and industrial sewage	10
Animal wastes	10
Urban solid wastes	11
Mining wastes	11
Consumer goods wastes	11
Unintentional Releases	12
In Which Directions Should We Go?	13
Recommendations	16
A. Principles	16
B. Actions	17
C. Coordination and Systems Studies	23
D. Baseline Measurement Programs	25
E. Development and Demonstration	26
F. Research	29
G. Manpower	33
H. Incompleteness of Recommendations	38
Appendixes:	
X1. Challenging Tasks for the Men and Women Who Can Improve the Quality of Our Environment	39
X2. Organizational Questions	48
X3. A "General" Index of Chemical Pollution	57
X4. Standards Development	59
X5. Metropolitan Problems	62
X6. Air Problems	66
X7. Water Quality	70

Subpanel Reports

		Page
Y1.	Soil Contamination	74
Y2.	Health Effects of Environmental Pollution	91
Y3.	Benchmark Surveillance	102
Y4.	Atmospheric Carbon Dioxide	111
Y5.	Solid Wastes	134
Y6.	Combined Sewers	157
Y7.	Effects of Chlorinating Wastes	168
Y8.	Agricultural Wastes	170
Y9.	Aquatic Blooms	173
Y10.	Effects of Pollutants on Living Organisms Other Than Man	192
Y11.	Improved Pest Control Practices	227
Index		293

Acknowledgements

The study was conducted under the general supervision of Colin M. MacLeod, Deputy Director, Office of Science and Technology.

The Panel drew on scientists and engineers from within the Federal Government, from state governments, universities and industry to form subpanels of experts, each of which explored a different problem. These busy men put in, on the average, several weeks of their time talking to scientists, studying and evaluating information published and unpublished, and writing reports. The reports are included as the "Y" Appendixes.

The members of the subpanels are listed on the following pages.

SOIL CONTAMINATION

H. Stanley Bennett, *Chairman*
Dean, Division of Biological Sciences
University of Chicago

Martin Alexander
Associate Professor of Soil Science
New York State College of Agriculture
Cornell University, Ithaca

Sterling B. Hendricks
Soil and Water Conservation Research Division
Agricultural Research Service
U.S. Department of Agriculture
Beltsville, Maryland

H. L. Lucas
Professor and Director of Biomathematics Training Program
Institute of Statistics
North Carolina State University, Raleigh

Thomas J. Sheets, *Staff*
Crops Research Division
Agricultural Research Service
U.S. Department of Agriculture
Beltsville, Maryland
(Present address) Associate Professor of Entomology and Crop Science
North Carolina State University, Raleigh

HEALTH EFFECTS OF ENVIRONMENTAL POLLUTION

James L. Whittenberger, *Chairman*
Professor of Public Health
Harvard School of Public Health

Aarie J. Haagen-Smit
Professor of Biochemistry
California Institute of Technology, Pasadena

Lincoln E. Moses
Executive Head
Department of Statistics
Stanford University

William H. Stewart (member until June 1965)
Office of the Secretary
U.S. Department of Health, Education, and Welfare, Washington

John R. Bagby, Jr., *Staff*
Communicable Disease Center
Public Health Service
U.S. Department of Health, Education, and Welfare, Atlanta, Georgia

H. Bruce Dull, *Staff*
Communicable Disease Center
Public Health Service
U.S. Department of Health, Education, and Welfare, Atlanta, Georgia

BENCHMARK SURVEILLANCE

Aarie J. Haagen-Smit, *Chairman*
Professor of Biochemistry
California Institute of Technology
Pasadena

Louis H. Roddis, *Vice Chairman*
President
Pennsylvania Electric Company
Johnstown

Nyle C. Brady
Director of Science and Education
U.S. Department of Agriculture
(until August 31, 1965)
Director of the Cornell University Experiment Station
Director of Research
New York State College of Agriculture
Cornell University, Ithaca

Raymond J. Jessen
Professor of Business Statistics
Graduate School of Business Administration
University of California, Los Angeles

James L. Whittenberger
Professor of Public Health
Harvard School of Public Health

W. J. Youden
4821 Upton Street NW.
Washington

John L. Buckley, *Staff*
Technical Assistant
Office of Science and Technology
Washington

ATMOSPHERIC CARBON DIOXIDE

Roger Revelle, *Chairman*
Director, Center for Population Studies
Harvard University

Wallace Broecker
Professor of Geology
Columbia University, New York

Harmon Craig
Professor of Geochemistry
Department of Earth Sciences
University of California, La Jolla

Charles D. Keeling
Scripps Institution of Oceanography
La Jolla, California

J. Smagorinsky
Weather Bureau
Environmental Sciences Services Administration
U.S. Department of Commerce
Suitland, Maryland

SOLID WASTES

John C. Calhoun, Jr., *Chairman*
Science Adviser to the Secretary
U.S. Department of the Interior
(until February 5, 1965)
Vice President for Programs
Texas A & M University System
College Station

Patrick Conley
Senior Fellow
Mellon Institute, Pittsburgh

Aarie J. Haagen-Smit
Professor of Biochemistry
California Institute of Technology
Pasadena

Norman Hackerman
Vice Chancellor for Academic Affairs
University of Texas, Austin

Leonhard Katz
President
Astro Dynamics, Inc.
2d Avenue, Northwest Industrial Park
Burlington, Massachusetts

George J. Maslach
Dean, College of Engineering
University of California, Berkeley

Louis H. Roddis
President
Pennsylvania Electric Company
Johnstown

James E. Hill, *Staff*
Bureau of Mines
U.S. Department of the Interior
Washington

COMBINED SEWERS

John C. Geyer, *Chairman*
Chairman
Department of Sanitary Engineering
and Water Resources
The Johns Hopkins University
Baltimore

Leonhard Katz
President
Astro Dynamics, Inc.
2d Avenue, Northwest Industrial Park
Burlington, Massachusetts

EFFECTS OF CHLORINATING WASTES

Martin Alexander, *Chairman*
Associate Professor of Soil Science
New York State College of Agriculture
Cornell University, Ithaca

John C. Geyer
Chairman
Department of Sanitary Engineering and
Water Resources
The Johns Hopkins University, Baltimore

Deric O'Bryan, *Staff*
Geological Survey
U.S. Department of the Interior
Washington

AGRICULTURAL WASTES

Martin Alexander, *Chairman*
Associate Professor of Soil Science
New York State College of Agriculture
Cornell University, Ithaca

Nyle C. Brady
Director of Science and Education
U.S. Department of Agriculture
(until August 31, 1965)
Director of the Cornell University
Experiment Station
Director of Research, New York State
College of Agriculture
Cornell University, Ithaca

Deric O'Bryan, *Staff*
Geological Survey
U.S. Department of the Interior
Washington

AQUATIC BLOOMS

Martin Alexander, *Chairman*
Associate Professor of Soil Science
New York State College of Agriculture
Cornell University, Ithaca

John B. Moyle
Department of Conservation
St. Paul, Minnesota

Ruth Patrick
Academy of Natural Sciences
Philadelphia, Pennsylvania

Leon Weinberger
Division of Water Supply
and Pollution Control
Public Health Service
U.S. Department of Health, Education,
and Welfare, Washington

Deric O'Bryan, *Staff*
Geological Survey
U.S. Department of the Interior
Washington

EFFECTS OF POLLUTANTS ON LIVING ORGANISMS OTHER THAN MAN

David Pimentel, *Chairman*
Head, Department of Entomology
and Limnology
New York State College of Agriculture
Cornell University, Ithaca

Don W. Hayne
Professor of Experimental Statistics
Institute of Statistics
North Carolina State University
Raleigh

Louis A. Krumholz
Professor of Biology
University of Louisville

John T. Middleton
Director, Air Pollution Research Center
University of California
Riverside

Lionel A. Walford
Director, Sandy Hook Marine Laboratory
Bureau of Sport Fisheries and Wildlife
U.S. Department of the Interior
Highlands, New Jersey

John L. Buckley, *Staff*
Technical Assistant
Office of Science and Technology
Washington

IMPROVED PEST CONTROL PRACTICES

David Pimentel, *Chairman*
Head, Department of Entomology and
Limnology
New York State College of Agriculture
Cornell University, Ithaca

Donald A. Chant
Chairman, Department of Biological
Control
University of California, Riverside

Arthur Kelman
Professor of Plant Pathology and Forestry
North Carolina State University, Raleigh
Present Address—
Chairman, Department of Plant
Pathology
University of Wisconsin, Madison

Robert L. Metcalf
Vice Chancellor
University of California, Riverside

L. D. Newsom
Head, Department of Entomology
Louisiana State University, Baton Rouge

Carroll N. Smith, *Staff*
Entomology Research Division
Agricultural Research Service
U.S. Department of Agriculture
Gainesville, Florida

Introduction

> Environmental pollution is the unfavorable alteration of our surroundings, wholly or largely as a by-product of man's actions, through direct or indirect effects of changes in energy patterns, radiation levels, chemical and physical constitution and abundances of organisms. These changes may affect man directly, or through his supplies of water and of agricultural and other biological products, his physical objects or possessions, or his opportunities for recreation and appreciation of nature.

The production of pollutants and an increasing need for pollution management are an inevitable concomitant of a technological society with a high standard of living. Pollution problems will increase in importance as our technology and standard of living continue to grow.

Our ancestors settled in a fair and unspoiled land, easily capable of absorbing the wastes of its animal and human populations. Nourished by the resources of this continent, the human inhabitants have multiplied greatly and have grouped themselves to form gigantic urban concentrations, in and around which are vast and productive industrial and agricultural establishments, disposed with little regard for state or municipal boundaries.

Huge quantities of diverse and novel materials are dispersed, from city and farm alike, into our air, into our waters and onto our lands. These pollutants are either unwanted by-products of our activities or spent substances which have served intended purposes. By remaining in the environment they impair our economy and the quality of our life. They can be carried long distances by air or water or on articles of commerce, threatening the health, longevity, livelihood, recreation, cleanliness and happiness of citizens who have no direct stake in their production, but cannot escape their influence.

Pollutants have altered on a global scale the carbon dioxide content of the air and the lead concentrations in ocean waters and human populations. Pollutants have reduced the productivity of some of our finest agricultural soils, and have impaired the quality and the safety of crops raised on others. Pollutants have produced massive mortalities of fishes in rivers, lakes and estuaries and have damaged or destroyed

commercial shellfish and shrimp fisheries. Pollutants have reduced valuable populations of pollinating and predatory insects, and have appeared in alarming amounts in migratory birds. Pollutants threaten the estuarine breeding grounds of valuable ocean fish; even Antarctic penguins and Arctic snowy owls carry pesticides in their bodies.

The land, water, air and living things of the United States are a heritage of the whole nation. They need to be protected for the benefit of all Americans, both now and in the future. The continued strength and welfare of our nation depend on the quantity and quality of our resources and on the quality of the environment in which our people live.

The pervasive nature of pollution, its disregard of political boundaries including state lines, the national character of the technical, economic and political problems involved, and the recognized Federal responsibilities for administering vast public lands which can be changed by pollution, for carrying out large enterprises which can produce pollutants, for preserving and improving the nation's natural resources, all make it mandatory that the Federal Government assume leadership and exert its influence in pollution abatement on a national scale.

We attempt here to describe the problem, to distinguish between what is known and what is not, and to recommend steps necessary to assure the lessening of pollution already about us and to prevent unacceptable environmental deterioration in the future.

APPENDIX Y4

Atmospheric Carbon Dioxide

ROGER REVELLE, *Chairman*

WALLACE BROECKER
HARMON CRAIG
C. D. KEELING
J. SMAGORINSKY

Contents

	Page
Section I. Carbon Dioxide From Fossil Fuels—The Invisible Pollutant	112
Introduction	112
The Recent Increase in Atmospheric Carbon Dioxide	114
Partition of Carbon Dioxide Among the Atmosphere, the Ocean, and the Biosphere	117
Probable Future Content of Carbon Dioxide in the Atmosphere	119
Possible Effects of Increased Atmospheric Carbon Dioxide on Climate	121
Other Possible Effects of an Increase in Atmospheric Carbon Dioxide	123
Melting of the Antarctic Ice Cap	123
Rise of Sea Level	123
Warming of Sea Water	123
Increased Acidity of Fresh Waters	124
Increase in Photosynthesis	124
Other Possible Sources of Carbon Dioxide	124
Oceanic Warming	124
Burning of Limestone	125
Decrease in the Carbon Content of Soils	125
Change in the Amount of Organic Matter in the Ocean	125
Changes in the Carbon Dioxide Content of Deep Ocean Water	125
Changes in the Volume of Sea water	125
Carbon Dioxide From Volcanoes	126
Changes Due to Solution and Precipitation of Carbonates	126
Conclusions and Findings	126
Section II. Detailed Computations	128
References	131

Section I. CARBON DIOXIDE FROM FOSSIL FUELS—THE INVISIBLE POLLUTANT

INTRODUCTION

Only about one two-thousandth of the atmosphere and one ten-thousandth of the ocean are carbon dioxide. Yet to living creatures, these small fractions are of vital importance. Carbon is the basic building block of organic compounds, and land plants obtain all of their carbon from atmospheric carbon dioxide. Marine plants obtain carbon from the dissolved carbon dioxide in sea water, which depends for its concentration on an equilibrium with the carbon dioxide of the atmosphere. Marine and terrestrial animals, including man, procure, either directly or indirectly, the substance of their bodies and the energy for living from the carbon compounds made by plants.

All fuels used by man consist of carbon compounds produced by ancient or modern plants. The energy they contain was originally solar energy, transmuted through the biochemical process called photosynthesis. The carbon in every barrel of oil and every lump of coal, as well as in every block of limestone, was once present in the atmosphere as carbon dioxide.

Over the past several billion years, very large quantities of carbon dioxide have entered the atmosphere from volcanoes. The total amount was at least forty thousand times the quantity of carbon dioxide now present in the air. Most of it became combined with calcium or magnesium, freed by the weathering of silicate rocks, and was precipitated on the sea floor as limestone or dolomite. About one-fourth of the total quantity, at least ten thousand times the present atmospheric carbon dioxide, was reduced by plants to organic carbon compounds and became buried as organic matter in the sediments. A small fraction of this organic matter was transformed into the concentrated deposits we call coal, petroleum, oil shales, tar sands, or natural gas. These are the fossil fuels that power the world-wide industrial civilization of our time.

Throughout most of the half-million years of man's existence on earth, his fuels consisted of wood and other remains of plants which had grown only a few years before they were burned. The effect of this burning on the content of atmospheric carbon dioxide was negligible, because it only slightly speeded up the natural decay processes that continually recycle carbon from the biosphere to the atmosphere. During the last few centuries, however, man has begun to burn the fossil fuels that were

locked in the sedimentary rocks over five hundred million years, and this combustion is measurably increasing the atmospheric carbon dioxide.

In the geologic past, the quantity of carbon dioxide in the atmosphere was determined by the equilibrium between rates of weathering and photosynthesis, and the rate of injection of volcanic carbon dioxide. On an earthwide average, both weathering and photosynthesis must speed up when the carbon dioxide content of the air is increased, and slow down when it is diminished; consequently, over geologic time the carbon dioxide in the air must have risen when volcanic activity was high, and must have gone down when volcanoes were quiescent. On a human scale, the times involved are very long. The known amounts of limestone and organic carbon in the sediments indicate that the atmospheric carbon dioxide has been changed forty thousand times during the past four billion years, consequently the residence time of carbon in the atmosphere, relative to sedimentary rocks, must be of the order of a hundred thousand years.

The present rate of production of carbon dioxide from fossil fuel combustion is about a hundred times the average rate of release of calcium and magnesium from the weathering of silicate rocks. As long as this ratio holds, precipitation of metallic carbonates will be unable to maintain an unchanging content of carbon dioxide in the atmosphere. Within a few short centuries, we are returning to the air a significant part of the carbon that was slowly extracted by plants and buried in the sediments during half a billion years.

Not all of this added carbon dioxide will remain in the air. Part of it will become dissolved in the ocean, and part will be taken up by the biosphere, chiefly in trees and other terrestrial plants, and in the dead plant litter called humus. The part that remains in the atmosphere may have a significant effect on climate: carbon dioxide is nearly transparent to visible light, but it is a strong absorber and back radiator of infrared radiation, particularly in the wave lengths from 12 to 18 microns; consequently, an increase of atmospheric carbon dioxide could act, much like the glass in a greenhouse, to raise the temperature of the lower air. [Water vapor also absorbs infrared radiation, both in the range of the CO_2 band centered at 15 microns, and at wave lengths near 6.3 microns. With the average concentration of water vapor in the lower air at mid latitudes, the effect of carbon dioxide absorption is reduced to about half that which would exist in an absolutely dry atmosphere. (Möller, 1963.) Ozone, which is an important constituent of the upper air, also absorbs some infrared at wave lengths around 9.6 microns, but its principal effect on air temperature is due to its absorption of ultraviolet and visible sunlight.]

The possibility of climatic change resulting from changes in the quantity of atmospheric carbon dioxide was proposed independently by the

American geologist, T. C. Chamberlain (1899) and the Swedish chemist, S. Arrhenius (1903), at the beginning of this century. Since their time, many scientists have dealt with one or another aspect of this question, but until very recently there was little quantitative information about what has actually happened. Even today, we cannot make a useful prediction concerning the magnitude or nature of the possible climatic effects. But we are able to say a good deal more than formerly about the change in the quantity of atmospheric carbon dioxide, and about the partition of carbon dioxide from fossil fuel combustion among the atmosphere, the ocean, and the biosphere.

THE RECENT INCREASE IN ATMOSPHERIC CARBON DIOXIDE

During the five years from 1958 through 1962, 5.3 x 10^{16} grams of carbon dioxide were produced by the combustion of coal, lignite, petroleum and other liquid hydrocarbons, and natural gas (see Tables 1 and 2).

TABLE 1.—*Carbon Dioxide Produced by Fossil Fuel Combustion, 1950–62*

[10^{16} grams]

Year	Coal [1]	Lignite [2]	Liquid Hydrocarbons [3]	Natural Gas [4]	Total	As % of Atmospheric CO_2 in 1950
1950	0.37	0.09	0.17	0.04	0.67	0.29
1951	.38	.09	.20	.05	.72	.31
1952	.38	.09	.21	.05	.73	.31
1953	.38	.09	.22	.05	.74	.32
1954	.38	.09	.23	.06	.76	.32
1955	.41	.10	.25	.06	.82	.35
1956	.44	.11	.27	.07	.89	.38
1957	.45	.13	.29	.07	.94	.40
1958	.46	.14	.29	.08	.97	.41
1959	.48	.14	.32	.09	1.03	.44
1960	.50	.14	.34	.10	1.08	.46
1961	.48	.15	.36	.10	1.09	.46
1962	.50	.15	.39	.11	1.15	.49
Total	5.61	1.51	3.54	.93	11.59	4.93

[1] Assumed carbon content, coal=75 percent.

[2] Assumed carbon content, lignite=45 percent.

[3] Assumed carbon content, liquid hydrocarbons=86 percent.

[4] Assumed carbon content, natural gas=70 percent. (Corresponding to a mixture by volume of 80 percent CH_4, 15 percent C_2H_6 and 5 percent N_2.)

Source: Computed from Table 2.

ing this period more than 40% of the total CO_2 increase from fossil fuel combustion occurred. We must conclude that climatic "noise" from other processes has at least partially masked any effects on climate due to past increases in atmospheric CO_2 content.

OTHER POSSIBLE EFFECTS OF AN INCREASE IN ATMOSPHERIC CARBON DIOXIDE

Melting of the Antarctic ice cap.—It has sometimes been suggested that atmospheric warming due to an increase in the CO_2 content of the atmosphere may result in a catastrophically rapid melting of the Antarctic ice cap, with an accompanying rise in sea level. From our knowledge of events at the end of the Wisconsin period, 10 to 11 thousand years ago, we know that melting of continental ice caps can occur very rapidly on a geologic time scale. But such melting must occur relatively slowly on a human scale.

The Antarctic ice cap covers 14 million square kilometers and is about 3 kilometers thick. It contains roughly 4×10^{16} tons of ice, hence 4×10^{24} gram calories of heat energy would be required to melt it. At the present time, the poleward heat flow across 70° latitude is 10^{22} gram calories per year, and this heat is being radiated to space over Antarctica without much measurable effect on the ice cap. Suppose that the poleward heat flux were increased by 10% through an intensification of the meridional atmospheric circulation, and that all of this increase in the flow of energy were utilized to melt the ice. Some 4,000 years would be required.

We can arrive at a smaller melting time by supposing a change in the earth-wide radiation balance, part of which would be used to melt the ice. A 2% change could occur by the year 2000, when the atmospheric CO_2 content will have increased perhaps by 25%. Since the average radiation at the earth's surface is about 2×10^5 gram calories per square centimeter per year, a 2% change would amount to 2×10^{22} calories per year. If half this energy were concentrated in Antarctica and used to melt the ice, the process would take 400 years.

Rise of sea level.—The melting of the Antarctic ice cap would raise sea level by 400 feet. If 1,000 years were required to melt the ice cap, the sea level would rise about 4 feet every 10 years, 40 feet per century. This is a hundred times greater than present worldwide rates of sea level change.

Warming of sea water.—If the average air temperature rises, the temperature of the surface ocean waters in temperate and tropical regions could be expected to rise by an equal amount. (Water temperatures in the polar regions are roughly stabilized by the melting and freezing of ice.) An oceanic warming of 1° to 2°C (about 2°F) oc-

curred in the North Atlantic from 1880 to 1940. It had a pronounced effect on the distribution of some fisheries, notably the cod fishery, which has greatly increased around Greenland and other far northern waters during the last few decades. The amelioration of oceanic climate also resulted in a marked retreat of sea ice around the edges of the Arctic Ocean.

Increased acidity of fresh waters.—Over the range of concentrations found in most soil and ground waters, and in lakes and rivers, the hydrogen ion concentration varies nearly linearly with the concentration of free CO_2. Thus the expected 25% increase in atmospheric CO_2 concentration by the end of this century should result in a 25% increase in the hydrogen ion concentration of natural waters or about a 0.1 drop in pH. This will have no significant effect on most plants.

Increase in photosynthesis.—In areas where water and plant nutrients are abundant, and where there there is sufficient sunlight, carbon dioxide may be the limiting factor in plant growth. The expected 25% increase by the year 2000 should significantly raise the level of photosynthesis in such areas. Although very few data are available, it is commonly believed that in regions of high plant productivity on land, such as the tropical rain forests, phosphates, nitrates and other plant nutrients limit production rather than atmospheric CO_2. This is probably also true of the oceans.

Biological processes are speeded up by a rise in temperature, and in regions where other conditions are favorable higher temperatures due to increased CO_2 might result in higher plant production.

OTHER POSSIBLE SOURCES OF CARBON DIOXIDE

We are fairly certain that fossil fuel combustion has been the only source of CO_2 coming into the atmosphere during the last few years, when accurate measurements of atmospheric carbon dioxide content have been available. Carbon dioxide may have been produced by other sources during earlier times but it is not now possible to make a quantitative estimate. However we can examine the order of magnitude of some of the possible inputs from other sources, on the basis of our knowledge of the processes that might be involved.

Oceanic warming.—The average temperature of the ocean cannot have increased by more than 0.15°C during the past century, since any greater warming would have caused a larger rise in sea level than the observed value of about 10 centimeters. A more probable upper limit is .05°C, because most of the sea level rise can be accounted for by glacial melting. An average .05°C rise would correspond to 0.5° in the top 400 meters. This would cause a nearly 3% rise in the CO_2 partial pressure.

After equilibration with the atmosphere, the partial pressure in both the air and the uppermost ocean layer would be higher by about 2.5%.

Burning of limestone.—Annual world production of carbon dioxide from the use of limestone for cement, fluxing stone, and in other ways, is about 1% of the total from fossil fuel combustion, or 4×10^{-5} of the atmospheric CO_2 content per year.

Decrease in the carbon content of soils.—Since the middle of the Ninetenth Century, the world's cultivated farmland has been enlarged by about 50%. This is an increase of close to a billion acres or 1.6 million square miles, corresponding to 2.7% of the land area of the earth, and perhaps to 5% of forests and grass lands. Most soil humus is believed to be concentrated in forests and grassy areas. Assume that the total humus is equal to twice the amount of carbon in the atmosphere and that half the carbon in the humus of the newly cultivated lands has been oxidized to carbon dioxide. The total injected into the atmosphere from this source becomes less than 5% of the atmospheric CO_2.

Change in the amount of organic matter in the ocean.—About 7% of the marine carbon reservoir consists of organic material. Since a 1% change in the carbon dioxide content of the ocean changes the CO_2 pressure by 12.5%, a decrease by 1% in the marine organic carbon (which would increase the total oceanic carbon dioxide by .07%) would raise the carbon dioxide pressure of the ocean and the atmosphere by about 1%. An increase in the temperature of water near the surface, during the past one hundred years, could have speeded up the rate of oxidation of organic matter relative to its rate of production by photosynthesis. Measurements of the content of organic matter in the ocean are neither accurate enough nor sufficiently extended over time to allow a direct estimate of this possibility. A change of several percent could have occurred without detection.

Changes in the carbon dioxide content of deep ocean water.—The deep ocean waters contain about 10% more carbon dioxide than they would if they were at equilibrium with the present atmospheric content. This is a result of the sinking of dead organic remains from the surface waters and their subsequent oxidation in the depths. The combination of biological and gravitational processes can be thought of as a pump that maintains a relatively low carbon dioxide content in the surface waters and in the atmosphere. If the pump ceased to act, the atmospheric carbon dioxide would eventually be increased five fold. Variations in the effectiveness of the pump could have occurred without detection during the past 100 years, and could have caused notable changes in the atmospheric carbon dioxide content.

Changes in the volume of sea water.—During the Ice Age the volume of sea water varied by about 5%. Changes of this magnitude would change the carbon dioxide content of the atmosphere by 10 to 15%.

But during the last several thousand years, variations in oceanic volume have been small. During the past hundred years, world average sea level has varied by less than 10 centimeters. This very small volume change would have no appreciable effect on the atmospheric carbon dioxide.

Carbon dioxide from volcanoes.—Over geologic time, volcanic gases have been the principal sources of new carbon dioxide injected into the atmosphere. On the average the influx of volcanic CO_2 must have balanced the extraction from the atmosphere by rock weathering. The present rate of influx of volcanic CO_2 is close to a hundred fold less than that from fossil fuel combustion. No data exist on the worldwide level of volcanic activity over geologic time. It is conceivable that the level has fluctuated by two orders of magnitude, and that the fluctuations persisted for millenia, or even for millions of years.

Changes due to solution and precipitation of carbonates.—Calcium and magnesium carbonate precipitation on the sea floor lower the total CO_2 content of ocean water, but increase the carbon dioxide pressure and the free CO_2 content. Conversely, chemical weathering of limestone and dolomite on land lower the atmospheric CO_2 and the free CO_2 content of the sea, but increase the total oceanic CO_2. The rates of these processes are about one order of magnitude lower than the present rate of production of carbon dioxide by fossil fuel combustion.

We conclude that the only sources of carbon dioxide comparable in magnitude to fossil fuel combustion during the last 100 years could have been a decrease in soil humus due to the increase in the area of cultivated lands, a decrease in the content of "dissolved" organic matter in the ocean, or a lowering of the carbon dioxide content of deep ocean waters. Marked changes in the oceanic regime would have been necessary for the latter two processes to have significant effects. As we have shown, none of the three processes are likely to be significant at the present time. Nor are any oceanographic data available which suggest that the required changes in the ocean occurred during the last hundred years.

CONCLUSIONS AND FINDINGS

Through his worldwide industrial civilization, Man is unwittingly conducting a vast geophysical experiment. Within a few generations he is burning the fossil fuels that slowly accumulated in the earth over the past 500 million years. The CO_2 produced by this combustion is being injected into the atmosphere; about half of it remains there. The estimated recoverable reserves of fossil fuels are sufficient to produce nearly a 200% increase in the carbon dioxide content of the atmosphere.

By the year 2000 the increase in atmospheric CO_2 will be close to 25%. This may be sufficient to produce measurable and perhaps marked

changes in climate, and will almost certainly cause significant changes in the temperature and other properties of the stratosphere. At present it is impossible to predict these effects quantitatively, but recent advances in mathematical modelling of the atmosphere, using large computers, may allow useful predictions within the next 2 or 3 years.

Such predictions will need to be checked by careful measurements: a series of precise measurements of the CO_2 content in the atmosphere should continue to be made by the U.S. Weather Bureau and its collaborators, at least for the next several decades; studies of the oceanic and biological processes by which CO_2 is removed from and added to the atmosphere should be broadened and intensified; temperatures at different heights in the stratosphere should be monitored on a worldwide basis.

The climatic changes that may be produced by the increased CO_2 content could be deleterious from the point of view of human beings. The possibilities of deliberately bringing about countervailing climatic changes therefore need to be thoroughly explored. A change in the radiation balance in the opposite direction to that which might result from the increase of atmospheric CO_2 could be produced by raising the albedo, or reflectivity, of the earth. Such a change in albedo could be brought about, for example by spreading very small reflecting particles over large oceanic areas. The particles should be sufficiently buoyant so that they will remain close to the sea surface and they should have a high reflectivity, so that even a partial covering of the surface would be adequate to produce a marked change in the amount of reflected sunlight. Rough estimates indicate that enough particles partially to cover a square mile could be produced for perhaps one hundred dollars. Thus a 1% change in reflectivity might be brought about for about 500 million dollars a year, particularly if the reflecting particles were spread in low latitudes, where the incoming radiation is concentrated. Considering the extraordinary economic and human importance of climate, costs of this magnitude do not seem excessive. An early development of the needed technology might have other uses, for example in inhibiting the formation of hurricanes in tropical oceanic areas.

According to Manabe and Strickler (1964) the absorption and reradiation of infrared by high cirrus clouds (above five miles) tends to heat the atmosphere near the earth's surface. Under some circumstances, injection of condensation or freezing nuclei will cause cirrus clouds to form at high altitudes. This potential method of bringing about climatic changes needs to be investigated as a possible tool for modifying atmospheric circulation in ways which might counteract the effects of increasing atmospheric carbon dioxide.

Annex 17

"Proceedings of the American Petroleum Institute: Annual Meeting General Session", *American Petroleum Institute,* 1965, pages 12-15

The original records can be found at the University of Wyoming Library (*see* University of Wyoming Library catalogue, available at: https://uwyo.primo.exlibrisgroup.com/discovery/fulldisplay?docid=alma991012539089708111&context=L&vid=01UOW_INST:quicksearch&lang=en&search_scope=MyInst_and_CI&adaptor=Local%20Search%20Engine&tab=Everything&query=any,contains,american%20petroleum%20institute%201965&offset=0 (last accessed on 12 March 2024). The University of Wyoming can be contacted for assistance by phone (at (800) 442-6757) or email (at libcirc@uwyo.edu)

AMERICAN PETROLEUM INSTITUTE

PROCEEDINGS
1965

LIBRARY
OF THE
UNIVERSITY OF WYOMING
LARAMIE

NOTE—Statements contained herein, although prepared for use in publications of the American Petroleum Institute, represent the expressed opinion of the author.

SECTION I—GENERAL

Annual Meeting General Sessions
Divisional Reports
Extracts from Minutes of Meetings of Board of Directors
Officers, Board of Directors, and Executive Committee of the Institute
General Committees of the Institute's Divisions of Production, Refining, Marketing, Transportation, Finance and Accounting, and Science and Technology; Committee on Public Affairs

SECTION II—MARKETING

Midyear Meeting Sessions of the Division of Marketing, Abstracts
Other Meetings of the Division of Marketing, Abstracts

SECTION III—REFINING

Group Sessions and Dinner Session of the 29th Midyear Meeting of the Division of Refining

SECTION IV—PRODUCTION

Meeting of the General Committee of the Division of Production—Annual Meeting
Division of Production District and Midyear Meeting Papers, Abstracts

SECTION V—TRANSPORTATION

Meeting of the General Committee of the Division of Transportation—Annual Meeting
Annual Pipeline Conference, Abstracts
Annual Tanker Conference, Abstracts
Annual Conference on Highway Transportation
Annual Conference on Industrial Traffic

Additional copies of each section of the Proceedings may be obtained at $1.00 per copy.

TABLE OF CONTENTS

PROCEEDINGS OF THE AMERICAN PETROLEUM INSTITUTE, 1965

SECTION I—GENERAL

Page

Foreword 3

Annual Meeting General Sessions

First General Session, November 8

Presentation of National Safety Council Association Award, Brig. Gen. John D. Lawlor 8
Award of API Gold Medal, J. Ed. Warren 9
Remarks by Recipient, M. J. Rathbone 9
Meeting the Challenges of 1966, Frank N. Ikard 12

Second General Session, November 9

The Sound Ingredients of a Great Society, David Rockefeller 18
The Next Hundred Years—Thirty Years Later, C. C. Furnas 23

Third General Session, November 10

Address, Hon. Stewart L. Udall 30
Competition and Cooperation, J. Ed. Warren 33

Divisional Report

Science and Technology 36

Appendix

Extracts from Minutes of Meetings of the Board of Directors 47
Officers, Board of Directors, and Executive Committee 50
General Committees of the Divisions of Production, Refining, Marketing, Transportation, Finance and Accounting, and Science and Technology; Committee on Public Affairs 55

SECTION II—MARKETING

General Committee—Minutes and Reports, available from the API Division of Marketing at no charge, contains, in addition to the minutes of the midyear meeting, complete papers which are listed in this Table of Contents under "General Committee" (except the first paper).

Minutes of other committee meetings, as well as complete papers of those abstracted herein and listed in this Table of Contents under each of the other committee headings, are also available on request from the Division of Marketing.

Page

Report of Division of Marketing, A. B. Hersberger 5
Certificate of Appreciation Awards 9

Abstracts of Presentations During Midyear Meeting

General Committee

The Jobber and the Petroleum Industry, W. R. Williams and Wilfred H. Hall 10
Commercial Services Signs and the Federal Highway Act: The Traveling Motorist, R. G. Gardner 10
How Oil Marketers Can Participate in the Federal Government's Job Development Program, Stanley H. Ruttenberg 10
The Power of Positive Marketing, Charles F. Jones 11

MEETING THE CHALLENGES OF 1966 †

FRANK N. IKARD*

Welcome to the 45th Annual Meeting of the American Petroleum Institute.

As always, it is good to see so many in attendance. These meetings of ours provide a yearly opportunity to reflect on past performance, assess current problems, and formulate future programs. But they mean much more than that. They offer concrete evidence of the need for industry people to explore these matters not separately, but together; to advance our best thinking not in private isolation, but in open convention.

It is commonplace and almost trite to observe that the challenges we face together, in noncompetitive areas, grow in number, size, and complexity year by year. But perhaps it's worth observing that as they do, they tend to involve more segments of our industry and more people in our industry more deeply than in the past.

The year 1965 has been no exception. A broad stream of activities has called for an unusual degree of leadership by the Board of Directors, particularly by Chairman J. Ed. Warren. Chairmen in the past have observed that the first year of their term tended to be the more active year, with the second affording some time for reflection and forward planning. I doubt if Ed *found* time for that—he had to *make* it—on top of an extraordinarily active schedule.

The year 1965 has also been a year in which we've heavily depended on the help of the thousands of volunteers throughout the industry. I wish to thank them at this time for their extensive participation, and the entire API staff joins me in this expression of appreciation. We hope their enthusiasm will inspire many more to take part in industry affairs in the coming year.

Federal and State Legislative Activity

In observing that this has been a most active year, particularly in government relations, I have in mind the readings of a fairly reliable thermometer—federal and state legislative activity. The record shows that in the first session of the 89th Congress, just completed, more than 14,000 bills were introduced. This is almost as many as were introduced in *both* sessions of the 88th Congress. So the thermometer tells us that federal legislative activity is running at double speed. Going right along with the trend, the number of bills of interest to our industry was also up. In 1965, our industry kept a close watch on no fewer than 200 pieces of proposed federal legislation.

State governments were also very legislative-minded, with about 100,000 bills introduced. Of these, about 4,000 would have affected our industry in some way and required close study.

It takes no crystal ball to see that our involvement in government matters will intensify in the year ahead.

The industry is well-positioned to meet the challenges and opportunities of 1966. The issues that concerned us in 1965—air and water conservation, oceanography, taxes, wage and hour legislation, and highway sign legislation—to name just a very few—alerted industry people to the need for doing their homework. Many more people in our industry had to learn more about some unfamiliar subjects. And many more of us learned not only *why* it was important to make the industry's voice heard and its opinions felt, but also *how* to do it. As a result of the experiences of 1965, then, we can face the issues of 1966 with a feeling that we are at least better prepared.

A swift review—of just a few of the upcoming issues—suggests the variety of challenges 1966 will hold out to us. As Mr. Dunlop said, I think it is really opportunity.

Government Fact-Gathering

First, consider the area of government fact-gathering.

A year ago at this time, I commented on the government interagency group that is studying government facts and figures. Shortly afterward, the study group criticized the present industry fact-gathering as being inadequate, particularly in the areas of reserves, productive capacity, wells drilled, transportation and deliverability, and expenditures and revenues.

We believed a year ago—and we believe now—that any facts and figures the industry is asked to provide ought to be relevant to national needs—not just a display of federal curiosity. Figures we are asked to provide ought to be obtainable without placing an undue physical or financial burden on the industry. And if the figures we do provide are to be used as the basis for framing new policies, they ought to be *firm* figures—not just informed guesses, as in the case of indicated or ultimate reserves.

Industry itself has recognized the need for more complete data. Our response to this recognized need, and to the findings of the government study group, has been constructive. Task groups, under the chairmanship of Mr. Gunness, will be developing improved fact-gathering in three areas—reserves and productive capacity, drilling statistics, and the economics of exploration and drilling.

These, of course, are just the initial steps in the general overhaul of our fact-gathering services. Much remains to be done in 1966 and beyond. But you can be sure that our positive action in this area lends weight

* President, American Petroleum Institute, New York, N.Y.

† Presented at a general session during the 45th Annual Meeting of the American Petroleum Inst., in the Conrad Hilton Hotel, Chicago, Ill., Nov. 8, 1965; presiding, J. Ed. Warren, chairman, API Board of Directors.

to our opinions in the whole area of government fact-gathering.

Oil and Gas Taxation

Another issue worth comment at this time—one that especially underscores the need for wider participation in industry affairs—is that of percentage depletion.

The historic 27½-percent depletion rate has been maintained for decades, despite many challenges, for several important reasons. First, the wisdom of the provision and the established rate have been self-evident. Time and time again, Congress has correctly traced the continued discovery of new petroleum and the continued expansion of reserves to the historic and appropriate tax treatment of the industry. But equally important is the fact that the industry people have supported percentage depletion with a united voice. And because we spoke in a single voice, our position was clearly understood.

Now it appears that percentage depletion will once again go under a microscope—partly, at least, in the study of the balance of payments question.

Any policy—even a good policy—ought to be subject to periodic review. But it is one thing to review a policy to see if it is working; it is quite another to suggest that it has to be tinkered with or dismantled to see if it is working.

Land Law Review

Another area that will demand our wider interest and attention involves the work of the Public Land Law Review Commission. This commission was drawn up by Congress to review all laws dealing with public lands. Its duties come into important focus when you consider that one-third of the land area of the United States falls within the purview of these laws.

There are indications that this will be no routine examination. It could well develop into a thorough-going review of policies relating to domestic and foreign development of oil and gas. Chairman Wayne Aspinall says that his commission will be following the course of tariffs, quotas, proposed international commodity agreements, and the development of petrochemical complexes. Along with it will be further study of depletion provisions.

The industry is assisting in the work of that commission through representation by several of its outstanding members. But many more people in our industry will ultimately become involved. The findings and announcements of the commission will trigger lively discussion and debate. Industry people at all levels must be prepared to take part. Many more of us will have to become practitioners of public affairs—articulators of the industry's point of view.

Now, the three issues I've touched on—government fact-finding, oil and gas taxation, and land law review—were selected primarily for illustrative purposes—to show why more participation in industry affairs will be necessary in 1966. But none of them ranks in immediacy with the final issue I want to discuss. It will, without question, overshadow all others in the demands it will make on us. I refer, of course, to air and water conservation.

Air and Water Conservation

The fact that our industry will continue to be confronted with problems of air and water conservation for many years to come is demonstrated by the massive report of the Environmental Pollution Panel of the President's Science Advisory Committee, which was presented to President Johnson over the weekend.

This report unquestionably will fan emotions, raise fears, and bring demands for action. The substance of the report is that there is still time to save the world's peoples from the catastrophic consequence of pollution, but time is running out.

One of the most important predictions of the report is that carbon dioxide is being added to the earth's atmosphere by the burning of coal, oil, and natural gas at such a rate that by the year 2000 the heat balance will be so modified as possibly to cause marked changes in climate beyond local or even national efforts. The report further states, and I quote: ". . . the pollution from internal combustion engines is so serious, and is growing so fast, that an alternative nonpolluting means of powering automobiles, buses, and trucks is likely to become a national necessity."

The report, however, does conclude that urban air pollution, while having some unfavorable effects, has not reached the stage where the damage is as great as that associated with cigarette smoking. Furthermore, it does not find that present levels of pollution in air, water, soils, and living organisms are such as to be a demonstrated cause of disease or death in people; but it is fearful of the future. As a safeguard, it would attempt to assert the right of man to freedom from pollution and to deny the right of anyone to pollute air, land, or water.

There are more than 100 recommendations in this sweeping report, and I commend it to your study. Implementation of even some of them will keep local, state, and federal legislative bodies, as well as the petroleum and other industries, at work for generations.

The scope of our involvement is suggested, once again, by the thermometer of legislative activity this past year. On the federal level, hearings and committee meetings relating to air and water conservation were held almost continuously. The results, of course, are the Water Quality Act of 1965 and an important amendment to the Clean Air Act of 1963.

Turning to the state level, more than 350 bills dealing with air and water conservation were considered by 41 state legislatures. One hundred and seventy-five of these related to air pollution control, and 190 were related to water pollution control. As for the results of all this, 30 air pollution bills passed in 18 states, and 35 water bills in 19 states.

The signs of heavier industry involvement next year are unmistakable. The Water Quality Act, for example, provides that states are to set water quality criteria by

June of 1967—criteria that must be acceptable to the Department of Health, Education, and Welfare (HEW). If an individual state fails to act, the department will set water criteria in its stead.

As for the Clean Air Act amendment, the new provision gives HEW the authority to set standards for exhaust emissions from new motor vehicles. And it provides for increased federal air pollution research, including a study of automotive hydrocarbon emissions from the carburetor and fuel tank. There will also be further studies on ways to cut down sulfur oxide emissions resulting from the burning of residual oil and coal.

Obviously, a large and necessary job lies ahead for this nation. Our industry must give its fullest cooperation in this national effort to improve our air and water resources. At the same time, we must also do what we can to put a good cause on a rational track.

Industry cooperation is not made easier by the emotionalism with which the matter is now charged—an emotionalism we can expect to see intensified. Some writers, politicians, and even research people have found that strong words on pollution are a short way and a certain route to attention.

We *must* not permit the job ahead of us in air and water conservation—either its size or its complexity—to become obscured by rash statements and fanciful notions. Clear water and clear air will only come about through clear thinking.

Our position was put forward in a letter to the President last January, in response to his comments about air and water conservation in his State of the Union message. We pointed out that past experience in this field indicates the waste of money and time that can be involved in false starts. And we firmly stated our belief that well-meaning programs can founder where they are based on supposition unsupported by scientific knowledge; developed through inadequate research.

We pointed out to the President—and it is worth reminding ourselves here today—that our industry's concern for water quality is sincere and long standing. Thirty-seven years ago, at a time when many local governments scarcely gave thought to water purity, the industry formed the API Committee on Disposal of Refinery Wastes. The industry can take a great deal of pride, too, in its solid support of this effort all during the 1930's—when there were perhaps more pressing economic problems.

Nor is industry concern with clean air a recent matter, provoked by headlines of the moment. We have been sponsoring research and publishing our findings for more than 10 years—starting long before the national spotlight was thrown on this problem.

I thought you would be interested in the results of some recent studies that indicate the extent of our industry's commitment in air and water conservation.

API sponsorship of basic research over the years has involved substantial sums. This basic research has been carried on in some 20 different university laboratories and research institutions. It has ranged from studies of the effect of pollutants on crustaceans to studies on the composition of diesel exhaust. In continuation of these efforts, further research—principally to establish needed factual information on matters of current interest in the area of air conservation—is right now under consideration within the API Board of Directors.

The API research effort is, of course, only a small part of industry spending. A study of expenditures by companies for *water* conservation is not completed, but we *do* have figures on *air* conservation. They show that in the past 10 years, companies have spent more than $210 million on air conservation research and new and improved control facilities. For 1966, these companies have earmarked more than $41 million for these purposes—almost double the average annual rate of the previous 10 years.

Expenditures by individual companies on water conservation have lead to achievements worth talking about. A typical example is the East Coast refinery with a water treatment system so efficient that an oyster bed thrives just below the point where treated waters are released. Or the inland refinery—again typical—with a water reclaim system so efficient that it has greatly reduced its requirements from city water mains and recently won compliments from water officials. Or the California refinery that uses schools of small fish to check the quality of effluent in its refinery ponds.

Such achievements have not been spectacular in the newspaper headline sense. None have been crash programs to seek one-shot solutions. Rather, they have proceeded in a calm, sensible, programmed way and have made—and will continue to make—a real and lasting contribution to air and water conservation.

One recent industry effort has seen the development of a procedure to avert potentially harmful air pollution episodes. Any city could use it. When alerted by a monitoring system and weather forecast to a threatened buildup of pollutants, the community would take control steps to reduce emissions. These steps might include temporary fuel switching, changing of plant operations, and cutting down on incineration and open burning.

In short, we have an achievable, economical solution to a real pollution problem.

Our overall record in air and water conservation is good—a record of which we can be proud. But in 1966 it can serve a larger purpose than merely giving us a chance to point with pride. These past and present efforts, and our record of concern over many years, merit the deep attention of anyone seriously interested in conserving air and water. Industry people with expertise in these areas—and many more of them now exist than in the past—must make their expertise available.

Conclusion

In conclusion, then, the challenges of 1966 will be many and varied. They call, first of all, for even wider

and more active participation by all of us. Those among us who have been reluctant to take part in these matters must be urged toward a more active role.

But, of course, we need more than just added participation—more voices added to the chorus. Success in any program depends also upon unity. Certainly we benefit from diversity of opinion and individuality of viewpoint. But our industry is best understood, and its needs are more readily appreciated, when it can strike a single note. Our industry thrives today because it has identified those areas that could help, or impede, its progress; and when it has responded, it has done so in a clear voice, easily understood.

So, we look toward 1966 as a year of great challenge and opportunity. It can also be a year of achievement if we have broad participation and strong support, which I know we will have, in these areas of common concern.

Annex 18

S. Manabe & R. Wetherald, “Thermal Equilibrium of the Atmosphere with a Given Distribution of Relative Humidity”, *Journal of the Atmospheric Sciences,* 1967, pp. 241-259, pages 241-242

Thermal Equilibrium of the Atmosphere with a Given Distribution of Relative Humidity

SYUKURO MANABE AND RICHARD T. WETHERALD

Geophysical Fluid Dynamics Laboratory, ESSA, Washington, D. C.

(Manuscript received 2 November 1966)

ABSTRACT

Radiative convective equilibrium of the atmosphere with a given distribution of relative humidity is computed as the asymptotic state of an initial value problem.

The results show that it takes almost twice as long to reach the state of radiative convective equilibrinm for the atmosphere with a given distribution of relative humidity than for the atmosphere with a given distribution of absolute humidity.

Also, the surface equilibrium temperature of the former is almost twice as sensitive to change of various factors such as solar constant, CO_2 content, O_3 content, and cloudiness, than that of the latter, due to the adjustment of water vapor content to the temperature variation of the atmosphere.

According to our estimate, a doubling of the CO_2 content in the atmosphere has the effect of raising the temperature of the atmosphere (whose relative humidity is fixed) by about 2C. Our model does not have the extreme sensitivity of atmospheric temperature to changes of CO_2 content which was adduced by Möller.

1. Introduction

This study is a continuation of the previous study of the thermal equilibrium of the atmosphere with a convective adjustment which was published in the JOURNAL OF THE ATMOSPHERIC SCIENCES (Manabe and Strickler, 1964). Hereafter, we shall identify this study by M.S. In M.S. the vertical distribution of absolute humidity was given for the computation of equilibrium temperature, and its dependence upon atmospheric temperature was not taken into consideration. However, the absolute humidity in the actual atmosphere strongly depends upon temperature. Fig. 1 shows the distribution of relative humidity as a function of latitude and height for summer and winter. According to this figure, the zonal mean distributions of relative humidity of two seasons closely resemble one another, whereas those of absolute humidity do not. These data suggest that, given sufficient time, the atmosphere tends to restore a certain climatological distribution of relative humidity responding to the change of temperature. If the moisture content of the atmosphere depends upon atmospheric temperature, the effective height of the source of outgoing long-wave radiation also depends upon atmospheric temperature. Given a vertical distribution of relative humidity, the warmer the atmospheric temperature, the higher the effective source of outgoing radiation. Accordingly, the dependence of the outgoing long-wave radiation is less than that to be expected from the fourth-power law of Stefan-Boltzman. Therefore, the equilibrium temperature of the atmosphere with a fixed relative humidity depends more upon the solar constant or upon absorbers such as CO_2 and O_3, than does that with a fixed absolute humidity, in order to satisfy the condition of radiative convective equilibrium. In this study, we will repeat the computation of radiative convective equilibrium of the atmosphere, this time for an atmosphere with a given distribution of relative humidity instead of that for an atmosphere with a given distribution of absolute humidity as was carried out in M.S.

As we stated in M.S., and in the study by Manabe and Möller (1961), the primary objective of our study of radiative convective equilibrium is the incorporation of radiative transfer into the general circulation model

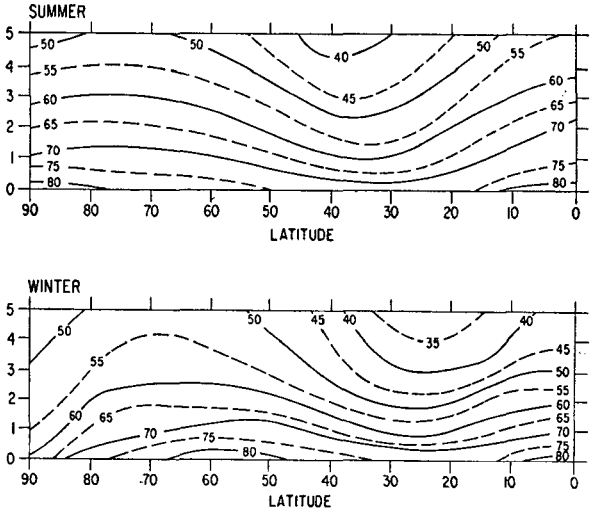


FIG. 1. Latitude-height distribution of relative humidity for both summer and winter (Telegadas and London, 1954).

of the atmosphere. Adopting the scheme of the computation of radiative transfer which was developed in M.S., Manabe *et al.* (1965) successfully performed the numerical integration of the general circulation of the atmosphere involving the hydrologic cycle. In order to avoid a substantial increase in the number of degrees of freedom, the distribution of water vapor, which emerged as the result of the hydrologic cycle of the model atmosphere, was not used for the computation of radiative transfer. Instead, the climatological distribution of absolute humidity was used. The next step is the numerical integration of the model with complete coupling between radiative transfer and the hydrologic cycle. Before undertaking this project, it is desirable to answer the following questions by performing a series of computations of radiative-convective equilibrium of the atmosphere with fixed relative humidity.

1) How long does it take to reach a state of thermal equilibrium when the atmosphere maintains a realistic distribution of relative humidity that is invariant with time?
2) What is the influence of various factors such as the solar constant, cloudiness, surface albedo, and the distributions of the various atmospheric absorbers on the equilibrium temperature of the atmosphere with a realistic distribution of relative humidity?
3) What is the equilibrium temperature of the earth's surface corresponding to realistic values of these factors?

There is no doubt that this information is indispensable for the successful integration of the fundamental model of the general circulation mentioned above.

Recently, Möller (1963) discussed the influence of the variation of CO_2 content in the atmosphere on the magnitude of long-wave radiation at the earth's surface, and on the equilibrium temperature of the earth's surface. Assuming that the absolute humidity is independent of the atmospheric temperature, he obtained an order-of-magnitude dependence of equilibrium temperature upon CO_2 content similar to those obtained by Plass (1956), Kondratiev and Niilisk (1960), and Kaplan (1960). However, he obtained an extremely large dependence for a certain range of temperature when he assumed that relative humidity (instead of absolute humidity) of the atmosphere was given. One shortcoming of this study is that the conclusion was drawn from the computation of the heat balance of earth's surface instead of that of the atmosphere as a whole. Therefore, it seems to be highly desirable to re-evaluate this theory, using as a basis the computation of radiative convective equilibrium of the atmosphere with a fixed relative humidity. The results are presented in this study.

2. Radiative convective equilibrium

a. Description of the model. As we explained in the previous paper and in the introduction, the radiative convective equilibrium of the atmosphere with a given distribution of relative humidity should satisfy the following requirements:

1) At the top of the atmosphere, the net incoming solar radiation should be equal to the net outgoing long-wave radiation.
2) No temperature discontinuity should exist.
3) Free and forced convection, and mixing by the large-scale eddies, prevent the lapse rate from exceeding a critical lapse rate equal to 6.5C km^{-1}.
4) Whenever the lapse rate is subcritical, the condition of local radiative equilibrium is satisfied.
5) The heat capacity of the earth's surface is zero.
6) The atmosphere maintains the given vertical distribution of relative humidity (new requirement).

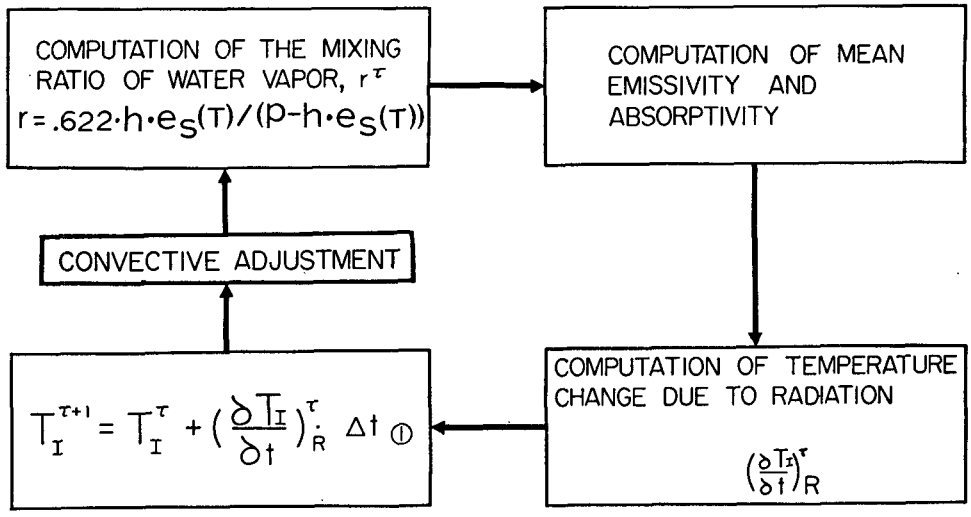


FIG. 2. Flow chart for the numerical time integration.

Annex 19

"Report on Sources, Abundance, and Fate of Gaseous Atmospheric Pollutants", *Stanford Research Institute*, February 1968, pages 1-3, 8-10, 105-110

The complete report can be accessed through the Université libre de Bruxelles Library (*see* Université libre de Bruxelles Library catalogue, available at: https://cibleplus.ulb.ac.be/discovery/fulldisplay?docid=alma991005133589704066&context=L&vid=32ULDB_U_INST:32ULB_VU1&lang=fr&search_scope=MyInst_and_CI&adaptor=Local%20Search%20Engine&tab=Everything&query=any,contains,Sources,%20abundance,%20and%20fate%20of%20gaseous%20atmospheric%20pollutants&offset=0 (last accessed on 12 March 2024). The Université libre de Bruxelles Library can be contacted for assistance by email at bsh@ulb.be.

STANFORD RESEARCH INSTITUTE
MENLO PARK, CALIFORNIA

[redacted]

Final Report

February 1968

SOURCES, ABUNDANCE, AND FATE OF GASEOUS ATMOSPHERIC POLLUTANTS

Prepared for:

AMERICAN PETROLEUM INSTITUTE
1271 AVENUE OF THE AMERICAS
NEW YORK, N.Y. 10020

ATTN: MR. W. A. BURHOUSE
ASSISTANT DIRECTOR

By: E. ROBINSON AND R. C. ROBBINS
III

SRI Project PR-6755

B 4007

Approved: N. K. HIESTER, DIRECTOR
CHEMICAL DEVELOPMENT AND ENGINEERING DIVISION

[redacted]

I INTRODUCTION

It is a popular misconception that almost everything present in the earth's atmosphere, except nitrogen, oxygen, and a few inert rare gases, is an air pollutant or the remnant of pollution activities. This is not the case. There are sources in the natural environment of a wide variety of gaseous and particulate materials which are commonly classed as air pollutants when they are emitted by man-made sources. In addition, the atmosphere possesses a number of mechanisms which act to remove, sometimes at a quite rapid rate, most if not all of the materials emitted into it.

It is, of course, also obvious that while these atmospheric scavenging mechanisms are quite effective they can be overburdened by excessive emissions occurring in relatively short periods of time or in limited geographical areas. The gradual accumulation of carbon dioxide in the atmosphere is a case where the available environmental scavenging mechanisms are significantly lagging the pollutant emission rate. On a much smaller scale, the air pollution problems in major urban areas are examples of situations where the pollutant emission rate seriously overburdens the scavenging processes for significant but limited periods of time within the confines of the urban area.

The topic of this report, the atmospheric cycles of trace chemicals including but not being restricted to air pollutants, is one that has rarely received detailed consideration. Instead it often seems to be tacitly assumed that pollutants once released into the atmosphere will disappear as soon as the air mass moves across the city boundary. It is also often assumed, apparently, that commonly identified pollutants are uniquely related to man's activity and that pollutant emissions constitute

a permanent and ever-worsening burden for our atmospheric environment. These assumptions are drastic oversimplifications and can lead their proponents far from reality.

It is the purpose of this report to examine our present state of knowledge of the atmospheric cycles followed by a variety of common gaseou materials. This will be done by analyzing the major natural and urban pollution sources, estimating the effectiveness of applicable atmospheric reaction processes, and determining the effectiveness of the processes by which the material is finally removed from the atmosphere. It will be apparent that our knowledge of these atmospheric processes is, in many cases, fragmentary. Where this is the case, further research is called for and will be pointed out.

Sources of the various materials have been estimated from the available literature, but a detailed intercomparison of source data has not been undertaken because a detailed "emissions inventory" was not within the scope of this program. In general, the magnitudes of the various pollutant sources can be estimated reasonably well while the possible natural sources can only be crudely defined.

We have in a general sense divorced our considerations from a detai reporting and analysis of conditions within specific urban areas and fro studies which report the periodic "highest-ever" type of statistics. Th total atmospheric system is so much greater than the polluted envelope o any one city that the transient effects noted in a given area are important to our study only to the degree that they indicate sources of pollu tants that can affect the atmospheric system.

In many ways this study is a first effort at solving the problem o the integrated effects of natural and urban emanations in the atmosphere Progress has been made here, but more needs to be done.

II SUMMARY AND CONCLUSIONS

A. Summary

This analysis of the sources, abundance, and fate of gaseous atmospheric pollutants has considered three families of compounds--sulfurous, nitrogenous, and organic; and two inorganic carbon compounds--carbon monoxide and carbon dioxide. With the exception of CO_2, we have followed similar patterns in our analyses of these materials and have produced rather detailed analyses. The presentation of CO_2 is only a brief review of the current state of thinking.

This analysis has included estimates of annual world-wide emissions of pollutants: SO_2, H_2S, CO, NO_2, NH_3, and organics. The magnitudes of the natural emanations of a variety of materials have also been considered, although we must admit that the means of estimating these emissions are very crude because so little study has been made of emissions from other than urban air pollution sources. The following paragraphs give the highlights of our analyses.

1. Sulfur Compounds

Sulfur compounds, in the form of SO_2, are currently the most topical of the numerous air pollutants. Sulfur enters the atmosphere as air pollutants in the form of SO_2, H_2S, H_2SO_4, and particulate sulfates; and as natural emanations in the form of H_2S and sulfates. On an annual basis, the tonnage of sulfur which is discharged into the atmosphere amounts to 220×10^6 tons. Of this sulfur, about one third comes from air pollution sources, mostly in the form of SO_2, and the rest comes from natural processes. It is estimated that H_2S from natural processes accounts for almost one half of the total sulfur released to the atmosphere, 100×10^6 out of the 220×10^6 tons.

5. Carbon Dioxide

A brief review of our present understanding of CO_2 in the atmosphere indicates that here we have a clear example of a situation where pollutan emissions are significant enough to cause measurable changes in the ambie concentrations. Measured increases in CO_2 in the atmosphere are about 0.06 ppm per month. If CO_2 levels continue to rise at present rates, it is likely that noticeable increases in temperature could occur. Changes in temperature on a world-wide scale could cause major changes in the earth's environment over the next several hundred years including change: in the polar ice caps.

It seems ironic that given this picture of the likely result of mas sive CO_2 emissions so little concern is given to CO_2 as an important air pollutant.

B. Conclusions

Important factors resulting from our analysis of atmospheric trace components and pollutants are summarized in Table I. This table indicat the nature and size of the natural and pollutant sources, the estimated concentrations in the ambient atmosphere, probable scavenging reactions, estimated residence times, and the most important references which perta to these various materials. This tabulation is, of course, amplified ir the main body of this report.

In our discussions of atmospheric residence times for the various materials we have considered, it seems that the residence times seem to be either a few days or a few years. In the "few days" classification the more reactive gases: SO_2, H_2S, NO, NO_2, and NH_3. In the longer "f years" classification are the significantly less reactive materials: C N_2O, CH_4, and CO_2. In the case of the more reactive gases the troposph scavenging and reaction processes are relatively well known and include photochemical, homogeneous, and heterogeneous reactions. For the latte

Table I

SUMMARY OF SOURCES, CONCENTRATIONS, AND MAJOR REACTIONS OF ATMOSPHERIC TRACE GASES

CONTAMINANT	MAJOR POLLUTION SOURCES	NATURAL SOURCES	ESTIMATED EMISSIONS		ATMOSPHERIC BACKGROUND CONCENTRATIONS	CALCULATED ATMOSPHERIC RESIDENCE TIME	REMOVAL REACTIONS AND SINKS	PRINCIPAL REFERENCES	REMARKS
			Pollution	Natural					
SO_2	Combustion of coal and oil	Volcanoes	146×10^6 tons	None	0.2 ppb	4 days	Oxidation to sulfate by ozone or after absorption by solid and liquid aerosols	Ericksson (1959, 1960, 1963) Junge (1963) Lodge and Pate (1966)	Photochemical oxidation with NO_2 and HC may be the process needed to give rapid transformation of $SO_2 \rightarrow SO_4$
H_2S	Chemical processes, sewage treatment	Volcanoes, biological action in swamp areas	3×10^6 tons	100×10^6 tons	0.2 ppb	2 days	Oxidation to SO_2	Junge (1963) Smith *et al.* (1961)	Only one set of background concentions available
CO	Auto exhaust and other combustion	Forest fires	220×10^6 tons	11×10^6 tons	0.1 ppm	<3 yr	None known, but large sink necessary	Bates and Witherspoon (1952) SRI Project Reports	
NO NO_2	Combustion	Bacterial action in soil (?)	53×10^6 tons	500×10^6 tons	1 ppb	5 days	Oxidation to nitrate after sorption by solid and liquid aerosols, hydrocarbon photochemical reactions	Junge (1963) Leighton (1961) Lodge and Pate (1966)	Very little work done on natural processes
NH_3	Waste treatment	Biological decay	4×10^6 tons	5900×10^6 tons	6 ppb to 20 ppb	2 days	Reaction with SO_2 to form $(NH_4)_2SO_4$, oxidation to NO_3 nitrate	Ericksson (1952) Georgii (1963) Junge (1963) Lodge and Pate (1966)	No quantitative rate data on oxidation of NH_3 to NO_3 which seems to be dominant process in atmosphere
N_2O	None	Biological action in soil	None	1000×10^6 tons	0.25 ppm	1-3 yr	Photo dissociation in stratosphere, biological action in soil	Bates and Hays (1967)	No information on proposed absorption of N_2O by vegetation
Hydrocarbons	Combustion exhaust, chemical processes	Biological processes	88×10^6 tons	480×10^6 tons	CH_4: 1.5 ppm non CH_4: <1 ppb	16 yr (CH_4)	Photochemical reaction with NO/NO_2, O_3; large sink necessary for CH_4	Bates and Witherspoon (1952) Ehhalt (1967) Koyama (1963) SRI Project Reports	"Reactive" hydrocarbon emissions from pollution 27×10^6 tons
CO_2	Combustion	Biological decay, release from oceans	1.3×10^{10} tons	10^{12} tons	320 ppm	4 yr	Biological absorption and photosynthesis, absorption in oceans	Revelle (1965)	Atmospheric concentrations increasing by 0.06 ppm per month

materials, our low reactivity class, we postulate that the controlling scavenging process is in the biosphere and that the absorption and react: for CO, CH_4, and N_2O are generally parallel to the CO_2 absorption and photosynthesis process. Although this is only speculation at this time, our available facts, in general, support such an argument. For example, the calculated residence time for CO requires a tropospheric scavenging mechanism, and the biosphere is apparently the most logical one availabl A similar argument holds for CH_4, although the magnitude of the natural source is less well documented. For N_2O, a relatively short resident ti of about four years would reconcile estimates of the likely rate of emis sion from the soil and the much slower photochemical dissociation of N_2O in the stratosphere. We believe that the absorption processes which can occur within the respiration cycle of vegetation will establish upper limits for the residence times of these less-reactive gases and that the residence times will be of the same order as for CO_2, i.e., a few years.

The atmosphere and our environment obviously hold many secrets, including many things that we would like to know about the trace gases i the troposphere. It will require a considerable amount of research to expand our knowledge in this area because it will be necessary to deal with large areas of the world and relatively small concentrations of material. However, this study of the unpolluted, ambient atmosphere mus be an integral part of our program of air pollution research. Otherwise we will be looking at only a very small part of our total environment a will have no knowledge of when concentrations are reaching a critical s Thus too small a scope in environmental pollution studies will fail to provide a useful early warning of changing conditions.

VII CARBON DIOXIDE IN THE ATMOSPHERE

The most commonly emitted air pollutant is carbon dioxide, CO_2. In fact it is so common and such an integral part of all our activities that air pollution regulations typically specify that CO_2 emissions are not to be considered as pollutants. This is perhaps fortunate for our present mode of living, centered as it is around carbon combustion. However, this seeming necessity, the CO_2 emission, is the only air pollutant which has been proven to be of global importance to man's environment on the basis of a long period of scientific investigation. Because of this obvious relation we believe that any discussion of atmospheric pollutants should also include a discussion of CO_2, and therefore we have added this brief summary. This discussion is based on the summary article "Atmospheric Carbon Dioxide," prepared for the Environmental Pollution Panel, President's Science Advisory Committee, by a committee headed by Dr. Roger Revelle (Revelle et al., 1965). Unless otherwise referenced the facts presented here come from this source.

The possibility that changes in atmospheric CO_2 could change world climate is not a new idea. It was first proposed independently in America by Chamberlain in 1899 and in Sweden by S. Arrhenius in 1903. Since then it has been the source of much discussion and investigation, and while we know a great deal more about the problem, we still cannot quantitatively evaluate the impact of the accumulation of CO_2 in the atmosphere in terms of climatic change.

A. Changes in Atmospheric Carbon Dioxide

The basic problem involved with CO_2 in the atmosphere is that in our use of fossil fuel we are putting back into the atmosphere as CO_2 within

a relatively short period of time, a few hundred years, a significant part of the carbon which was extracted by plants and buried by rock sediments over a period of half a billion years. The natural scavenging processes for removing CO_2 from the atmosphere are not sufficient to maintain a stable equilibrium in the atmosphere in the presence of this increase in emissions.

Between 1860 and 1940 the consumption of fossil fuel accounted for the release to the atmosphere of an amount of CO_2 equivalent to 7.9% of the total amount of CO_2 in the 1860 ambient atmosphere. By 1950, the added CO_2 amounted to 10.3%; by 1959, 13.8%; and by 1962, 15.2%. During this latter period careful measurements of CO_2 were made on Mauna Loa, Hawaii, and at the South Pole. These two sets of measurements, with an accuracy of about ±0.1 ppm, permitted an estimate to be made of the secular change in CO_2 in the ambient atmosphere. A plot of these data from Mauna Loa is shown in Fig. 6. The polar and Hawaiian results show without

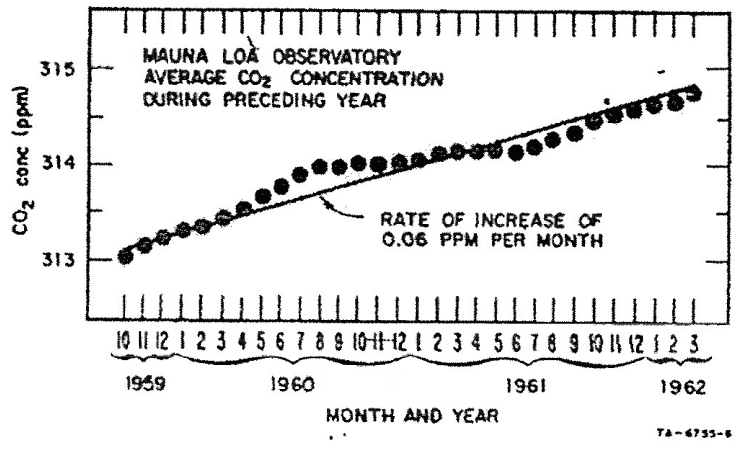


FIG. 6 ANNUAL AVERAGE CO_2 CONCENTRATIONS, MAUNA LOA, HAWAII (Bolin and Keeling, 1963)

any doubt that in the five years between 1958 and 1963, the CO_2 content of the atmosphere increased by 1.36% for an average increase of 0.23% or 0.06 ppm per month. Fuel emission data show that the CO_2 increase in the atmosphere in this latest period is just about half the amount of CO_2 released to the atmosphere.

This information can be used to estimate the possible amount of CO_2 which could be emitted to the atmosphere by fuel combustion. Total recoverable fuels are estimated to be about 10^{12} tons with a CO_2 equivalent of 7.9×10^{18} g or 336% of the 1950 atmospheric CO_2. If, as indicated by the 1958-63 data, half of this stays in the atmosphere, then the atmospheric CO_2 concentration would increase by almost 170% to about 830 ppm.

The speed with which this change might occur would depend on the rate of fossil fuel consumption. If the fuel-use growth rate were to remain at the 1959 rate, 0.35% per year, by the year 2000 the release of CO_2 to the atmosphere will have increased about 28% above the 1950 amount. However, if our present trends continue and our use of fuel continues to expand at about the 5% rate experienced more recently, then the amount of CO_2 injected into the atmosphere will be about 60% of the 1950 amount. In these latter two cases, if half the injected CO_2 actually remains in the atmosphere, in the year 2000 the CO_2 concentrations could be between 14 and 30% higher than in 1950. A consideration of likely world energy requirements indicates that a 25% increase in CO_2 concentrations is realistic.

B. Possible Effects of Increased Atmospheric Carbon Dioxide

We are concerned with the possible changes in atmospheric CO_2 content because CO_2 plays a significant role in establishing the thermal balance of the earth. This occurs because CO_2 is a strong absorber and back radiator in the infrared portion of the spectrum, especially between 12 and

18 μ. As such CO_2 prevents the loss of considerable heat energy from the earth and radiates it back to the lower atmosphere, the so-called "greenhouse" effect. Thus the major changes which are speculated about as possibly resulting from a change in atmospheric CO_2 are related to a change in the earth's temperature.

The latest data available for estimating CO_2 temperature effects are those of Moller (1963). From Möller's data a CO_2 increase of 25% would result in an increase in temperature at the earth's surface of between 1.1 and 7°F, depending on the assumption made regarding the likely humidity changes accompanying this temperature change. If the amount of water vapor in the atmosphere remained unchanged, the smaller increase would occur, but if the relative humidity were to remain constant then the larger calculated increase would prevail. If, instead of a 25% increase, the CO_2 content were to double, the expected change would be about three times this figure. For atmospheric calculations, Möller's model is still a relatively simple one and has not included all of the possible major interactions occurring in the atmosphere. For this reason it is likely that Möller's calculations overestimate the effects on temperature of an increase in CO_2. More comprehensive models are under development and should be available shortly.

If the earth's temperature increases significantly, a number of events might be expected to occur, including the melting of the Antarctic ice cap, a rise in sea levels, warming of the oceans, and an increase in photosynthesis. The first two items are of course related since the increase in sea level would be mainly due to the added water from the ice cap. Estimates of the possible rate at which the Antarctic ice cap might melt have been made. If the poleward heat flux were increased 10%, the ice cap could disappear in about 4000 years. A shorter time, about 400 years, is estimated if it is considered that half the energy associated with a 2% increase in radiation were used to melt the polar ice cap. A 2% increase might result from a 25% increase in CO_2 by the year 2000.

With regard to sea level changes, if 1000 years were required to melt the Antarctic ice cap, the resulting 400 foot rise in sea level would occur at a rate of 4 feet per 10 years. This is 100 times greater than presently observed changes.

Changes in ocean temperature would change the distribution of fish and cause a retreat in the polar sea ice. This has happened in recent time on a very limited scale.

Changes in CO_2 might also bring about increased photosynthesis in areas where CO_2 might be a limiting factor in present growth patterns. Where temperature has been a limiting factor to growth and development, an increase in biological activity might be expected.

Although there are other possible sources for the additional CO_2 now being observed in the atmosphere, none seems to fit the presently observed situation as well as the fossil fuel emanation theory.

C. Summary of Carbon Dioxide in the Atmosphere

In summary, Revelle makes the point that man is now engaged in a vast geophysical experiment with his environment, the earth. Significant temperature changes are almost certain to occur by the year 2000 and these could bring about climatic changes.

Since Revelle's report, McCormick and Ludwig (1966) have studied the possible world-wide change of atmospheric fine particles. An increase in fine particulate material will have the effect of increasing the reflectivity of the earth's atmosphere and reducing the amount of radiation received from the sun. Thus this effect would be the opposite of that caused by an increase in CO_2. The argument has been made that the large-scale cooling trend observed in the northern hemisphere since about 1955 is due to the disturbance of the radiation balance by fine particles and that this effect has already reversed any warming trend due to CO_2.

It is clear that we are unsure as to what our long-lived pollutants are doing to our environment; however, there seems to be no doubt that the potential damage to our environment could be severe. Whether one chooses the CO_2 warming theory as described in detail by Revelle and others or the newer cooling prospect indicated by McCormick and Ludwig, the prospect for the future must be of serious concern.

It seems ironic that in our view of air pollution technology we take such a serious concern with small-scale events such as the photochemical reactions of trace concentrations of hydrocarbons, the effect on vegetation of a fraction of a part per million of SO_2, when the abundant pollutants which we generally ignore because they have little local effect, CO_2 and submicron particles, may be the cause of serious world-wide environmental changes.

Annex 20

G. S. Benton, "Carbon Dioxide and its Role in Climate Change", *Proceedings of the National Academy of Sciences,* 1970, pp. 898-899

Proceedings of the National Academy of Sciences
Vol. 67, No. 2, pp. 898–899, October 1970

Carbon Dioxide and its Role in Climate Change

George S. Benton

THE JOHNS HOPKINS UNIVERSITY, BALTIMORE, MARYLAND 21218

Contributed to the Symposium on Aids and Threats from Technology, April 29, 1970

Climate is variable. In historical times, many significant fluctuations in temperature and precipitation have been identified. In the period from 1880 to 1940, the mean temperature of the earth increased about 0.6°C; from 1940 to 1970, it decreased by 0.3–0.4°C. Locally, temperature changes as large as 3–4°C per decade have been recorded, especially in sub-polar regions.

The cause of these changes has been under extensive study. One factor is the steady increase in carbon dioxide which has been observed, presumably as a result of the combustion of fossil fuels. In the late 19th century, prior to the industrial revolution, the carbon dioxide content of the atmosphere was about 290 ppm. This had risen to 314 ppm in 1960, and to just over 320 ppm in 1970. Aircraft observations by the Atmospheric Physics and Chemistry Laboratory of the Environmental Science Services Administration have clearly shown the importance of metropolitan areas as a source of carbon dioxide.

The effect of carbon dioxide is to increase the earth's temperature by absorbing outgoing terrestrial radiation. Recent numerical studies have indicated that a 10% increase in carbon dioxide should result, on the average, in a temperature increase of about 0.3°C at the earth's surface. The present rate of increase of 0.7 ppm per year would therefore (if extrapolated to 2000 A.D.) result in a warming of about 0.6°C—a very substantial change.

A second cause of climatic change is particulate loading of the atmosphere. Some meteorologists have attributed the cooling of the earth since 1940 primarily to such pollution of the atmosphere by man. However, the net effect of particulate matter on climate is difficult to analyze. Such pollutants, depending upon their size distribution and the elevation at which they occur, both intercept incoming solar radiation and trap outgoing radiation from the earth. The first process tends to depress the temperature of the earth's surface; the latter tends to increase it. To further complicate matters, the effect of pollution by natural volcanic activity must be considered. Unlike most activities of man, violent volcanic eruptions inject particulates directly into the stratosphere, where they are most effective in cooling the earth. The drop in the earth's temperature since 1940 has been paralleled by a substantial increase in natural volcanism. The effect of such volcanic activity is probably greater than the effect of man-made pollutants.

Finally, the possibility of other factors in climatic change must be considered. Solar radiation may change slightly in intensity or wavelength distribution; other natural explanations have been suggested. Our measurements of radia-

tion balance and our understanding of the dynamics of climate are not sufficient to evaluate quantitatively the possible importance of these other natural causes.

Several concluding statements may be advanced. Climate varies naturally, for reasons which are only poorly understood. Superimposed on natural climatic change are variations due to man, primarily as a result of the increase of carbon dioxide and particulate pollution. At present, the natural causes of climatic change are probably more important than the effects of man-made gaseous and particulate pollution. However, the balance is changing as industrialization, urbanization, and transportation continue to grow at an accelerating rate. Some years from now, man will control his climate, inadvertently or advertently. Before that day arrives, it is essential that scientists understand thoroughly the dynamics of climate. Only by such an understanding and by active intervention can man assure himself in the long run that this planet will continue to be a suitable place to live.

Annex 21

"A Study of Climatological Research as it Pertains to Intelligence Problems", *The United States of America Central Intelligence Agency,* August 1974, pages 1-3

Central Intelligence Agency

Washington, D.C. 20505

2 December 2015

Reference: F-2015-02095

This is a final response to your 1 July 2015 Freedom of Information Act (FOIA) request for **"a copy of the following six CIA documents:**

1. **FDD-6440, World Press Treatment of the Use of Gas in Vietnam (translation), May 6, 1965.**
2. **Potential Implications of Trends in World Population, Food Production and Climate, August 1974.**
3. **A Study of Climatological Research as it Pertains to Intelligence Problems, August 1974.**
4. **China: The Coal Industry, November 1976.**
5. **Deception Maxims: Fact and Folklore, April 1980, XD-OSD/NA.**
6. **The Biological and Chemical Warfare Threat, January 1997."**

We processed your request in accordance with the FOIA, 5 U.S.C. § 552, as amended, and the CIA Information Act, 50 U.S.C. § 3141, as amended. Our processing included a search for records as described in our 22 July 2015 acceptance letter.

We completed a thorough search for records responsive to your request and located the enclosed three documents, consisting of 114 pages, which we determined are releasable to you in their entirety. Because you are entitled to the first 100 pages free, and the cost for the remaining pages is minimal, in accordance with our regulations, as a matter of administrative discretion, there is no charge for processing your request.

Sincerely,

Michael Lavergne

Michael Lavergne
Information and Privacy Coordinator

Enclosures

C06464613

Approved for Release: 2015/10/28 C06464613

A Study of Climatological Research as it Pertains to Intelligence Problems

AUGUST 1974

Approved for Release: 2015/10/28 C06464613

C06464613

Approved for Release: 2015/10/28 C06464613

TABLE OF CONTENTS

	Page Number
PREFACE	
SUMMARY	1
WHAT ARE THE INTELLIGENCE ISSUES?	5
CLIMATIC PHENOMENA AND THE STATE OF THE ART	7
The State of the Art of Climatology	8
Thermal Distribution of Energy	8
Energy Reaching the Earth	9
Earth's Atmosphere	12
Current Approaches to Climatology	15
Lambian School	15
Smagorinsky-ian School	16
Budyko-ian School	19
RECENT MILESTONES	21
The Wisconsin Study	21
People, Places and Approaches	26
San Diego Conference	27
National Climate Plan	29
CONCLUSIONS	31
BIBLIOGRAPHY	33

Approved for Release: 2015/10/28 C06464613

C06464613

Approved for Release: 2015/10/28 C06464613

PREFACE

This document was originally prepared as a classified working paper, and to make it available to interested persons without the proper clearances, certain portions have been edited. An attempt has been made not to diminish the document's technical content.

Approved for Release: 2015/10/28 C06464613

C06464613

Approved for Release: 2015/10/28 C06464613

SUMMARY

Approved for Release: 2015/10/28 C06464613

C06464613

Approved for Release: 2015/10/28 C06464613

SUMMARY

The western world's leading climatologists have confirmed recent reports of a detrimental global climatic change. The stability of most nations is based upon a dependable source of food, but this stability will not be possible under the new climatic era. A forecast by the University of Wisconsin projects that the earth's climate is returning to that of the neo-boreal era (1600-1850)—an era of drought, famine, and political unrest in the western world.

A responsibility of the Intelligence Community is to assess a nation's capability and stability under varying internal or external pressures. The assessments normally include an analysis of the country's social, economic, political, and military sectors. The implied economic and political intelligence issues resulting from climatic change range far beyond the traditional concept of intelligence. The analysis of these issues is based upon two key questions:

- Can the Agency depend on climatology as a science to accurately project the future?

- What knowledge and understanding is available about world food production and can the consequences of a large climatic change be assessed?

Climate has not been a prime consideration of intelligence analysis because, until recently, it has not caused any significant perturbations to the status of major nations. This is so because during 50 of the last 60 years the Earth has, on the average, enjoyed the best agricultural climate since the eleventh century. An early twentieth century world food surplus hindered U.S. efforts to maintain and equalize farm production and incomes. Climate and its affect on world food production was considered to be only a minor factor not worth consideration in the complicated equation of country assessment. Food production, to meet the growing demands of a geometrically expanding world population, was always considered to be a question of matching technology and science to the problem.

The world is returning to the type of climate which has existed over the last 400 years. That is, the abnormal climate of agricultural-optimum is being replaced by a normal climate of the neo-boreal era.

The climate change began in 1960, but no one including the climatologists recognized it. Crop failures in the Soviet Union and India during the first part of the sixties

Approved for Release: 2015/10/28 C06464613

C06464613

Approved for Release: 2015/10/28 C06464613

were attributed to the natural fluctuation of the weather. India was supported by massive U.S. grain shipments that fed over 100 million people. To eat, the Soviets slaughtered their livestock, and Premier Nikita Khrushchev was quietly deposed.

Populations and the cost per hectare for technological investment grew exponentially. The world quietly ignored the warning provided by the 1964 crop failure and raced to keep ahead of a growing world population through massive investments in energy, technology, and biology. During the remainder of the 1960s, the climate change remained hidden in those back washes of the world where death through starvation and disease were already a common occurrence. The six West African countries south of the Sahara, known as the Sahel, including Mauretania, Senegal, Mali, Upper Volta, Niger, and Chad, became the first victims of the climate change. The failure of the African monsoon beginning in 1968 has driven these countries to the edge of economic and political ruin. They are now effectively wards of the United Nations and depend upon the United States for a majority of their food supply.

Later, in the 1970s one nation after another experienced the impact of the climatic change. The headlines from around the world told a story still not fully understood or one we don't want to face, such as:

- Burma (March 1973)–little rice for export due to drought
- North Korea (March 1973)–record high grain import reflected poor 1972 harvest
- Costa Rica and Honduras (1973)–worst drought in 50 years
- United States (April 1973)–"flood of the century along the Great Lakes"
- Japan (1973)–cold spell seriously damaged crops
- Pakistan (March 1973)–Islam planned import of U.S. grain to off-set crop failure due to drought
- Pakistan (August 1973)–worst flood in 20 years affected 2.8 million acres
- North Vietnam (September 1973)–important crop damaged by heavy rains
- Manila (March 1974)–millions in Asia face critical rice shortage
- Ecuador (April 1974)–shortage of rice reaching crisis proportion; political repercussions could threaten its stability

Approved for Release: 2015/10/28 C06464613

C06464613

Approved for Release: 2015/10/28 C06464613

- USSR (June 1974)–poor weather threatens to reduce grain yields in the USSR
- China (June 1974)–droughts and floods
- India (June 1974)–monsoons late
- United States (July 1974)–heavy rain and droughts cause record loss to potential bumper crop.

During the last year every prominent country has launched a major new climatic forecasting program.

- USSR reorganized their climatic forecasting groups and replaced the head of the Hydrometerological Service.
- Japan is planning to launch a major earth synchronous (U.S. manufactured) meterological satellite and has secured complete collection, processing, and analysis systems from the U.S.
- China has made major purchases of meterological collection and analysis equipment from western industrial sources.
- India is studying the application of climatic modification to secure a more homogeneous distribution of moisture from an erratic drought/flood monsoon.
- The U.S. National Academy of Sciences is preparing its recommendation for a National Climatic Research Program.
- The National Science Foundation (NSF) and the National Oceanographic and Atmospheric Agency (NOAA) have developed a National Climate Plan which will be presented to the Office of Mangement and Budget (OMB) for funding in FY 76.

Climate is now a critical factor. The politics of food will become the central issue of every government. On July 19, 1974, the Kiev Domestic Service reported massive rains and quoted an old proverb from Lvov Oblast, "The rains come not on the day for which we pray but only when we are making hay." The climate of the neo-boreal time period has arrived.

Approved for Release: 2015/10/28 C06464613

Annex 22

W. S. Broecker, “Climatic Change: Are We on the Brink of a Pronounced Global Warming?”, *Science,* 1975, pp. 460-463

Table 1. Data for the determination of the turquoise bead source area; ppm, parts per million.

Element	Snaketown			Himalaya		Crescent
	Group A	Group B	Unclassified	Group A	Group B	
			Trace element data (ppm)			
Co	1.67	1.78	1.95	1.30	1.78	1003.0
Cr	1.66	1.44	1.20	1.54	2.30	67.3
Eu	0.26	0.32	0.28	0.27	0.63	*
Sb	2.10	2.90	1.43	1.76	2.10	4.66
Sc	35.1	101.5	15.1	36.2	106.4	65.3
Ta	*	*	*	*	*	326.0
			Similarity coefficients			
Snaketown						
Group A	1.000					
Group B	.825	1.000				
Unclassified	.544	.337	1.000			
Himalaya						
Group A	.946	.808	.613	1.000		
Group B	.861	.991	.565	.840	1.000	
Crescent	.143	.177	.092	.208	.101	1.000

*Not detected.

limits for the Himalaya-Snaketown turquoise, but were present in many of the other samples. These basic differences served to distinguish the California source area from other localities by simple examination of the data.

The Snaketown beads fell into two groups of five and seven samples each, based on Sc contents of 35 ppm (group A) and 100 ppm (group B), with 1 sample unclassified. The data for samples from the Himalaya mine also fell into the same two groups, emphasizing the need for multiple samples from each geographic source area.

In order to characterize the mine areas statistically, it was necessary to compare the concentrations of all trace elements simultaneously. The multivariate statistic devised by Borchardt *et al.* (*8*), in which the ratio of each element concentration in a pair of samples is summed and divided by the number of elements, was found to be the most useful for these data (*9*). The coefficients thus obtained are representative of the degree of similarity, or dissimilarity, between two or more samples. That is, the coefficients are a means of quantifying the degree of correlation based on sample analytical data. Perfect similarity results in a value of 1.0, and large differences result in coefficients near zero. Borchardt *et al.* determined by replicate analyses that coefficients above .800 were indicative of an accurate correlation at the 95 percent confidence level. Conversely, values below .560 indicated that a pair of samples probably were not from the same site.

Table 1 shows the correlation coefficient matrix for the two Snaketown groups, the unclassified bead, the two Himalaya mine groups, and for the Crescent mine in Nevada. On the basis of Borchardt's criterion, there is good correlation between samples from Snaketown A and Himalaya A, and between Snaketown B and Himalaya B. The Crescent sample is clearly unrelated.

The similarity coefficients, then, substantiated the conclusion that trace element patterns for the Snaketown beads correlated with that of turquoise from the Himilaya group of mines near Halloron Springs, but not with the data from the 23 other mines analyzed. The 13 turquoise beads, however, represent only a portion of the turquoise from the site. Since turquoise was widely traded in the Southwest, it is possible that other sources may by represented in other artifacts from Snaketown.

Cultures and cultural ties are constantly changing, and it is expected that trade patterns will also change with time because of political and economic pressures, or the depletion of a resource procurement area. Chemical analysis of a commonly utilized material such as turquoise is one method of detecting, or monitoring, these changes. Further identification of source areas utilized by particular cultural groups should provide additional information on the nature of prehistoric resource acquisition and exchange routes.

ANNE COLBERG SIGLEO
Department of Geosciences,
University of Arizona,
Tucson 85721

References and Notes

1. The chemical formula for turquoise is $CuAl_6(PO_4)_4(OH)_8 \cdot 4H_2O$.
2. A. M. C. Sigleo, thesis, University of New Mexico (1970).
3. These are Mineral Park, Canyon Creek, and Courtland, Arizona; Miami, Morenci, and Bisbee have no reported prehistoric workings.
4. E. W. Haury, *Kiva* **31**, 1 (1965).
5. J. Murdoch and R. W. Webb, *Calif. Div. Mines Geol. Bull. No. 189* (1966).
6. R. A. Schmitt, T. A. Linn, Jr., W. Wakita, *Radiochim. Acta* **13**, 200 (1970); G. E. Gordon, K. Randle, G. G. Goles, J. B. Corliss, M. H. Beeson, S. S. Oxley, *Geochim. Cosmochim. Acta* **32**, 369 (1968).
7. F. J. Flanagan, *Geochim. Cosmochim. Acta* **37**, 1189 (1973).
8. G. A. Borchardt, P. J. Aruscavage, H. T. Millard, Jr., *J. Sediment. Petrol.* **42**, 301 (1972).
9. The similarity coefficient
$$d_{ab} = \sum_{1}^{n} R_i/n$$
where $R_i = X_{ia}/X_{ib}$ if $X_{ib} \geq X_{ia}$; or X_{ib}/X_{ia} if $X_{ia} > X_{ib}$; X_{ia} = the content of element i in sample a; X_{ib} = content of element i in sample b; and n = the number of elements.
10. I thank G. W. Nelson and M. E. Wacks for help with the analytical aspects of this research; the Arizona State Museum, Tucson, for the artifacts; Geodata Systems, Inc., for permission to collect turquoise samples on their property; and G. A. Borchardt for the use of his similarity coefficient program.

7 March 1975; revised 20 May 1975.

Climatic Change: Are We on the Brink of a Pronounced Global Warming?

Abstract. *If man-made dust is unimportant as a major cause of climatic change, then a strong case can be made that the present cooling trend will, within a decade or so, give way to a pronounced warming induced by carbon dioxide. By analogy with similar events in the past, the natural climatic cooling which, since 1940, has more than compensated for the carbon dioxide effect, will soon bottom out. Once this happens, the exponential rise in the atmospheric carbon dioxide content will tend to become a significant factor and by early in the next century will have driven the mean planetary temperature beyond the limits experienced during the last 1000 years.*

The fact that the mean global temperature has been falling over the past several decades has led observers to discount the warming effect of the CO_2 produced by the burning of chemical fuels. In this report I present an argument to show that this complacency may not be warranted. It is possible that we are on the brink of a several-decades-long period of rapid warming. Briefly, the argument runs as follows. The ^{18}O record in the Greenland ice core (*1*) strongly suggests that the present cooling is one of a long series of similar natural climatic fluctuations. This cooling has, over the last three decades, more than compensated for the warming effect produced by the CO_2 released into the atmosphere as a by-product of chemical fuel combustion. By analogy with similar events in the past, the present natural cooling will, however,

bottom out during the next decade or so. Once this happens, the CO_2 effect will tend to become a significant factor and by the first decade of the next century we may experience global temperatures warmer than any in the last 1000 years. The remainder of this report will be devoted to the elaboration of the assumptions used in constructing the curves shown in Fig. 1 which displays this projection.

Of the climatic effects induced by man, only that for CO_2 can be conclusively demonstrated to be globally significant. It is difficult to determine the significance of the next most important climatic effect induced by man, "dust," because of uncertainties with regard to the amount, the optical properties, and the distribution of man-made particles (*2, 3*). Man-made heat currently runs a poor third to CO_2 and dust. Its effects will, for at least a few decades, remain entirely local (*4*). In this report only the interaction of the CO_2 effect and natural climatic change is considered. As other anthropogenic effects are shown to be significant and as means to quantitatively predict their future influence on global temperatures are developed, they can be included in models such as this. Meanwhile it is important to consider the potential impact of the two causes of change for which we do have quantitative information.

A number of people have made estimates of the change in global temperature that would result if the atmospheric CO_2 content were to double. These estimates range from 0.8° to 3.6°C. Manabe and Wetherald's value (*5*) of 2.4°C, based on a model assuming fixed relative humidity and cloudiness, is the most widely used. The difference between this estimate and that of 0.8°C by Rasool and Schneider (*3*) has been largely resolved. When an improved infrared radiation scheme is introduced into the Manabe-Wetherald calculation, the result drops to 1.9°C (*6*). However, Manabe and Wetherald (*6*) have suggested, on the basis of some preliminary three-dimensional calculations, that the effect in polar regions is much larger than for the "typical" atmospheric column. This polar amplification leads to an enhancement of the global effect, bringing the value up to somewhat above 2.4°C. Although surprises may yet be in store for us when larger computers and a better knowledge of cloud physics allow the next stage of the modeling to be accomplished, the magnitude of the CO_2 effect has probably been pinned down to within a factor of 2 to 4 (*7*).

The response of the global temperature to the atmospheric CO_2 content is not linear. As the CO_2 content of the atmosphere rises, the absorption of infrared radiation will "saturate" over an ever greater portion of the band. Rasool and Schneider (*3*) point out that the temperature increases as the logarithm of the atmospheric CO_2 content. Thus, if doubling of the CO_2 content raises the temperature by 2.4°C, then a 10 percent increase in the CO_2 content will raise the temperature by 0.32°C.

Table 1. Reconstruction and prediction of atmospheric CO_2 contents based on fuel consumption data.

Year	Chemical fuel CO_2 ($\times 10^{16}$ g)	Excess atmospheric CO_2* ($\times 10^{16}$ g)	Excess atmospheric CO_2 (%)	Excess atmospheric CO_2 (ppm)	CO_2 content of the atmosphere† (ppm)	Global temperature increase‡ (°C)
1900	3.8	1.9	0.9	2	295	0.02
1910	6.3	3.1	1.4	4	297	.04
1920	9.7	4.8	2.2	6	299	.07
1930	13.6	6.8	3.1	9	302	.09
1940	17.9	8.9	4.1	12	305	.11
1950	23.3	11.6	5.3	16	309	.15
1960	31.2	15.6	7.2	21	314§	.21
1970	44.0	22.0	10.2	29	322§	.29
1980‖	63	31	14	42	335	.42
1990‖	88	44	20	58	351	.58
2000‖	121	60	28	80	373	.80
2010‖	167	83	38	110	403	1.10

*On the assumption that 50 percent of the CO_2 produced by the burning of fuel remains in the atmosphere. †The preindustrial atmospheric partial pressure of CO_2 is assumed to be 293 ppm. ‡Assumes a 0.3°C global temperature increase for each 10 percent rise in the atmospheric CO_2 content. §Value observed on Hawaii for 1960, 314 ppm; value for 1970, 322 ppm (*8*). ‖Post-1972 growth rate taken to be 3 percent per year.

With respect to the amounts of CO_2 to be expected in the atmosphere, we are in a position to make fairly accurate estimates. Measurements carried out by Keeling and his co-workers on the island of Hawaii over the past 15 years suggest that the CO_2 content of the atmosphere rose an average of 0.7 part per million (ppm) per year from 1958 to 1972 (*8*). Had all the CO_2 generated by the burning of chemical fuels remained in the atmosphere, the rate of increase in the atmospheric CO_2 content should have been about 1.5 ppm/year. Thus, about half of the CO_2 added to the atmosphere is seemingly being removed to the sea (through combination with the CO_3^{2-} ion) and to the terrestrial biosphere (through enhanced photosynthesis). Calculations based on the model of Broecker *et al.* suggest that uptake by the sea can account for the removal of 35 ± 10 percent of the CO_2 produced (*9*). Other investigators (*10*), using oceanic mixing models which neglect short-term transfer between the surface ocean and the main oceanic thermocline, conclude that considerably smaller fractions of the CO_2 have gone into the ocean. In order to match the observed rate of increase in the atmospheric CO_2 content, these authors are required to put what I consider to be an inordinately large part of the CO_2 into the terrestrial biosphere. If the ocean is currently the main sink for the "missing" CO_2, the models suggest that, if our CO_2 production continues to increase at the rate of several percent per year, the fraction of this CO_2 remaining in the atmosphere will remain nearly constant over the next several decades (*9*). If, on the other hand, a major fraction of the chemical fuel CO_2 is being removed to the terrestrial biosphere, we are not in as good a position to state how the distribution coefficient between the atmosphere and other reservoirs will change with time. On the time scale of a few dec-

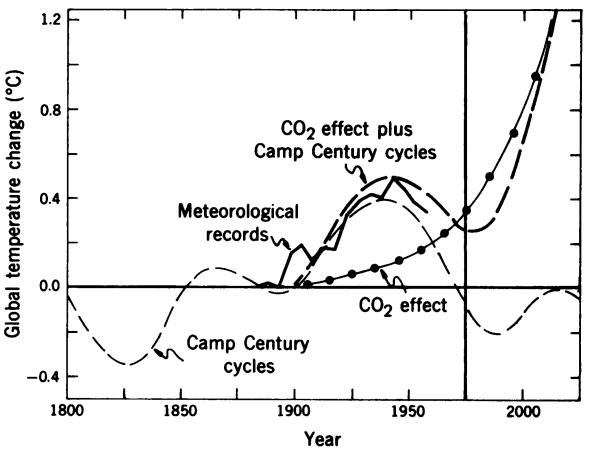


Fig. 1. Curves for the global temperature change due to chemical fuel CO_2, natural climatic cycles, and the sum of the two effects. The measured temperature anomaly for successive 5-year means from meteorological records over the last century is given for comparison.

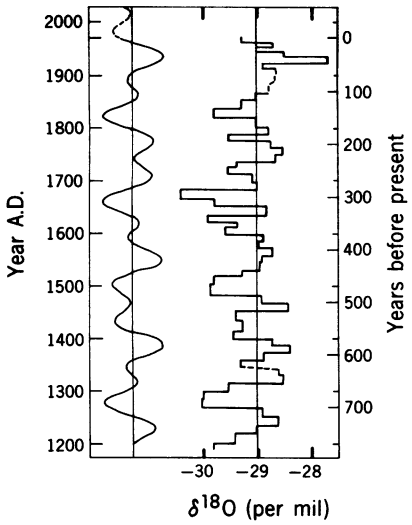


Fig. 2. Difference (per mil) between the $^{18}O/^{16}O$ ratio in decade composites of Greenland ice from the Camp Century site and mean ocean water as obtained by Dansgaard and his co-workers (*1*). A decrease of 1 per mil in the ^{18}O content corresponds to a 1.5°C drop in air temperature. The curve on the left is the simulation of the isotope curve obtained by combining sinusoidal curves with periods of 80 and 180 years.

ades, however, there is no reason to believe that it will change greatly.

The global temperature increase due to CO_2 in Fig. 1 is calculated on the basis of the following assumptions: (i) 50 percent of the CO_2 generated by the burning of chemical fuels has in the past and will in the near future remain in the atmosphere; (ii) the United Nations fuel consumption estimates are used to 1960 (*11*); between 1960 and 1975 a growth rate of 4.5 percent per year is used, and from 1975 on a 3 percent growth rate is predicted; (iii) for each 10 percent increase in the atmospheric CO_2 content the mean global temperature increases by 0.3°C. These calculations are summarized in Table 1.

Meteorological records of the mean global temperature are adequate only over the last century. The mean global temperature (successive 5-year means) obtained from these records by Mitchell (*12*) is given in Fig. 1. From this record alone little can be said about the causes of climatic fluctuations. It is too short and may be influenced by pollution. Obtaining comparable information from historic and natural records for previous centuries has proved very difficult. There is no simple relation between the indices used and the temperature, and regional noise tends to mask the global picture. In my estimation the only existing record which may give a picture of the natural fluctuations in global temperature over the last 1000 years is that from the ice core taken at Camp Century in northwestern Greenland. The air temperature over this site is being recorded in terms of the ratio of ^{18}O to ^{16}O in the snow which falls. Because of the polar amplification of global climatic changes [noted both in this century's meteorological records (*12*) and in models (*6*)], a strong signal emerges from the regional noise. Measurements on snow generated over a range of polar temperatures show that for each 1°C of cooling the ^{18}O content of the precipitation drops by about 0.7 per mil (*13*). The time scale is obtained by extrapolation of the accumulation rates established by counting seasonal couplets (*14*). The widely quoted results of Dansgaard and his coworkers of measurements on the Camp Century core (*1*) are reproduced in Fig. 2. Clearly the fluctuation in global temperature documented by meteorological observations over the last century is not unique; similar changes have occurred in a more or less regular fashion throughout the last 1000 years. Dansgaard and his co-workers have shown by power spectral techniques that cycles of 80 and 180 years appear in this record. The model curve to the left of the isotopic curve (Fig. 2) is their best fit to the data based on the use of only 80- and 180-year cycles.

The amplitude of the last half "cycle" in Greenland (1900 to 1940) as recorded in the ice is about the same as that recorded by meteorological observations (both give about 1.5°C warming) (*2, 3*). Also the ice core record is roughly in phase with the global change recorded meteorologically. Consistent with the Manabe-Wetherald model (*6*), the amplitude of the temperature change in the polar region is several times larger than the global average.

The curve of natural fluctuations drawn in Fig. 1 was obtained as follows. The pattern of the fluctuations is that obtained by Dansgaard and his co-workers (*1*), assuming that the 80- and 180-year periods dominate the natural record. The amplitude of the curve is reduced so that, when summed with the CO_2 effect, it yields a reasonable match to the global temperature curve for the last century (that is, a fourfold reduction due to polar amplification is made).

Table 2. Projections based on an analogy to individual Camp Century cycles over the last 800 years.

Warm peak No.*	Years to next cold minimum*	Projected date for next cold minimum
1	40	1980
2	25	1965
3	40	1980
4	35	1975
5	55	1995
6	30	1970
7	25	1965
8	35	1975
9	35	1975
Mean	35	1975
Simulation†	50	1990

*See Fig. 3. †See Fig. 2.

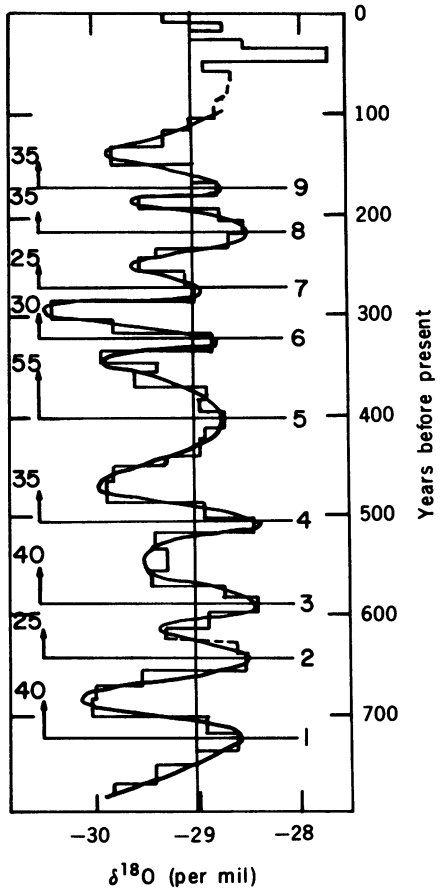


Fig. 3. Spacings between warm maxima and cold minima for the "smoothed" Camp Century ice core ^{18}O curve.

The resultant curve obtained by combining the CO_2 effect with the simulated natural curve shows dramatically what will happen if the natural cooling trend bottoms out and swings into the next warming phase according to the schedule postulated here. Global temperature would begin a dramatic rise which would continue for about four decades (that is, half the 80-year cycle). This warming would by the year 2000 bring average global temperatures beyond the range experienced during the last 1000 years. Until chemical fuel consumption is dramatically reduced, global temperatures would continue to rise. Future natural cycles would merely modulate this ever-steepening rise (40-year periods of more rapid increase followed by 40-year periods of less rapid increase).

Although the details of the argument presented here depend largely on the results of Dansgaard *et al.* (*1*), simulation of the Camp Century cycles, the sense of the argument, is not dependent on these results. As shown in Fig. 3 and Table 2, a similar conclusion with regard to the timing of the forthcoming natural minima would be reached by analogy with almost

any portion of the Greenland record over the last 700 years. If anything, the simulation puts the next minimum farther into the future than would estimates based strictly on analogies with previous "cycles." Thus, whereas the exact date of the minimum shown in the extended natural climate curve (Fig. 1) is uncertain, its occurrence in the next decade is probable. The rate of warming beyond the minimum is also open to question. As the CO_2 effect will dominate, the uncertainty here lies mainly in the estimates of future chemical fuel use and in the magnitude of the warming per unit of excess atmospheric CO_2. The major point of the argument is that over the past 30 years the warming trend due to CO_2 has been more than countered by a natural cooling. This compensation cannot long continue both because of the rapid growth of the CO_2 effect and because the natural cooling will almost certainly soon bottom out. We may be in for a climatic surprise. The onset of the era of CO_2-induced warming may be much more dramatic than in the absence of natural climatic variations.

The agricultural consequences of this ensuing warming are not obvious (neither are the implications to global sea level). A knowledge of the mean global temperature tells us little about the rainfall patterns in the chief grain-producing regions. There is little doubt, however, that this gradual warming will lead to changes in the pattern of global precipitation. Our efforts to understand and eventually to predict these changes must be redoubled.

WALLACE S. BROECKER
Lamont-Doherty Geological Observatory and Department of Geological Sciences, Columbia University, Palisades, New York 10964

References and Notes

1. W. Dansgaard, S. J. Johnson, H. B. Clausen, C. C. Langway, Jr., in *Late Cenozoic Glacial Ages*, K. K. Turekian, Ed. (Yale Univ. Press, New Haven, Conn., 1971), p. 37; W. Dansgaard, S. J. Johnsen, H. B. Clausen, N. Gundestrup, *Medd. Grønland* **197** (No. 2), 1 (1973).
2. S. H. Schneider and W. W. Kellogg, in *Chemistry of the Lower Atmosphere*, S. I. Rasool, Ed. (Plenum, New York, 1973), p. 203; G. Yamamoto and M. Tanaka, *J. Atmos. Sci.* **29**, 1405 (1972); R. A. Bryson, *Weatherwise* **21**, 56 (1968); *Climatic Modification by Air Pollution, II: The Sahelian Effect* (Institute for Environmental Studies, University of Wisconsin, Madison, 1973); *Science* **184**, 753 (1974); J. M. Mitchell, Jr., in *Global Effects of Environmental Pollution*, S. F. Singer, Ed. (Reidel, Dordrecht, Netherlands, and Springer-Verlag, New York, 1968); in *Man's Impact on the Climate*, W. H. Matthews, W. W. Kellogg, G. D. Robinson, Eds. (MIT Press, Cambridge, Mass., 1971), pp. 133 and 167; W. W. Kellogg and S. H. Schneider, *Science* **186**, 1163 (1974).
3. S. I. Rasool and S. H. Schneider, *Science* **173**, 138 (1971).
4. S. H. Schneider and R. D. Dennett, *Ambio* **4**, 65 (1975).
5. S. Manabe and R. T. Wetherald, *J. Atmos. Sci.* **24** 786 (1967).
6. S. Manabe, in *Man's Impact on the Climate*, W. H. Matthews, W. W. Kellogg, G. D. Robinson, Eds. (MIT Press, Cambridge, Mass., 1971), p. 238; S. Manabe and R. T. Wetherald, *J. Atmos. Sci.* **32**, 3 (1975).
7. S. H. Schneider, *J. Atmos. Sci.*, in press.
8. C. A. Ekdahl, Jr., and C. D. Keeling, in *Carbon and the Biosphere*, G. M. Woodwell and E. V. Pecan, Eds. (Technical Information Center, Office of Information Services, U.S. Atomic Energy Commission, Washington, D.C., 1973), p. 51.
9. W. S. Broecker, Y.-H. Li, T.-H. Peng, in *Impingement of Man on the Oceans*, D. W. Hood, Ed. (Wiley, New York, 1971), p. 287.
10. B. Bolin and E. Eriksson, in *The Atmosphere and the Sea in Motion, Rossby Memorial Volume*, B. Bolin, Ed. (Rockefeller Institute Press, New York, 1959), p. 130; L. Machta, in *The Changing Chemistry of the Oceans*, Proceedings of the 20th Nobel Symposium, D. Dryssen and D. Jagner, Eds. (Wiley, New York, 1972), p. 121; C. D. Keeling, in *Chemistry of the Lower Atmosphere*, S. I. Rasool, Ed. (Plenum, New York, 1973), chap. 6; L. Machta, in *Carbon and the Biosphere*, G. M. Woodwell and E. V. Pecan, Eds. (Technical Information Center, Office of Information Service, U.S. Atomic Energy Commission, Washington, D.C., 1973), p. 21; R. Bacastow and C. D. Keeling, *ibid.*, p. 86.
11. United Nations, *World Energy Supplies Statistical Papers*, Series J (United Nations, New York, 1950–1959).
12. J. M. Mitchell, *Arid Zone Monograph 20* (UNESCO, Paris, 1963), pp. 161–181.
13. W. Dansgaard, *Tellus* **16**, 436 (1964); L. Merlivat and C. Lorius, *Recherche (Paris)* **4** (No. 34), 457 (1973).
14. S. J. Johnsen, W. Dansgaard, H. B. Clausen, C. C. Langway, Jr., *Nature (Lond.)* **235**, 429 (1972).
15. Conversations with Steve Schneider of the National Center for Atmospheric Research were very helpful in straightening out questions I had with regard to varying estimates of the effects of CO_2 and dust. This work was supported by contract AT(11-1)2185 with the U.S. Atomic Energy Commission. This is contribution No. 2248 from the Lamont-Doherty Geological Observatory.

10 March 1975; revised 7 May 1975

Chlorinated Hydrocarbon Pollutants and Photosynthesis of Marine Phytoplankton: A Reassessment

Abstract. *The chlorinated hydrocarbons DDT and PCB's (polychlorinated biphenyls), ubiquitous pollutants of the marine environment, have been observed to reduce the cell division rate of marine phytoplankton, thereby indirectly reducing the total photosynthetic carbon fixation in treated cultures. The photosynthetic capacity of each cell was not affected. Total marine photosynthesis will likely remain undiminished by these compounds, although alterations in phytoplankton communities through selective toxicity could affect herbivore populations.*

Several persistent and ubiquitous chlorinated hydrocarbon pollutants of the marine environment, most notably PCB's (polychlorinated biphenyls) and DDT [1,1,1-trichloro-2,2-bis(*p*-chlorophenyl)ethane], can reduce the growth rate (*1, 2*) and have been reported to reduce photosynthesis (*2–4*) in some marine phytoplankton cultures. The decrease in carbon fixation observed in treated cultures (*2–4*), as measured by the incorporation of ^{14}C-labeled bicarbonate, could have resulted from an inhibition of the photosynthetic process itself, or it may have been due to a depressed growth rate, that is, fewer cells photosynthesizing in treated than in control cultures.

I conducted an experiment to determine whether algal photosynthesis on a per cell basis, as well as on a per culture basis, was affected by PCB's or DDT. The organochlorine concentrations used were above those found in natural waters (*5*); no attempt was made to determine the toxicity of environmentally realistic concentrations of these compounds, as was done elsewhere (*6*). The purpose of this study was to establish whether, in algae, photosynthetic carbon fixation itself is inhibited or whether just growth is affected by these chemicals.

The three algal species studied (*7*) were selected on the basis of their sensitivity to chlorinated hydrocarbons: the growth of *Thalassiosira pseudonana* and *Skeletonema costatum*, common marine diatoms, is affected by PCB's and DDT (*1*), and photosynthetic carbon fixation in cultures of *Coccolithus huxleyi* and the two diatoms is reportedly reduced by DDT (*2, 3*). Culture conditions and procedures have been described elsewhere (*8*). Methanolic solutions of PCB's (Aroclor 1254) or DDT were injected (*1*) into the cell suspensions at time zero to give initial PCB concentrations of 10 μg/liter (parts per billion) and DDT concentrations of 50 ppb in the medium. Equal volumes of methanol were added to the control cultures (*9*). These organochlorine compounds, at similar concentrations (or doses per cell), have been reported to substantially depress the net carbon fixation in monocultures of these algal species (*2, 3*). At 48 hours, 1 ml of medium was removed from each tube so that cell counts could be determined (*10*), 0.2 μc of [^{14}C]$NaHCO_3$ was added (*11*), and the cultures were incubated as before for about 5 hours. The same procedure was also carried out for dark controls. The cells were then gently filtered through 0.8-μm Millipore filters and washed with filtered seawater; the radioactivity of the filters was counted in a liquid scintillation counter (Tri-Carb, Packard). The entire experiment was repeated with the two diatom species.

Table 1 presents the 48-hour cell counts, photosynthetic carbon fixation per culture, and carbon uptake per cell (α). The dark uptake of ^{14}C, which varied with each species (being 2 percent of the illuminated *T. pseudonana* ^{14}C uptake, less than 1 percent with *S. costatum*, and 10 percent with *C. huxleyi*), was subtracted from the raw

Annex 23

"Second Status Report of the IIASA Project on Energy Systems 1975", *International Institute for Applied Systems Analysis,* 1975, pages 134-148

Research-Report
RR-76-1

SECOND STATUS REPORT OF THE IIASA PROJECT ON ENERGY SYSTEMS 1975

W. Häfele et al.

Research Reports provide the formal record of research conducted by the International Institute for Applied Systems Analysis. They are carefully reviewed before publication and represent, in the Institute's best judgment, competent scientific work. Views or opinions expressed herein, however, do not necessarily reflect those of the National Member Organizations supporting the Institute or of the Institute itself.

International Institute for Applied Systems Analysis
2361 Laxenburg, Austria

PREFACE

This is the written version of the second status report of the IIASA Project on Energy Systems. (The oral version was presented in October in Laxenburg, Austria, and later in Varna, Bulgaria.) By its nature, it is intended as an insight into the present status of the work of the energy project, not as a comprehensive book or a set of results that are final in one way or other.

The IIASA energy project began in the summer of 1973 and we expect it to continue until the end of 1978. Thus nearly half of the time available to us has elapsed. During this first period we focused on the conceptualization of the systems aspects of the energy problem. Now, the energy project is beginning to concentrate on a number of more specific and operational tasks.

The Introduction provides both an explanation of the overall approach and the frame for the individual contributions, which cover certain aspects in greater depth. Notwithstanding my overall responsibility as project leader, each author is responsible for his own independent contribution. Yet it is clear that this status report represents the results of the energy team as a whole.

To finish such a comprehensive status report requires much devoted help. We owe thanks to many, particularly to Maria Helm for patiently dealing with each of us and for putting everything together.

Wolf Häfele

TABLE OF CONTENTS

		Page
Preface.		iii
Part 1.	Introduction Wolf Häfele	1
Part 2.	Energy Resources.	23
2.1	Coal: Resources and Constraints Michel Grenon.	24
2.2	A Bayesian Approach to Discrimination Among Models for Exploring Geological Bodies Jacques G. Gros.	52
Part 3.	Energy Demand	55
3.1	Econometric Analysis of Energy Demand at IIASA Plamen Tsvetanov	56
3.2	A Global Scenario Wolfgang Sassin.	72
Part 4.	Options for Energy Supply	89
4.1	Solar Energy Systems Consideration Charles R. Bell.	90
4.2	Some Aspects of the Solar Case Study Austria Norbert Weyss.	101
4.3	Energy Systems Embedding Jacques G. Gros.	118
Part 5.	Constraints	133
5.1	Possible Impacts of Waste Heat on Global Climate Patterns Wolf Häfele.	134
5.2	Risk Assessment Harry J. Otway, Philip D. Pahner, Friedrich Niehaus.	149

Page

Part 6. Strategies. 173

6.1 Transition Strategies--A Linear Programming Model
Leo Schrattenholzer. 174

6.2 Resilience for Energy Systems
Wolf Häfele. 186

6.3 Strategies and Decisions
Wolfgang Sassin. 191

6.4 On Strategies and Fate
Cesare Marchetti 203

Part 7. After the Transition Period?. 219

7.1 Geoengineering and the Energy Island
C. Marchetti 220

Annex
Background Information on the IIASA Energy Project. 245

PART 5. CONSTRAINTS

5.1 Possible Impacts of Waste Heat on Global Climate Patterns

Wolf Häfele

The IIASA Energy Project is making an attempt to identify and understand constraints for the large-scale production and handling of energy. The observation was made several times that the impacts of waste heat on global climate patterns might possibly establish one such constraint (see, e.g., [1]). A. Weinberg and R.P. Hammond of the Oak Ridge National Laboratory (ORNL) in Tennessee were the first to take initiative in this matter. In 1970 they worked out a waste heat release scenario and made it available to W. Washington of the National Center for Atmospheric Research (NCAR) in Boulder, Colorado [2]. Then it became possible to operate large global circulation models (GCM). We are, of course, aware of the limitations of GCM's--among them computer time, input data, and perhaps most of all the failure to consider a coupling with the dynamics of oceans--but one should nevertheless try out what tools are available. Figure 1 shows the result of these early calculations by W. Washington [3]. The assumption was made in that scenario that with today's population distribution, a total of 75Q/year was released to the atmosphere. Above northern Africa there is a temperature increase of $+6^{\circ}$/C, above Scandinavia a cooling of -8°/C and so on. The pattern of Figure 1 depicts the difference between cases with and without waste heat releases. It was taken for January, after a period of 40 to 60 days of simulated waste heat release. The values are averages over a period of about 10 days. The pattern looks like a change of weather patterns. To extrapolate from such weather averages to the climate remained an open problem. Nevertheless, the differences appeared to be large.
W. Washington then repeated the calculation for negative waste heat releases; the evolving pattern of weather changes appears to be qualitatively the same (see Figure 2). In addition, when a random error of between -2°/C and $+2^{\circ}$/C (surface temperature) instead of a waste heat release was introduced, a similar pattern again evolved (see Figure 3). This reveals the problem of the signal-to-noise ratio: all three experiments in part seem to involve noise, and the calculability of weather over a longer time period becomes the central problem.

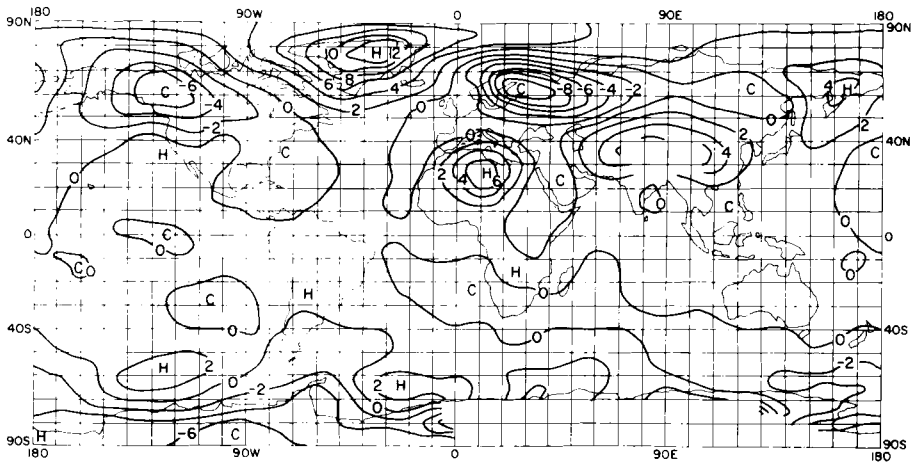


Figure 1. Positive thermal pollution
(Source: W. Washington, NCAR).

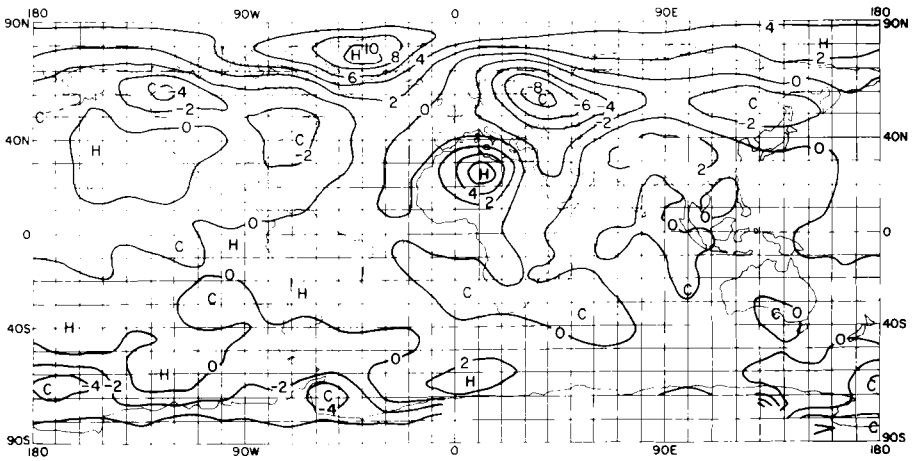


Figure 2. Negative thermal pollution
(Source: W. Washington, NCAR).

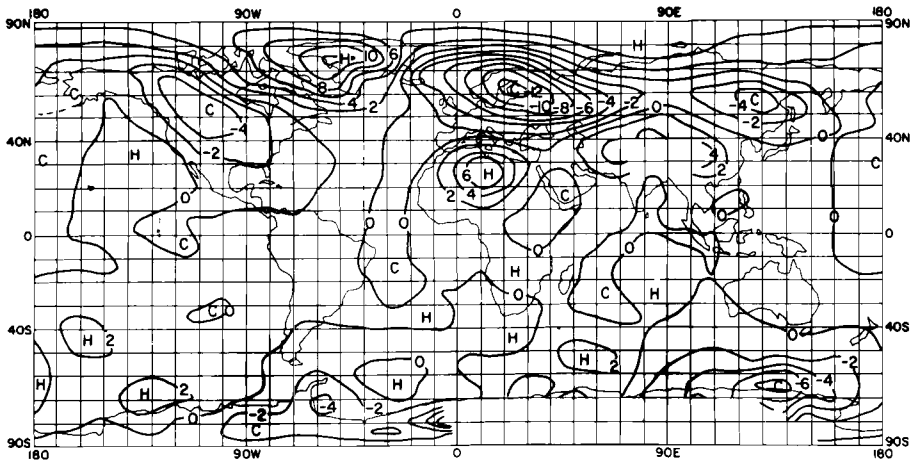


Figure 3. Random error experiment
(Source: W. Washington, NCAR).

The IIASA Energy Project wanted to understand these phenomena better because of the importance of waste heat releases as a possible constraint to energy strategies. Besides NCAR, the British Meteorological Office (BMO) at Bracknell, Herts., U.K., also conducted such numerical experiments using its own GCM [4]; it was therefore natural for IIASA to establish contacts with the BMO as well as NCAR. Figure 4 shows the weather differences for the northern hemisphere in the case of a sea-surface anomaly east of Newfoundland. Here an area of $10^6/km^2$ releases heat in the order of some 10^{14} watts. The BMO also conducted random-error experiments, and again the problem of the signal-to-noise ratio appeared. The BMO was kind enough to make its GCM available to the IIASA Energy Project. Together with some routines for evaluations, it was made operational at the Kernforschungszentrum Karlsruhe. At IIASA we then proposed the following waste heat release scenario. Waste heat was released at only two places in the northern hemisphere (the underlying idea is the concept of large energy parks). The amount of waste heat in each case was chosen to be $1.5 \cdot 10^{14}$ watts. This is in line with the heat releases of the BMO experiment and is a high but not inconceivable upper limit for mankind's energy production ($2 \cdot 5Q$/year). The hope was to see an impact of waste heat

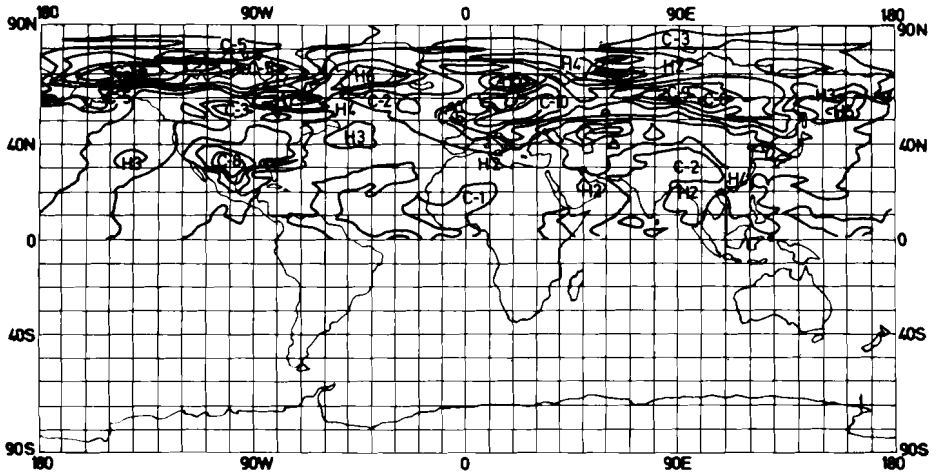


Figure 4. Positive thermal anomaly in Newfoundland (Source: BMO).

above a signal-to-noise ratio of one. Figure 5 shows the location that was chosen for the IIASA-1 experiment.

A second scenario was conceived (IIASA-2), in which the "energy park" east of Japan was retained while the one west of England was moved to equatorial regions west of Africa (see Figure 6). The amount of waste heat remained the same. In both areas the waste heat was released to the atmosphere and not to the waters. This is unrealistic, but the intention was to study an extreme and hypothetical case to find a discernible signal above noise level. In Figure 7 the grid-point configuration is given. For numerical reasons it was not possible to concentrate the entire release in one point. Instead, four points were chosen, representing power densities as indicated in the figure. Figure 8 thus shows the temperature distribution for the control random error experiment and experiments IIASA-1 and IIASA-2. Similar maps were drawn for pressure and wind velocities. Of particular interest are impacts on the precipitation pattern. We assume that this is a specially sensitive quantity and additionally of the utmost importance to any civilization. The precipitation results are thus given in Figure 9. Experiments IIASA-1 and IIASA-2 were conducted by A. Murphy of NCAR and C.H. Young, Bedford, Md., during their stay at IIASA.

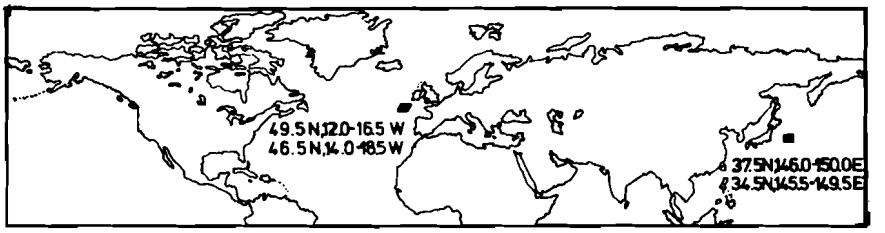


Figure 5. Locations of nuclear parks in Experiment IIASA–1.

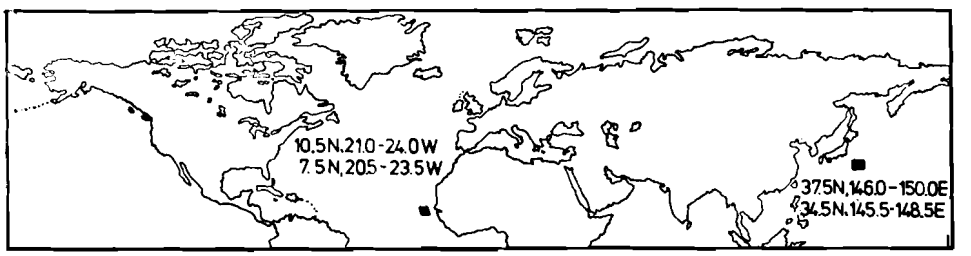


Figure 6. Locations of nuclear parks in Experiment IIASA–2.

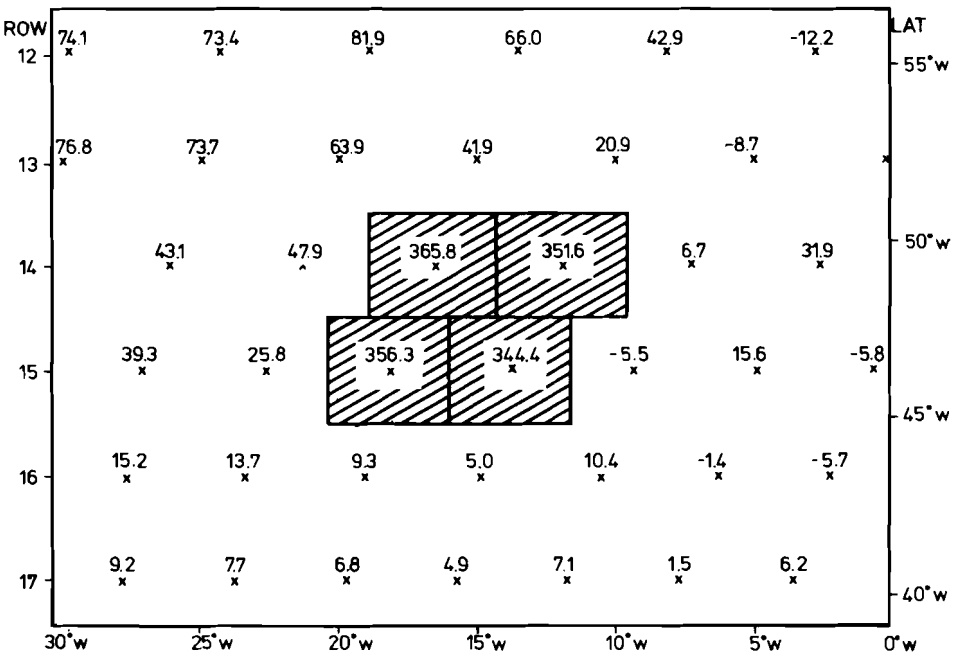


Figure 7. Atlantic Park – sensible heat values (watts · meter^{-2}).

With these results in hand we convened a small workshop of experts in April 1975. Our first impression from Figures 8 and 9 was confirmed: it is hard to see an effect that could be statistically significant and above noise level. At this workshop A. Murphy and A. Gilchrist decided to go a step further, relating the impact patterns not only to one reference case but to three cases by extracting the best σ^2 value from the latter. An average value for σ^2 from three experiments provides more information about the noise than one experiment. Figure 10 shows the precipitation results thus obtained for IIASA-1: this definitely seems to establish a clear signal above noise. There is a sharp decrease in precipitation over the Atlantic in the area of the park and Spain while the precipitation of Scandinavia is significantly enhanced. Figure 11 shows the related results for pressure changes.

The results of the IIASA-2 experiment with respect to pressure are shown in Figure 12. To facilitate comparison with the IIASA-1 case, we again give the IIASA-1 results for pressure in Figure 13 using the format of IIASA-2 results. It is interesting to note the seemingly smaller impact of this case. While we are fully aware of the complexities of these nonlinear mechanisms and hence the difficulties in drawing conclusions from such results, they should nevertheless be noted. IIASA will continue to explore these matters.

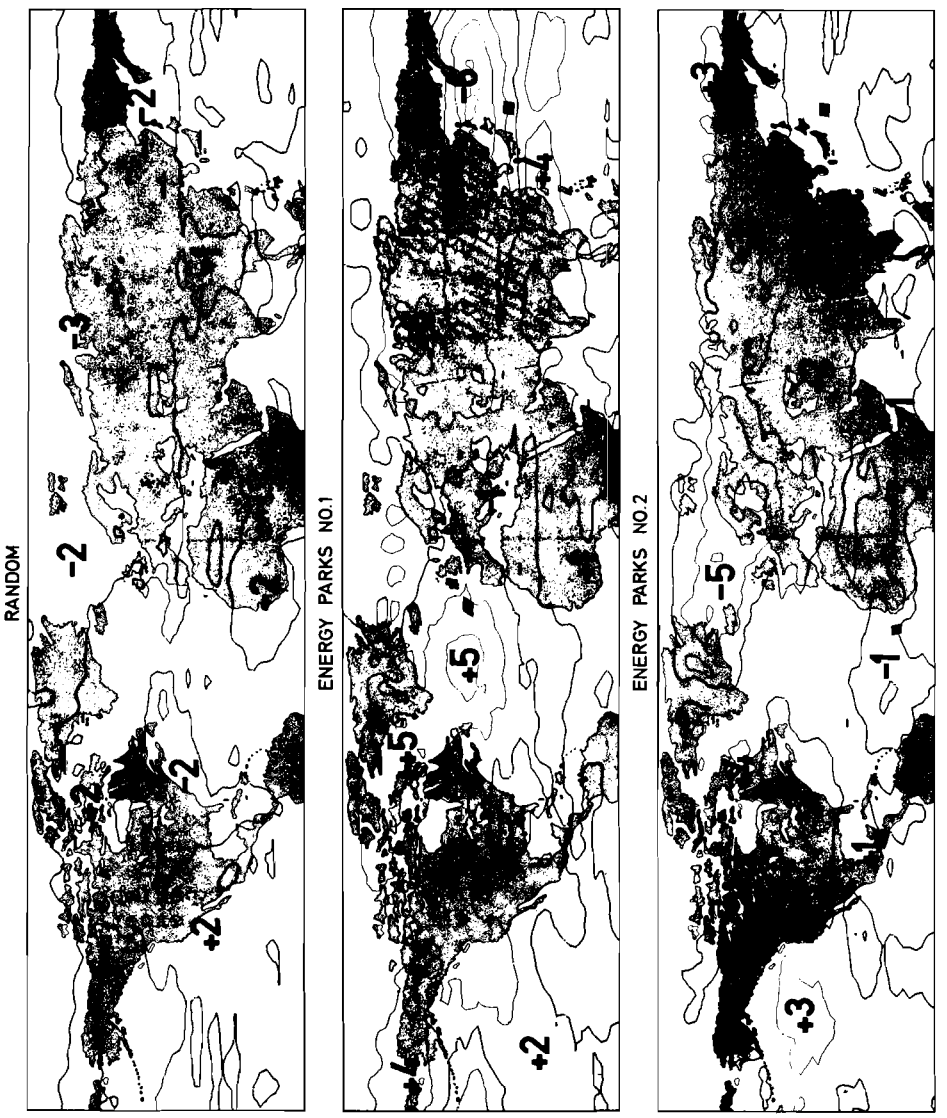

RANDOM
ENERGY PARKS NO.1
ENERGY PARKS NO.2
DIFFERENCES IN TEMPERATURE AT σ = 0.5 (T 5) WITH RESPECT TO CONTROL EXPERIMENT
(AVERAGE : DAYS 41-80, UNIT : °C, LIGHT/HEAVY ISOTHERMS : 2°C / 10°C)

Figure 8.

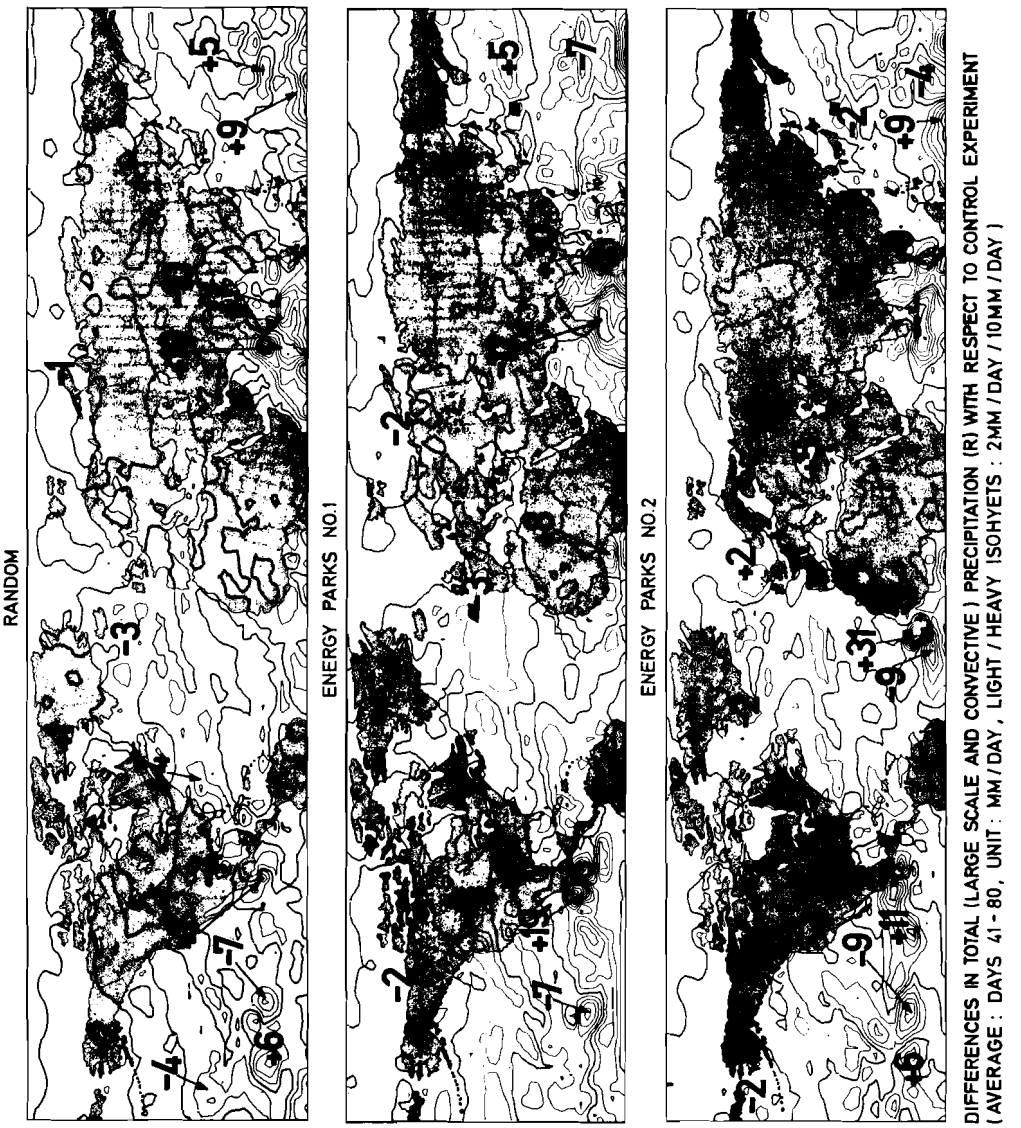

RANDOM
ENERGY PARKS NO.1
ENERGY PARKS NO.2
DIFFERENCES IN TOTAL (LARGE SCALE AND CONVECTIVE) PRECIPITATION (R) WITH RESPECT TO CONTROL EXPERIMENT
(AVERAGE : DAYS 41-80, UNIT : MM/DAY, LIGHT / HEAVY ISOHYETS : 2MM/DAY / 10MM/DAY)

Figure 9.

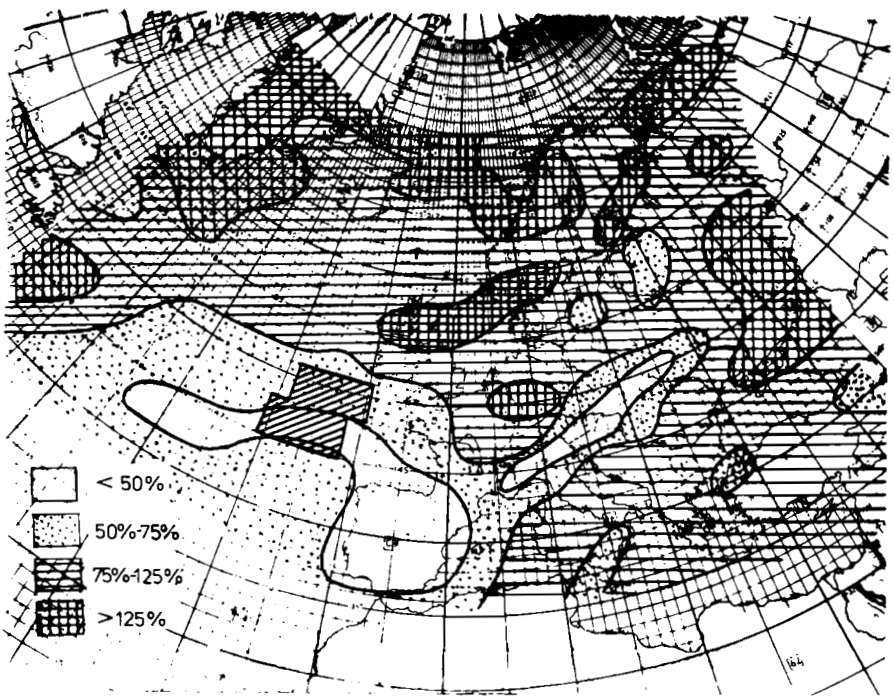


Figure 10. Ratio of rainfall with Atlantic Park and mean rainfall for three control integrations (day 41–80).

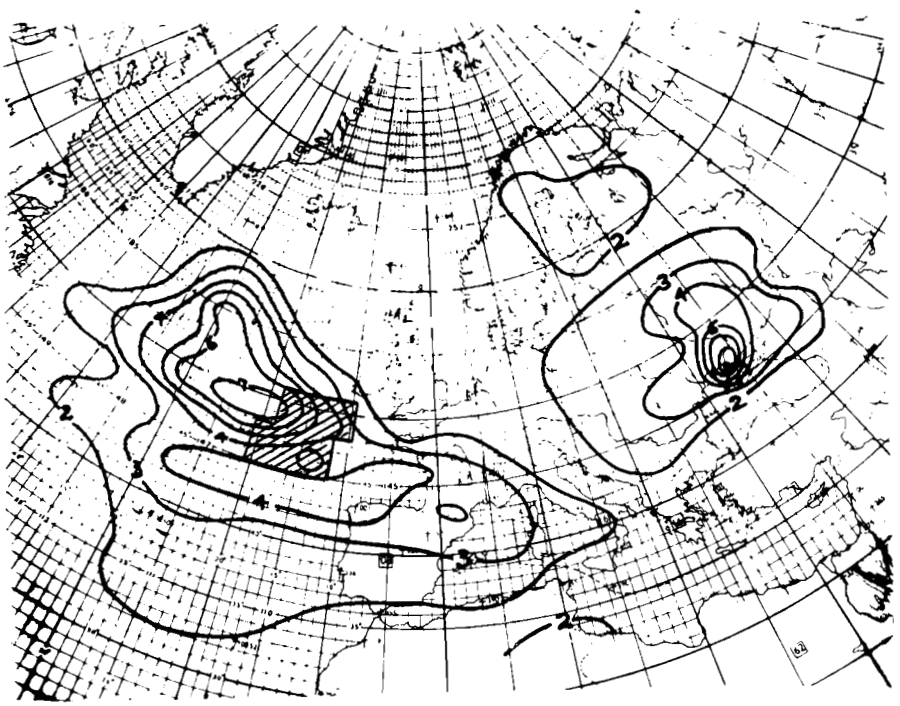


Figure 11. Ratio of surface pressure difference to range of surface pressure in controls.

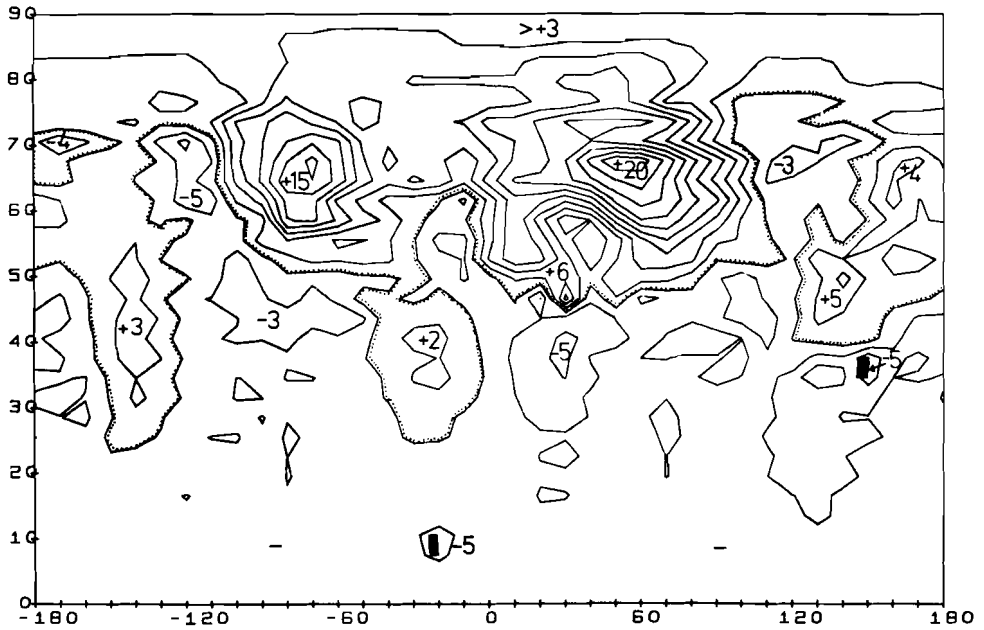


Figure 12. Differences in surface pressure with respect to average of controls–2 (average: days 41–80, unit: mb, isobars: 2mb).

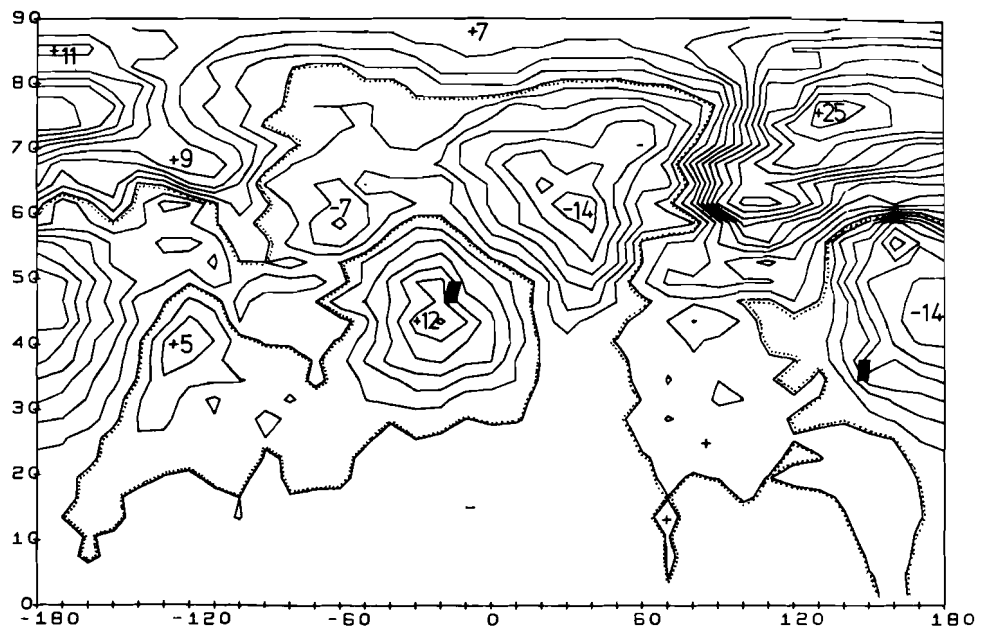


Figure 13. Differences in surface pressure with respect to average of controls–1. (average: days 41–80, unit: mb, isobars: 2mb).

It is now even more important to say a word about the truth value of these results. We rate it low because of the limitations inherent in the present GCM's. Rather, we interpret the results as a way of articulating the issue more clearly with the intention of thereby stimulating a larger long-range action of the meteorological community. In view of the importance of the underlying question, this seems to be necessary.

The IIASA Energy Group has received a contract from UNEP to carry these investigations further.

Waste heat releases pose a problem that is common to all sorts of primary energy production, conversion and use. Energy from fossil sources has a specific problem: the release of CO_2. Even if all other by-products, i.e. SO_2 or NO_x, were retained, CO_2 would still be released into the atmosphere. Increases in the CO_2 content of the atmosphere could lead to the so-called greenhouse effect, i.e. an increase in average global temperature to overcome the CO_2 infrared absorption barrier of the atmosphere. This has been estimated to be perhaps as high as 1 to 2°C for a doubling of the CO_2 content in the atmosphere, which would be enough to induce major climatic changes. Through these conceivable climatic changes, large-scale releases of CO_2 would create a risk. This risk, generated by fossil fuel waste disposal, may be considered in much the same sense as the risk from nuclear fuel waste disposal. Both should be evaluated by the same yardstick.

The problem of assessing the climatological consequences of the greenhouse effect are one side of the coin. More work is required as there are many other effects of a similar order of magnitude that compensate for each other [5].

The other side of the coin is a scenario for the release of CO_2 along with certain energy strategies. What are the orders of magnitude involved? W.D. Nordhaus extended his energy allocation model while he was at IIASA [6], allocating fossil and non-fossil fuel reserves to various markets of the world according to certain demands. Using the data of Machta [7], W.D. Nordhaus considers the CO_2 content and flow in the various layers of the atmosphere and the ocean; see Figure 14, where the CO_2 inputs the troposphere are also identified. In 1970 $2.8 \cdot 10^9$t/year of carbon was emitted, while the carbon content of the troposphere was at $51 \cdot 10^9$t. W. Sassin and W. Häfele considered a scenario [8] for a growing world population of ultimately $12 \cdot 10^9$ people, where an average of 5kW/capita is provided for each inhabitant using fossil energy. This implies a CO_2 disposal to the troposphere of $29 \cdot 10^9$t/year in the year 2020. Without further calculation, simply by looking at orders of magnitude as given in Figure 14, one realizes that there will be a problem of some sort. W.D. Nordhaus therefore considers a situation for standard maximum levels in the CO_2 content of the troposphere. This would finally lead to a limitation in the use of fossil fuels.

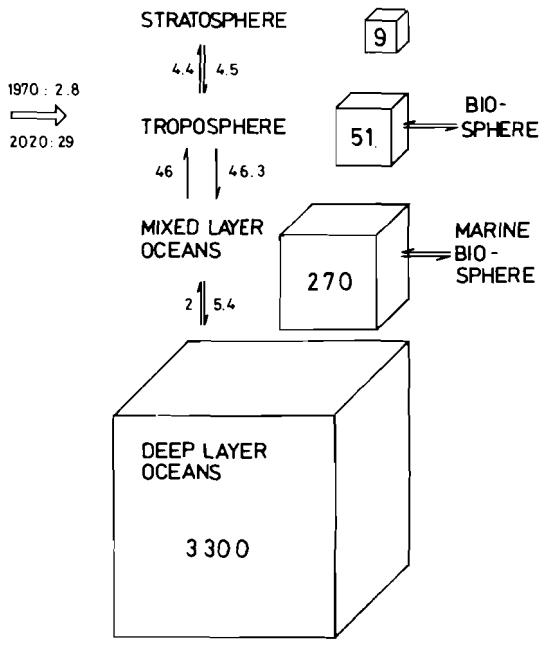


Figure 14. CO_2 reservoirs and CO_2 flow - C contents in 10^9 t, C flow rates in 10^9 t per year (1970 values) (Data: Ref. [7]).

The troposphere could fill up like a balloon, after which fossil power would have to be sharply reduced to values consistent with the rates of transfer from the troposphere to the upper layer of the ocean, and with those from the upper ocean layer to the deep seas. The latter rates are low and therefore so is the permissible fossil power in the scenario considered. Figure 15 gives W.D. Nordhaus' results for standards of CO_2 increases of 50 percent, 100 percent and 200 percent. Figure 16 then indicates the usable integrated amount of fossil fuel. Within the limits of the scenario considered, it appears that only a fraction of fossil resources could thus be used. This would necessitate the building up of non-fossil power as illustrated in Figure 17.

During 1975 R. Avenhaus together with G. Hartmann of the Kernforschungszentrum of Karlsruhe [9] also investigated the CO_2 problem. They considered the asymptotic equilibrium across the atmosphere and the ocean after a major input of man-made CO_2. There exists one condition for all contents and transfer coefficients involved, which can be used as a check for the consistency of measured data. All measured data but one can be used as input into this relation. If the transfer coefficient from the upper ocean layer to the deep sea were to be chosen as this one datum, for instance, one could compare the value

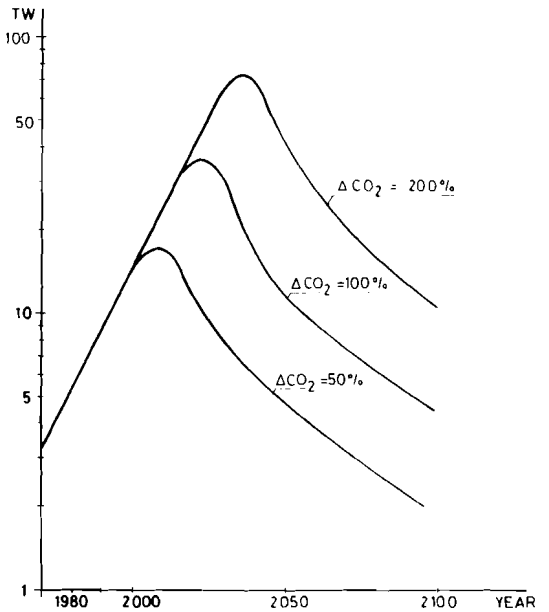


Figure 15. Necessary control of fossil energy consumption, if supplied in the form of coal, to stay below certain CO_2 levels in the troposphere (After: W.D. Nordhaus, IIASA).

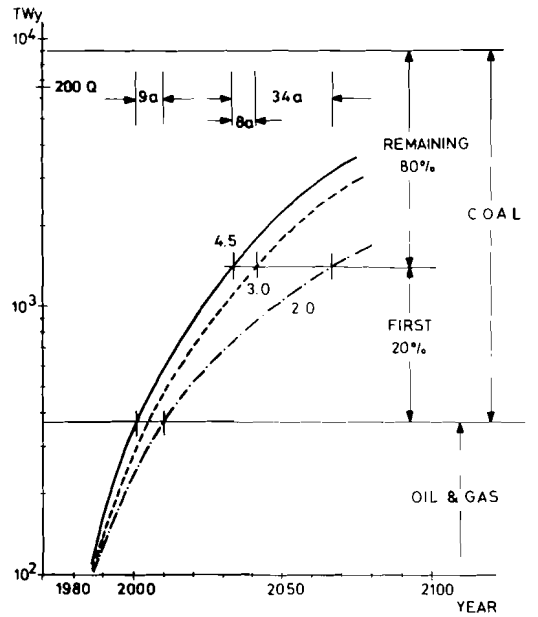


Figure 16. Fossil energy reserves and cumulated energy consumption.

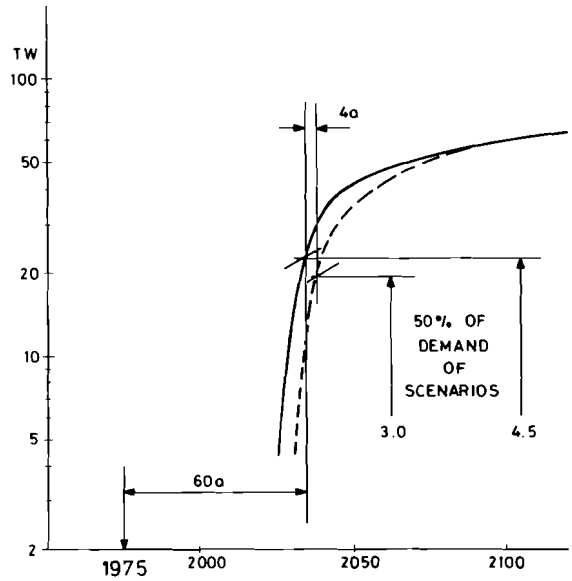


Figure 17. Required non–fossil power production: time for action.

required by the relation with the measured value. It appears that there are significant uncertainties. As this transfer coefficient is the smallest of all, thus dictating the time scale of adjustment to a new equilibrium, it is an important quantity and the uncertainty is relevant.

The interplay of scenario writing and evaluation with discipline-oriented groups is important. It provides brackets for the impacts that must be considered. In the case of the CO_2 problem, the brackets for the CO_2 increase to be tolerated are wide, one may say between 100 percent and 1,000 percent. It is therefore sufficient for the energy problem that the discipline-oriented groups study the greenhouse effect in such crude terms.

References

[1] Matthews, W.H., W.W. Kellogg and G.D. Robinson Eds. Man's Impact on the Climate. M.I.T. Press, Cambridge, Mass., 1971.

[2] Weinberg, A.M. and R.P. Hammond, "Global Effects of Increased Use of Energy," in Proceedings of Fourth International Conference on Peaceful Uses of Atomic Energy, September 6-16, 1971, Geneva. Volume 1, pp 171-184. United Nations/International Atomic Energy Agency, Vienna, 1972.

[3] Washington, W.M., "Numerical Climatic-Change Experiments: The Effect of Man's Production of Thermal Energy." Journal of Applied Meteorology, 11, 768-772, 1972.

[4] Rowntree, P.R., "Thermal and Orographic Forcing of the Northern Hemisphere Winter Circulation in a Numerical Model," in Proceedings of the WMO/IAMAP Symposium on Long Term Climatic Fluctuations, Climatic Research Unit, School of Environmental Sciences, University of East Anglia, Norwich, 1975. In preparation.

[5] Breyson, R.A., "'All Other Factors Being Constant...' - A Reconciliation of Several Theories of Climatic Change." Weatherwise, 56, April, 1968.

[6] Nordhaus, W., "Can We Control Carbon Dioxide?" Unpublished internal paper, International Institute for Applied Systems Analysis, Laxenburg, Austria, 1975.

[7] Machta, L., "The Role of the Oceans and Biosphere in the Carbon Dioxide Cycle." Nobel Symposium on The Changing Chemistry of the Oceans, August 1972, Göteborg, Sweden. John Wiley, New York, 1972, 121-145.

[8] Häfele, W. and W. Sassin, "Energy Strategies." Plenary Lecture, Third General Conference on Energy and Physics, Bucharest, September 9-12, 1975. To be published as a IIASA Research Memorandum and in Energy: The International Journal.

[9] Avenhaus, R. and G. Hartmann, "The Carbon Cycle of the Earth." RR-75-45, International Institute for Applied Systems Analysis, Laxenburg, Austria, 1975.

Annex 24

V. Ramanathan, “Greenhouse Effect Due to Chlorofluorocarbons: Climatic Implications”, *Science,* 1975, pp. 50-52

as an excursion. Genuine global paleomagnetic excursions can only be confirmed by evidence of spatial, temporal, and internal consistency in replicate cores or sampled sections from each of several areas. Until such evidence is available, it is premature to advocate the use of paleomagnetic excursions as magnetostratigraphic horizons.

KENNETH L. VEROSUB*
Departments of Geology and *Physics,*
Amherst College,
Amherst, Massachusetts 01002

References and Notes

1. N. A. Morner and J. P. Lanser, *Nature (Lond.)* **251**, 408 (1974).
2. M. Noel and D. H. Tarling, *ibid.* **253**, 705 (1975).
3. A complete review of all reported paleomagnetic excursions would require knowledge of the type of sediment sampled, the method of sampling, the signature of the excursion, the age and duration of the excursion, and the age and duration of overlying and underlying normal intervals. Such a review is not possible at present. Many reports are available only as abstracts of papers presented at meetings. In a few cases information has been disseminated solely as "personal communications" to other authors.
4. H. C. Clark and J. P. Kennett, *Earth Planet. Sci. Lett.* **19**, 267 (1973).
5. K. M. Creer, *ibid.* **23**, 34 (1974).
6. N. D. Opdyke, D. Ninkovich, W. Lowrie, J. D. Hays, *ibid.* **14**, 145 (1972).
7. J. C. Liddicoat and R. S. Coe, *Eos Trans. Am. Geophys. Union* **54**, 1075 (1973); *ibid.* **55**, 1109 (1974).
8. R. Nakajima, K. Yaskawa, N. Natsuhara, N. Kawai, S. Horie, *Nature (Lond.)* **244**, 8 (1973); K. L. Othburg, *EOS Trans. Am. Geophys. Union* **54**, 1075 (1973).
9. C. R. Denham and A. V. Cox, *Earth Planet. Sci. Lett.* **13**, 181 (1971).
10. M. Barbetti and M. W. McElhinny, *Nature (Lond.)* **239**, 327 (1972).
11. N. D. Opdyke, N. J. Shackleton, J. D. Hays, *EOS Trans. Am. Geophys. Union* **55**, 237 (1974).
12. M. W. McElhinny, *Paleomagnetism and Plate Tectonics* (Cambridge Univ. Press, London, 1973), pp. 83–89.
13. J. W. Graham, *J. Geophys. Res.* **54**, 131 (1954).
14. E. Antevs, *Am. Geogr. Soc. Res. Ser.* **11**, 1 (1922).
15. N. D. Watkins, *Earth Planet. Sci. Lett.* **4**, 341 (1968).
16. D. V. Kent, *Nature (Lond.)* **246**, 32 (1973); R. Løvlie, *Earth Planet. Sci. Lett.* **21**, 315 (1974).
17. J. Dymond, *Earth Planet. Sci. Lett.* **6**, 9 (1969).
18. An intermediate case of 50 percent remagnetization in a fold has been reported by N. Niitsuma, International Union of Geological Sciences International Geological Correlation Program Conference on Late Cenozoic Magnetostratigraphy, Tokyo and Otsu, Japan, 1974.
19. The importance of the "reinforcement syndrome" [N. D. Watkins, *Geol. Soc. Am. Bull.* **83**, 551 (1972)] should not be underestimated. The initial report of a paleomagnetic excursion will encourage other workers to reexamine previously unexplained or disregarded "curious" results and to reinterpret sedimentation rates so that the anomalous behavior seen by them is contemporaneous with the paleomagnetic excursion. Subsequent work will also focus on sediments of the same age. Reported excursions will then tend to cluster around a single date, whereas negative results showing no anomalous behavior will tend to remain unpublished because they are "not interesting." Thus the initial reports exert considerable leverage on the direction of future research.
20. Supported by NSF grant GA-43344. I thank Dr. C. E. Helsley and his colleagues at the University of Texas-Dallas and Dr. J. deBoer at Wesleyan University for the use of their paleomagnetic facilities. I thank Dr. C. R. Denham for useful criticisms of the manuscript.
* Present address: Department of Geology, University of California, Davis 95616.

24 March 1975

Greenhouse Effect Due to Chlorofluorocarbons: Climatic Implications

Abstract. *The infrared bands of chlorofluorocarbons and chlorocarbons enhance the atmospheric greenhouse effect. This enhancement may lead to an appreciable increase in the global surface temperature if the atmospheric concentrations of these compounds reach values of the order of 2 parts per billion.*

It has recently been suggested (*1, 2*) that atmospheric concentrations of chlorofluorocarbons (CF_2Cl_2 and $CFCl_3$) may increase by as much as 20 to 30 times the present-day value, 0.1 part per billion (ppb) by volume, if the present level of injection into the atmosphere is maintained. The primary reason for this expected buildup seems to be the lack of any significant tropospheric removal mechanisms for these compounds. In addition, Lovelock's (*3*) recent measurements indicate substantial concentrations ($\approx$ 0.1 ppb) of CCl_4 within the troposphere, and Lovelock suggests the presence of other chlorocarbons ($CHCl_3$, CH_3Cl, and CH_2Cl_2) within the atmosphere. The consequences of a significant buildup of these compounds for the chemical balance of the atmosphere has already been investigated (*1, 2, 4*). In this report I examine another important aspect of the problem, the impact on the overall thermal energy balance of the earth-atmosphere system due to a significant buildup in the concentrations of the chlorofluorocarbons and chlorocarbons.

The chlorofluorocarbons and chlorocarbons have strong infrared bands (*5–8*). The infrared bands of these compounds would absorb radiation from the surface and emit it at the atmospheric temperature. Since the atmosphere is at a lower temperature than the earth's surface, these bands would cause a reduction in the net infrared radiative flux (F, watts per square meter) emitted to space by the earth-atmosphere system. This trapping of the surface radiation by the infrared bands, also known as the greenhouse effect, would tend to increase the surface and atmospheric temperature. The strongest bands of these compounds are located in the spectral region 8 to 13 μm where the atmosphere is relatively transparent. Because of this relative transparency, the atmospheric and surface temperatures are most sensitive to constituents that have absorption bands in this spectral region. In order to estimate the increase in the surface temperature (T_s), the reduction in F due to the infrared bands of the chlorofluorocarbons and chlorocarbons is computed first. The procedure for the flux calculation is described only for chlorofluorocarbon bands since the same procedure can be applied to the chlorocarbon bands.

Table 1. Chlorofluorocarbon band positions and intensities.

Species	Band			
	Assignment	Center (μm)	Intensity (cm/mole)	Reference
CF_2Cl_2	ν_1	9.132	2.98×10^7	(*5*)
	ν_6	8.681	2.0×10^7	(*5*)
	ν_8	10.93	3.07×10^7	(*5*)
$CFCl_3$	ν_1	9.217	1.75×10^7	(*6*)
	ν_4	11.82	3.75×10^7	(*6*)

For this analysis I consider only bands in the region 8 to 12 μm, since these bands are stronger by two orders of magnitude than bands located elsewhere in the infrared spectrum (*5–8*). Table 1 shows the band centers and intensities. Radiative transfer within infrared bands can be conveniently formulated in terms of the total band absorptance, A (reciprocal centimeters) (*9, 10*). This is the total spectrally integrated absorption by the band, and for the present analysis the bands are optically thin (*11*), so A can be written as

$$A = SX \qquad (1)$$

where S is the band intensity and X is the amount of absorber. The formulation of F in terms of A is given by Cess and Ramanathan (*9*). Pertinent details of the flux calculations are given in (*12*).

The model atmosphere—that is, the vertical distribution of temperature, H_2O, and clouds—is adopted from Rasool and Schneider (*13*) and reflects the present-day globally averaged conditions. The mixing ratio, q, of CF_2Cl_2 and $CFCl_3$ is prescribed by

$$\begin{aligned} q &= K; && 0 \leqslant z \leqslant 12 \text{ km} \\ &= K\exp[(12 - z)/H]; && z > 12 \text{ km} \\ & && H = 3 \text{ km} \end{aligned} \qquad (2)$$

where z is the altitude with $z = 0$ denoting the surface, H is the prescribed scale height, and K is the tropospheric mixing ratio (parts per billion, by volume) which has been assumed constant. The shape of the mixing ratio profile given by Eq. 2 is consistent with the model predictions of Cicerone *et al.* (*2*).

When Eqs. 1 and 2 are combined with

This content downloaded from
157.231.106.246 on Wed, 22 Nov 2023 14:06:51 +00:00
All use subject to https://about.jstor.org/terms

the flux formulation given in (*9*), the following relations are obtained

$$\Delta F(CF_2Cl_2) = -0.307\,K(CF_2Cl_2)$$
$$\Delta F(CFCl_3) = -0.256\,K(CFCl_3) \quad (3)$$

where $\Delta F(CF_2Cl_2) = F(\text{with } CF_2Cl_2) - F$ (unperturbed). As expected, the outgoing flux decreases with the addition of chlorofluorocarbons. Further, $-\Delta F$ increases linearly with the mixing ratio since the band absorption increases linearly with the mixing ratio (see Eq. 1). The optically thin condition imposed on Eq. 1 restricts the applicability of Eq. 3 to values of K less than 5 ppb.

The implications of Eq. 3 for the global climate can be examined by invoking the global energy balance condition (*14*), which states that on a global average the net incoming solar radiation should be in balance with F. Since the net incoming solar radiation would not change with the addition of chlorofluorocarbons, the energy balance condition implies that F has to be the same for both the perturbed and the unperturbed atmosphere. Recall that the ΔF given by Eq. 3 was calculated by fixing the atmospheric and surface temperature. Hence, it follows that the decrease in F has to be compensated by an increase in the tropospheric and surface temperature. The decrease in F can be related to an equivalent change in T_s through the relation

$$\Delta T_s = -\frac{\Delta F}{dF/dT_s} \quad (4)$$

where dF/dT_s is obtained by differentiating Budyko's (*14*) empirical formulation for F with respect to T_s, which yields $dF/dT_s = 1.425$ watt m^{-2} $°K^{-1}$. The increase in T_s obtained by substituting Eq. 3 in Eq. 4 is shown in Fig. 1. The surface temperature calculations were also performed using the detailed radiative-convective model described by Ramanathan *et al.* (*15*) and the results were identical to those shown in Fig. 1; this verifies the simpler procedure defined by Eqs. 3 and 4. Chlorocarbons also have strong infrared bands, and the contributions of the chlorocarbons to the increase in T_s are listed in Table 2. If the addition of chlorofluorocarbons results in a net reduction in the atmospheric O_3 concentration, as has been predicted (*1, 2*), the results for ΔT_s will be slightly modified (*16*).

The increase in T_s will be higher by about 15 percent if the coupling between T_s, the amount of H_2O, and solar absorption by H_2O is included. Including this effect, it is seen from Fig. 1 that the mean global surface temperature could, under the assumption of this simplified model, increase by as much as 0.9°K if the concentrations of CF_2Cl_2 and $CFCl_3$ were each increased to 2 ppb. Such a concentration of chlorofluorocarbons is expected to be reached by the year 2000 if the present level of injection is maintained (*1, 2*). Further, Table 2 shows that the chlorocarbons can also have appreciable effects on T_s. The increase in T_s may be amplified several times in the polar regions because of the positive feedback mechanism between ice cover, albedo, and surface temperature (*17*). This possibility underscores the importance of these results. However, the model presented here is a simplified one that neglects several atmospheric feedback mechanisms and all effects due to circulation. Hence, these calculations should not be considered as a definitive prediction of the response of the actual atmosphere system, but rather as indicative of the potential consequences for the climate of anthropogenic sources of chlorofluorocarbons.

The significance of these results can best be evaluated by referring to the papers by Bryson (*18*) and Schneider (*19*), which indicate that a surface temperature change of the order of 0.5°K may be sufficient to substantially alter some of the important climatic variables (rainfall and ice cover) in at least parts of the globe. The effect of chlorofluorocarbons and chlorocarbons on the chemical balance of the earth-atmosphere system is currently a subject of concern. The major conclusion of this report is that their effect on the earth's thermal energy balance must also be given serious consideration.

Table 2. Chlorocarbon band parameters and contribution to surface temperature (T_s). In column 5 K is the tropospheric mixing ratio for the species identified in parentheses; applicability of the equations used in the calculations is restricted to $K < 5$ ppb.

Species	Band		Reference	Increase in T_s (°K)
	Center (μm)	Intensity (cm/mole)		
CCl_4	12.987	3.9×10^7	(*7*)	$0.14\,K(CCl_4)$
$CHCl_3$	13.00	2.7×10^7	(*6*)	$0.104\,K(CHCl_3)$
	8.19	4.2×10^6	(*6*)	
CH_2Cl_2	14.0	7.9×10^5	(*5*)	
	13.58	1.19×10^7	(*5*)	$0.052\,K(CH_2Cl_2)$
	7.92	3.282×10^7	(*5*)	
CH_3Cl	13.66	2.32×10^6	(*8*)	
	9.85	4.02×10^5	(*8*)	$0.013\,K(CH_3Cl)$
	7.14	1.9×10^6	(*8*)	

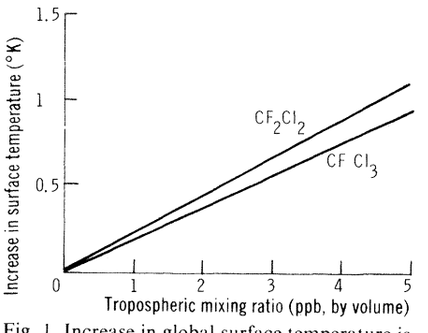


Fig. 1. Increase in global surface temperature is a function of the tropospheric concentrations of CF_2Cl_2 and $CFCl_3$. Results are for globally averaged conditions with 50 percent cloud cover.

V. RAMANATHAN*
NASA-Langley Research Center, Hampton, Virginia 23665

References and Notes

1. M. J. Molina and F. S. Rowland, *Nature (Lond.)* **249**, 810 (1974).
2. R. J. Cicerone, R. S. Stolarski, S. Walters, *Science* **185**, 1165 (1974).
3. J. E. Lovelock, *Nature (Lond.)* **252**, 292 (1974).
4. R. J. Cicerone, D. H. Stedman, R. S. Stolarski, *Geophys. Res. Lett.* **2**, 219 (1975).
5. J. Morcillo, L. J. Zamorano, J. M. V. Hereida, *Spectrochim. Acta Part A* **22**, 1969 (1966) for CF_2Cl_2 and CH_2Cl_2 bands.
6. W. B. Person, S. K. Rudys, J. H. Newton, *J. Phys. Chem.*, in press, for $CFCl_3$ and $CHCl_3$ bands.
7. C. F. Cook, W. B. Person, L. C. Hall, *Spectrochim. Acta Part A* **23**, 1425 (1967) for CCl_4 bands.
8. A. D. Dickson, I. M. Mills, B. Crawford, *J. Chem. Phys.* **27**, 445 (1957) for CH_3Cl bands.
9. R. D. Cess and V. Ramanathan, *J. Quant. Spectrosc. Radiat. Transfer* **12**, 933 (1972).
10. V. Ramanathan and R. D. Cess, *Astrophys. J.* **188**, 407 (1974).
11. The optically thin condition requires that $SX/\Delta\omega << 1$, where $\Delta\omega$ is the bandwidth (*9, 10*). Person *et al.* (*6*) suggest that $\Delta\omega \approx 100$ cm^{-1}. The maximum value of X that will be considered in this work is about 0.001 cm atm, so even for the strongest band $SX/\Delta\omega << 1$. Similar conclusions can also be reached from Person *et. al.*'s discussion.
12. In the flux calculations the band absorptance is defined as $A = 2SX$, where the factor 2 accounts for the angular integration over isotropic radiation. The bands of chlorofluorocarbons and chlorocarbons are overlapped by the continuum band of H_2O, and this overlap has been accounted for by multiplying the band absorptance by the transmissivity of the continuum band. The absorption coefficients for the continuum band of H_2O were obtained from K. J. Bignell, *Q. J. R. Meteorol. Soc.* **96**, 390 (1970).
13. S. I. Rasool and S. H. Schneider, *Science* **173**, 138 (1971).
14. M. I. Budyko, *Tellus* **21**, 611 (1969).
15. V. Ramanathan, L. B. Callis, and R. E. Boughner presented a brief description of the model at the fourth conference on the Climatic Impact Assessment Program (CIAP), Cambridge, Mass., 4 to 7 February 1975 (*J. Atmos. Sci.*, in press).
16. It has been indicated (*1, 2*) that increasing CF_2Cl_2 and $CFCl_3$ concentrations to 2 ppb would decrease O_3 by 10 percent. A 10 percent decrease in O_3, if distributed uniformly between 12 to 40 km, would decrease T_s by about 0.07°K (*15*). Ramanathan *et al.* (*15*) consider a uniform reduction in O_3 within the stratosphere while, as pointed out by R. E. Dickinson (private communication), the fluorocarbons reduce O_3 mainly above 30 km. Preliminary calculations indicate that reducing O_3 above 30 km might lead to a slight increase in T_s.
17. S. H. Schneider and R. E. Dickinson, *Rev. Geophys. Space Phys.* **12**, 447 (1974).
18. R. A. Bryson, *Science* **184**, 753 (1974).

This content downloaded from
157.231.106.246 on Wed, 22 Nov 2023 14:06:51 +00:00
All use subject to https://about.jstor.org/terms

19. S. H. Schneider, *Ambio* **4**, 65 (1975).
20. I thank the following for several enlightening discussions and suggestions: L. B. Callis, B. R. Barkstrom, R. E. Boughner, R. J. Cicerone, M. J. Molina, S. H. Schneider, and R. E. Dickinson. I am grateful to W. Person, D. Garvin, and the E. I. du Pont de Nemours & Co. for their prompt response to my request for the infrared data.
* Present address: Joint Institute for Acoustics and Flight Sciences, NASA-Langley Research Center, George Washington University, Hampton, Virginia 23665.

21 May 1975; revised 23 July 1975

Precambrian Eukaryotic Organisms: A Reassessment of the Evidence

Abstract. *Comparison of partially degraded unialgal cultures of* Chroococcus turgidus *with coccoid microfossils from the Late Precambrian Bitter Springs formation, Australia, suggests that the Precambrian fossil record has been seriously misinterpreted. Use of degradational features as taxonomic characters has resulted in unrealistically high estimates of Precambrian algal diversity. There is at present no compelling evidence for the presence of eukaryotic microfossils in rocks from the Bitter Springs formation or any older sedimentary sequences.*

A decade ago one of us (*1*) suggested that certain coccoid microfossils occurring in profusion in the then recently discovered cherts of the Late Precambrian Bitter Springs formation, central Australia, represented the earliest evidence of eukaryotic organisms in the evolutionary record of life. These fossil algae, which were found either as isolated cells or as loose aggregates of few to many individuals, were sometimes devoid of cellular contents, but often possessed an internal discrete structure excentrically or peripherally located with respect to the delimiting "wall." Cytoplasmic remnants (interpreted as inner cell walls) surrounded the internal body in certain cells. The well-defined internal structures were interpreted as nuclear or organellar bodies (*2–4*), and a series of supposedly discrete taxa of both prokaryotic and eukaryotic algae was erected on the assumption that the presence or absence of these blebs and coagulated protoplasmic remnants constituted valid taxonomic characters (*2, 3*). This interpretation was seriously questioned by Awramik *et al.* (*5*), who emphasized that this taxonomy failed to take into account the variability of internal structure caused by partial degradation of blue-green algae.

Because of the importance of proper interpretation of Precambrian fossils, we undertook a new series of degradation experiments and found that the entire range of morphologic variation exhibited by a dozen taxa of coccoid algae (supposedly both prokaryotic and eukaryotic) from the Ellery Creek locality of the Bitter Springs formation could be duplicated in detail by partially degrading a unialgal culture of the chroococcalean species *Chroococcus turgidus* (Kütz.) Nägeli. Our results suggest that the Precambrian fossil record has been seriously misread. The three-dimensional morphology of microfossils is generally not preserved by the cell wall as has been previously assumed, but rather by one or more mucoidal sheaths (*6*). The putative organellar remnants are in reality degraded protoplasm representing the entire contents of the cell. This fact, coupled with an appreciation of the morphologic variability within living chroococcalean species, indicates that there is no compelling evidence for the presence of eukaryotes in the Bitter Springs formation or any older rocks. It also demonstrates that published estimates of the taxonomic diversity of the Bitter Springs and other Precambrian floras are excessive.

The experimental procedure is simple. Unialgal cultures of cyanophytes were grown at room temperature in reduced natural light on mineral agar slants prepared with Bold's basal medium (*7*). As the cultures became stale, smears were prepared and stained with a dilute aqueous solution of safranin to enhance observation and photomicrography. A *Chroococcus turgidus* culture was selected for detailed examination because of its almost uncanny resemblance to described Bitter Springs fossils; however, other chroococcalean cultures exhibited a similar pattern of variation and degradation. This pattern has also been observed in algal mats growing in Massachusetts, Australia, and the Persian Gulf by Golubic and his colleagues (*5, 6*).

Figure 1, A to P, illustrates the range of morphologies which result from the partial degradation of a naturally morphologically varied population of blue-green algal cells. Diameters of individual cells of *Chroococcus turgidus* range from 6 to 20 μm or more; the average diameter is approximately 10 to 12 μm. The number of cells per packet varies from one to four, although unicells and dyads are by far the most common. The shape of the cells forming dyads is variable, ranging from spherical, gibbous, or hemispherical to lunate (Fig. 1, A to H). The number of sheaths per cell also varies, as does the degree of protoplast degradation (*6*). Particularly important is the observation first made by Awramik *et al.* (*5*) that decomposition leaves the sheath intact, but condenses the protoplast into a globular remnant identical in every respect to the "nuclei" and "organelles" observed in Precambrian fossils (Fig. 1O). The final product of this process is an empty sheath (Fig. 1P). In spite of the wide range of variation of the organisms pictured here, all represent a single species from a pure culture.

Comparison of the *C. turgidus* culture with coccoid fossils from the Ellery Creek locality of the Bitter Springs formation (Fig. 1, Q, DD, and GG) demonstrates a remarkable similarity between the two populations, which are separated in time by almost a billion years. It is no exaggeration to state that the Bitter Springs assemblage could easily represent the remains of a single species of *Chroococcus*, a species having the same range of variability as *C. turgidus*. The Bitter Springs organisms in question have been assigned to the following taxa: *Globophycus rugosum, Bigeminococcus lamellosus, B. mucidus, Eozygion grande, E. minutum, Myxoccoides reticulata, Glenobotrydion aenigmatis, G. majorinum, Gloeodinopsis lamellosa, Caryosphaeroides pristina, C. tetras*, and *Eotetrahedron princeps*. The last six taxa have been described as eukaryotes. All of the Bitter Springs taxa listed above can be found in three petrographic thin sections

Fig. 1. All photomicrographs × 1100; the bar in EE equals 20 μm. (A–P, EE). *Chroococcus turgidus* (Kütz.) Nägeli, demonstrating the variation in morphology and degree of degradation observable in a single unialgal culture. Arrows in (F) and (O) refer to pseudonuclear protoplasmic remnants within undegraded sheaths. The three groups of blue-green algae in (EE) duplicate in detail the putative mitotic sequence suggested for coccoid microfossils from the Bitter Springs formation. (M and N) Two views of a single tetrad. (Q–DD, GG) Microfossils found in slides TBS-22-1A, 1B, and 1C from the Ellery Creek locality of the Bitter Springs formation, the taxonomy according to Schopf and Blacic (*3*); (Q) *Gloeodinopsis lamellosa* Schopf; (R) *Globophycus rugosum* Schopf; (S and T) unnamed morphologic entities; (U) *Bigeminococcus mucidus* Schopf and Blacic (?); (V) *Eotetrahedron princeps* Schopf and Blacic. Arrow points to fold in degraded protoplasm which in this plane simulates a trilete scar; (W and Y) *Eozygion minutum* Schopf and Blacic; (X, Z, and CC) *E. grande* Schopf and Blacic. (X) and (CC) show two views of the same organism; (AA) unnamed triad; (BB) *Eotetrahedron princeps* Schopf and Blacic; (DD) *Myxococcoides reticulata* Schopf; (GG) *Glenobotrydion aenigmatis* Schopf; note pseudonucleus. (FF) Coccoid alga from the Gunflint formation, Ontario, exhibiting a pseudonucleus. (HH) *G. aenigmatis* Schopf from the Ross River locality of the Bitter Springs formation, showing prominent pseudonuclei. (II) Pseudonuclei within a blue-green algal sheath in chert from the Ross River locality of the Bitter Springs formation.

This content downloaded from
157.231.106.246 on Wed, 22 Nov 2023 14:06:51 +00:00
All use subject to https://about.jstor.org/terms

Annex 25

C. Keeling, et al., "Atmospheric carbon dioxide variations at Mauna Loa Observatory, Hawaii", *Tellus,* 1976, pp. 538-551, pages 538, 547-550

Atmospheric carbon dioxide variations at Mauna Loa Observatory, Hawaii

By CHARLES D. KEELING, ROBERT B. BACASTOW, ARNOLD E. BAINBRIDGE, CARL A. EKDAHL, JR, PETER R. GUENTHER, and LEE S. WATERMAN, *Scripps Institution of Oceanography, University of California at San Diego, La Jolla, California, USA* and JOHN F. S. CHIN, *National Oceanic and Atmospheric Administration, Mauna Loa Observatory, Hawaii*

(Manuscript received February 16, 1973; in final form January 27, 1976)

ABSTRACT

The concentration of atmospheric carbon dioxide at Mauna Loa Observatory, Hawaii is reported for eight years (1964–1971) of a long term program to document the effects of the combustion of coal, petroleum, and natural gas on the distribution of CO_2 in the atmosphere. The new data, when combined with earlier data, indicate that the annual average CO_2 concentration rose 3.4 % between 1959 and 1971. The rate of rise, however, has not been steady. In the mid-1960's it declined. Recently it has accelerated. Similar changes in rate have been observed at the South Pole and are evidently a global phenomenon.

Introduction

In conjunction with the Antarctic study of atmospheric carbon dioxide discussed in the preceding paper (Keeling et al., 1976), a nearly uninterrupted series of CO_2 measurements has been obtained with a continuously recording nondispersive infrared gas analyzer over a period of fourteen years at the Mauna Loa high altitude observatory on the island of Hawaii. The sampled air at the station, as shown by Pales & Keeling (1965), is approximately representative of air above the North Pacific trade wind inversion between 15° and 25° N.

Two major features of the data are a seasonal oscillation and a long term increase.

The seasonal oscillation, with little doubt, reflects the integrated uptake and release of CO_2 by land plants and soil (Junge & Czeplak, 1968). The amplitude of the seasonal oscillation is maximum in the Arctic (Kelley, 1969) and decreases southward until low values are reached in the mid-southern hemisphere (Bolin & Keeling, 1963). The amplitude also decreases with height above ground and is barely observable in the lower stratosphere (Bolin & Bischof, 1970; Bischof, 1973). The greater amplitude in the northern hemisphere is explained by the greater extent of boreal as compared with austral forests and grasslands. The decrease with height occurs because the seasonal oscillation, produced at ground level, is progressively attenuated upward by mixing.

Both the Antarctic and Mauna Loa data show an annual increase in CO_2 concentration of the order of 1 ppm (parts per million of dry air). This increase reflects the retention in the air of about half of the CO_2 produced by combustion of fossil fuels (Keeling, 1973). The rate of increase has not been strictly proportional to the rate of combustion of fossil fuels in either hemisphere.

Observing site

Mauna Loa Observatory is located 3 400 meters above sea level on an extensive lava flow on the north slope of the largest active volcano in the Hawaiian Islands. The observing site and its meteorological milieu have been described by Price & Pales (1959), Pales &

the same procedure used earlier by Pales & Keeling (1965). A minor association with regional weather patterns is suggested by short period oscillations of the daily averages, but the principal feature is a seasonal oscillation which repeats with remarkable regularity from year to year. This latter oscillation shows up clearly in monthly averages of the daily values as plotted in Fig. 5, and listed in Table 3.

In Table 4, column 2, are listed annual values of the steady data expressed on the adjusted CO_2 index scale. In column 3 of the same table are shown averages of the full data excepting only those values (about 4% of the total) which were evidently contaminated locally as shown by variable recorder traces. The full data (which we have also examined on a daily and monthly basis) hardly differ from the steady data because low values during afternoon dips tend to cancel with high values during midday peaks. Additional columns show the data reexpressed as CO_2 mole fractions.

Supplementary data. The individual reference gas calibrations and daily average atmospheric air measurements are too extensive to reproduce here. Those for 1964 through 1970 have been summarized in a detailed report (Ekdahl et al., 1971) and deposited with the National Auxiliary Publications Service of the American Society for Information Science.[1] All relevant calculations and supporting data are reported. A similar report of the measurements for 1971 will be prepared in conjunction with a subsequent article.

1969		1970		1971	
No. of days	Adjusted CO_2 index	No. of days	Adjusted CO_2 index	No. of days	Adjusted CO_2 index
29	320.08	31	321.16	29	322.60
22	320.85	27	322.03	28	323.05
30	321.90	31	323.03	29	323.65
28	322.82	30	324.20	28	324.29
28	323.45	27	324.09	30	325.51
24	322.76	28	323.90	29	325.06
26	321.89	28	322.61	25	323.93
27	319.61	20	321.14	23	322.12
25	318.56	21	319.75	27	320.24
31	318.03	25	319.75	25	320.37
30	318.94	26	320.56	30	321.60
31	320.35	27	321.57	31	322.70

Table 4. *Seasonally adjusted concentration of atmospheric CO_2 (in ppm) at Mauna Loa Observatory*

	Adjusted CO_2 index		CO_2 mole fraction	
Year (1)	Annual average[a] of steady data (2)	Annual average of full data (3)	Annual average of steady data (4)	From trend equation[b] (5)
1958	Incomplete			
1959	313.23	—	316.14	316.30
1960	314.04	—	317.03	317.06
1961	314.66	—	317.71	317.74
1962	315.43	—	318.57	318.37
1963	315.83	—	319.03	318.98
1964	316.35[c]	—	319.63[c]	319.60
1965	316.90	316.92	320.25	320.27
1966	317.50	317.60	320.92	321.02
1967	318.19	318.14	321.70	321.88
1968	318.99	318.92	322.58	322.88
1969	320.77	320.85	324.47	324.06
1970	321.98	322.20	325.79	325.45
1971	322.93	322.94	326.83	327.08

[a] Annual averages for 1959 to 1963 are derived from Table 1 of Pales & Keeling (1965), for 1964 to 1971 from Table 3 of this paper.
[b] Smoothed values of steady data, for 1 July of each year, as derived from the last four terms of eq. (6).
[c] Partially estimated according to values listed in Table 3.

Secular increase in CO_2

Two methods have been employed to separate the annual increase of about 0.8 ppm from the 6 ppm seasonal variation found in the Mauna Loa record. In the first method, monthly average adjusted CO_2 index values were fit to a function in time containing both a power series and Fourier harmonic terms. The harmonic frequencies were established by spectral analysis of the daily averages. The second meth-

[1] This information has been deposited with ASIS as NAPS document no. 02890. Order from ASIS-NAPS, c/o Microfiche Publications, 440 Park Avenue South, New York, New York 10016. Remit in advance for each NAPS accession number. Make check payable to Microfiche Publications. Photocopies are $87.25. Microfiches are $3.00. Outside the United States and Canada, postage is $4.00 for a photocopy or $1.00 for a fiche.

od filtered out the dominant harmonic terms with a moving average.

In the first approach the dominant frequencies in the daily average record of steady data from June 1964 through June 1971 were estimated from a discrete Fourier transform using the transform algorithm of Cooley & Tukey (1965). Transform terms were weighted to correspond to the cosine bell data window of Hann (Blackman & Tukey, 1959, pp. 14–15, 98; Hinnich & Clay, 1968), and afterwards converted to a power spectrum. Since the algorithm requires 2^N equally spaced data, days with no data were assigned values by linear interpolation of contiguous data, and spectra were obtained from both the first and last 2048 of the 2587 data points. The average of these two spectra is shown in Fig. 6. Since days without data are unclustered (see Figs. 4*a* through 4*h*) and constitute only 17% of the record, errors from interpolation have little effect on the analysis. The only significant harmonic contributions to the long term data record are the fundamental annual cycle and its first (6 months) harmonic.

To verify that very little information is contained in higher harmonics, monthly averages of the adjusted CO_2 index values were fit by the method of least squares to several trial functions consisting of power series of varying degree combined with a varying number of harmonic terms. For a given power series polynomial, the significance of the fundamental cyclic variation in combination with higher cyclic variations of 1/2 year, 1/3 year, 1/4 year, etc. was tested with the function:

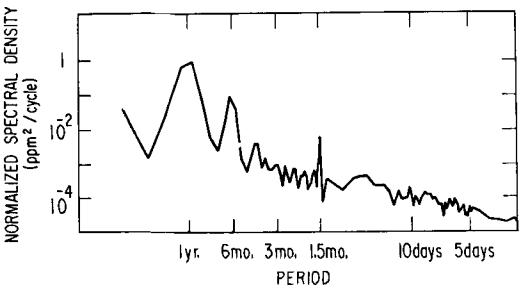


Fig. 6. Power spectrum of daily average concentrations of atmospheric CO_2 at Mauna Loa for the interval June, 1964 through June, 1971. The spectrum has been normalized to the maximum contribution from the one year cycle.

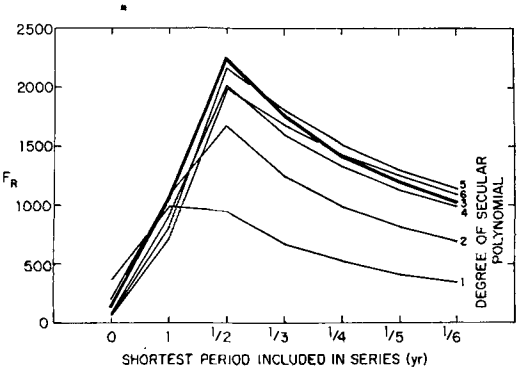


Fig. 7. The statistic F_R plotted versus varying numbers of harmonic terms, added to secular trend polynomials of varying degree as shown.

$$F_R = (R^2/n)/[(1-R^2)/(N-n-1)] \quad (4)$$

where R, the multiple correlation coefficient, tends toward unity as the "goodness of fit" increases; n is the number of parameters determined by the least squares fit; and N is the number of data. The statistic F_R, which follows the F distribution (Bevington, 1969, p. 199), was found to be maximized when only the fundamental and its first harmonic were included in the trial function (Fig. 7). Also, F_R was maximized when the secular trend included powers of time up through the third.

Accordingly, the monthly average adjusted CO_2 index values were corrected to the CO_2 mole fraction scale and then fit with the function:

$$X(t) = Q_1 \sin 2\pi t + Q_2 \cos 2\pi t + Q_3 \sin 4\pi t + Q_4 \cos 4\pi t + Q_5 + Q_6 t + C_7 t^2 + Q_8 t^3 \quad (5)$$

where X denotes the CO_2 mole fraction of dry air in ppm, t is the elapsed time, in years, relative to the first of January, 1958, and

$$\left.\begin{aligned} Q_1 &= 2.339 \text{ ppm} & Q_5 &= 313.802 \text{ ppm} \\ Q_2 &= -1.065 \text{ ppm} & Q_6 &= 1.213 \text{ ppm/yr} \\ Q_3 &= -0.343 & Q_7 &= -0.100 \text{ ppm/yr}^2 \\ Q_4 &= 0.583 \text{ ppm} & Q_8 &= 0.00545 \text{ ppm/yr}^3 \end{aligned}\right\} \quad (6)$$

The standard deviation of the monthly averages with respect to this function is 0.27 ppm. The secular trend, which we seek, is given by the last four terms of eq. (6), as shown by the

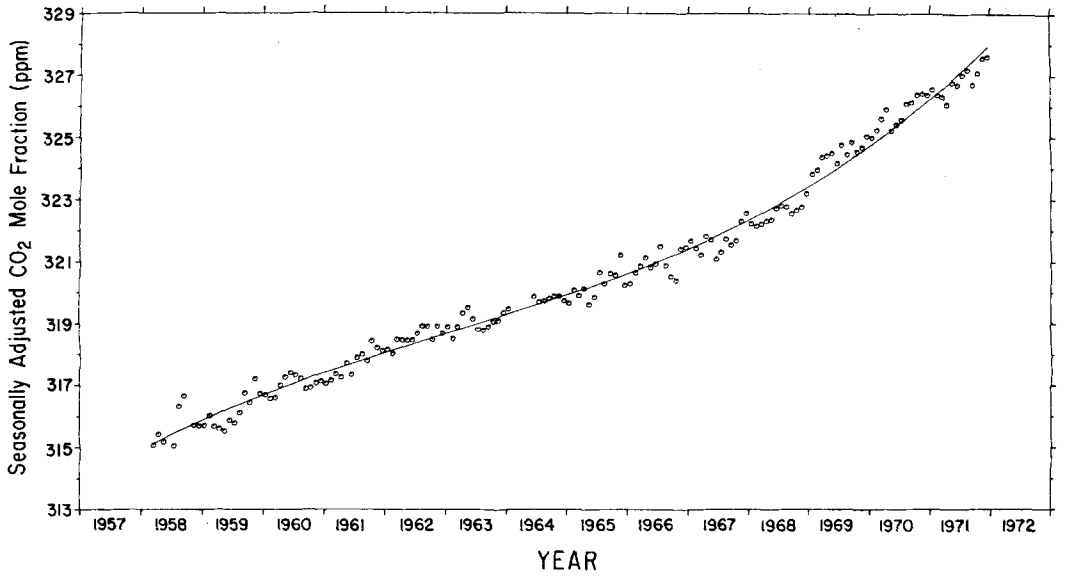


Fig. 8. Secular trend of atmospheric CO_2 mole fraction at Mauna Loa Observatory, based on a cubic trend function. Circles denote seasonally adjusted monthly averages. Concentrations are expressed as the CO_2 mole fraction of dry air in ppm.

curve in Fig. 8. Values of the trend for 1 July of each year are listed on the mole fraction scale in Table 4, column 5. The relative increase in concentration from 1959 to 1971 is 3.4%. This increase agrees closely with 3.1% found for the South Pole for the same time interval (Keeling et al., 1976).

To provide an independent estimate of the

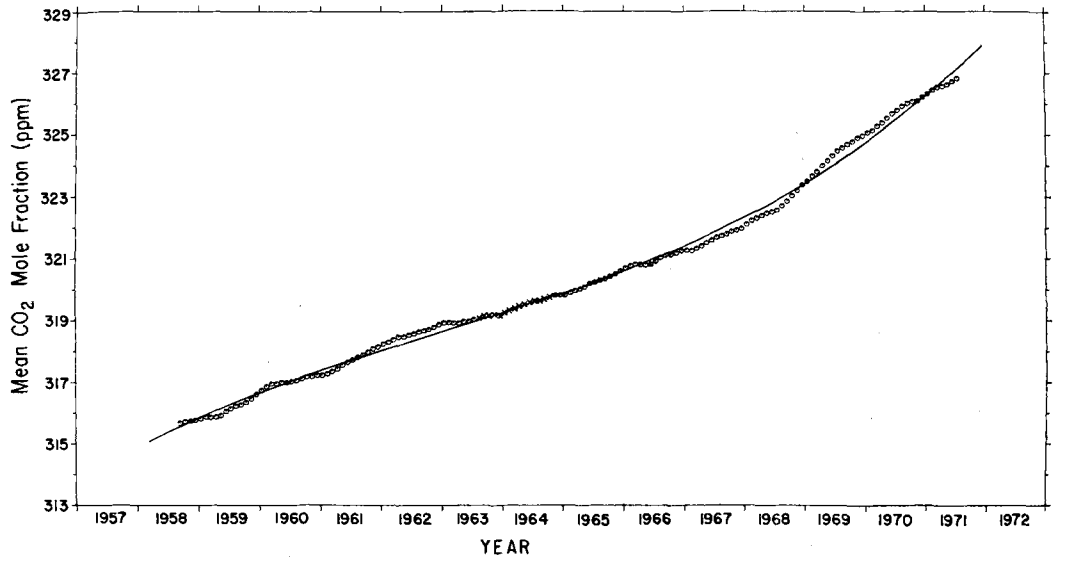


Fig. 9. Twelve month moving average of atmospheric CO_2 mole fraction at Mauna Loa Observatory. Circles: means plotted versus the seventh month of the appropriate 12 month interval. Crosses: means which include concentration estimates calculated from the oscillating power function for the period February, 1964 through May, 1964. Full curve: secular trend based on cubic trend function.

secular trend, the monthly averages were filtered with a simple twelve months moving average (Fig. 9) as was done by Pales & Keeling (1965). We have examined the extent to which this moving average distorts the long term trend by computing its continuous analogue for the cubic trend function. Using the parameters Q_5 to Q_8 of eq. (6), the maximum error, incurred at the end of the record, is entirely negligible (less than 0.02 ppm).

As already noted by Pales & Keeling (1965) for the period before 1964, the moving average suggests a weak two year cycle. The data record is of insufficient length to expect such a cycle to be evident in a spectral analysis (Fig. 6), but the possibility was tested for using the F_R statistic described above. We found that no subharmonic of the annual cycle (2 to 6 years were tested) possesses a large enough signal to noise level to render it detectable.

The moving average filter removes completely the one year cycle and its harmonics from the estimate of the secular trend. Other variability within any year of record is also attenuated, but random variations which persist over several months, such as unusually low summer or high winter means, are only moderately attenuated. In contrast, the cubic trend function (last four terms of eq. (6)) greatly attenuates not only the two dominant frequencies, but also all random variations with periods less than approximately 10 years; it thus produces a smoother estimate of the secular trend than does the moving average. Furthermore, the trend for all years is changed each time the length of record is altered, for example, by the accession of new data. At the other extreme, the succession of seasonally adjusted monthly averages (circles in Fig. 8) indicate the secular trend without suppressing any frequencies except the two dominant ones.

The data could, of course, be reprocessed using still other filters, but salient features are almost surely revealed using the three filters just discussed. The three versions of the trend so obtained have one striking feature in common: An apparent decline in the rate of increase of CO_2 during the early 1960's, followed by an increasing rate after 1967.

Confronted with the break in record in 1964, we are reluctant to rule out the possibility that the decline is at least partly an instrumental artifact. Unfortunately, no second record of atmospheric CO_2 concentrations in the northern hemisphere exists which can help us decide whether this decline is real or not. A possible slower rate of increase is not inconsistent with data of Bolin & Bischof (1970) based on aircraft samples collected over a broad region of the polar northern hemisphere, but as these authors point out, the irregularities of their sampling schedule (see their Table 2, p. 433) "hardly permit a search for possible secular variations in the annual increase".

If we disregard the temporary decline in rate during the early 1960's, the change in rate roughly approximates that of fossil fuel combustion which was 60% higher in 1971 than in 1959.

Conclusions

In extending the previously published five year record of atmospheric CO_2 concentrations at Mauna Loa Observatory by eight additional years, new features of CO_2 in air near the Hawaiian Islands are revealed, and previously noted features more precisely defined. Statistical analysis of daily and monthly averages of the original continuous data establish a seasonal oscillation described by annual and semiannual harmonic oscillations about a long term trend. This latter trend, obtained by subtracting the average seasonal oscillation from each of the original 14 years of record, is a rising function of time and is described, within the precision of the data, by either a cubic power series, a 12 month moving average, or a set of seasonally adjusted monthly averages.

The air at Mauna Loa Observatory may be slightly influenced by local processes which cannot be expunged from the record, but the observed long term trend of rising CO_2 appears clearly to be in response to increasing amounts of industrial CO_2 in the air on a global scale. We are thus convinced of the observatory's suitability to monitor global changes in atmospheric CO_2 concentration.

Acknowledgements

All members of the staff of the Mauna Loa Observatory contributed to maintaining this long term program. We especially thank Mr Howard Ellis, Dr Lothar Ruhnke, and Dr Ru-

Annex 26

P. H. Abelson, “Energy and Climate”, *Science,* 1977

2 September 1977, Volume 197, Number 4307 **SCIENCE**

AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE

Science serves its readers as a forum for the presentation and discussion of important issues related to the advancement of science, including the presentation of minority or conflicting points of view, rather than by publishing only material on which a consensus has been reached. Accordingly, all articles published in *Science*—including editorials, news and comment, and book reviews—are signed and reflect the individual views of the authors and not official points of view adopted by the AAAS or the institutions with which the authors are affiliated.

Editorial Board

1977: WARD GOODENOUGH, CLIFFORD GROBSTEIN, H. S. GUTOWSKY, N. BRUCE HANNAY, DONALD KENNEDY, NEAL E. MILLER, RAYMOND H. THOMPSON

1978: RICHARD E. BALZHISER, JAMES F. CROW, HANS LANDSBERG, EDWARD NEY, FRANK W. PUTNAM, MAXINE SINGER, PAUL E. WAGGONER, F. KARL WILLENBROCK

Publisher

WILLIAM D. CAREY

Editor

PHILIP H. ABELSON

Editoral Staff

Managing Editor
ROBERT V. ORMES

Business Manager
HANS NUSSBAUM

Assistant Managing Editor
JOHN E. RINGLE

Production Editor
ELLEN E. MURPHY

News and Comment: BARBARA J. CULLITON, *Editor;* LUTHER J. CARTER, CONSTANCE HOLDEN, DEBORAH SHAPLEY, NICHOLAS WADE, JOHN WALSH. *Editorial Assistant,* SCHERRAINE MACK

Research News: ALLEN L. HAMMOND, *Editor;* GINA BARI KOLATA, JEAN L. MARX, THOMAS H. MAUGH II, WILLIAM D. METZ, ARTHUR L. ROBINSON. *Editorial Assistant,* FANNIE GROOM

Associate Editors: ELEANORE BUTZ, MARY DORFMAN, SYLVIA EBERHART, JUDITH GOTTLIEB

Assistant Editors: CAITILIN GORDON, RUTH KULSTAD, LOIS SCHMITT

Book Reviews: KATHERINE LIVINGSTON, *Editor;* LINDA HEISERMAN, JANET KEGG

Letters: CHRISTINE KARLIK

Copy Editors: ISABELLA BOULDIN, OLIVER HEATWOLE

Production: NANCY HARTNAGEL, JOHN BAKER; YA LI SWIGART, ELEANOR WARNER; JEAN ROCKWOOD, LEAH RYAN, SHARON RYAN

Covers, Reprints, and Permissions: GRAYCE FINGER, *Editor;* CORRINE HARRIS, MARGARET LLOYD

Guide to Scientific Instruments: RICHARD SOMMER

Assistant to the Editors: RICHARD SEMIKLOSE

Membership Recruitment: GWENDOLYN HUDDLE

Member and Subscription Records: ANN RAGLAND

EDITORIAL CORRESPONDENCE: 1515 Massachusetts Ave., NW, Washington, D.C. 20005. Area code 202. General Editorial Office, 467-4350; Book Reviews, 467-4367; Guide to Scientific Instruments, 467-4480; News and Comment, 467-4430; Reprints and Permissions, 467-4483; Research News, 467-4321; Cable: Advancesci, Washington. For "Instructions for Contributors," write the editorial office or see page xi, *Science*, 26 March 1976.

BUSINESS CORRESPONDENCE: Area Code 202. Business Office, 467-4411; Circulation, 467-4417.

Advertising Representatives

Director: EARL J. SCHERAGO

Production Manager: MARGARET STERLING

Advertising Sales Manager: RICHARD L. CHARLES

Sales: NEW YORK, N.Y. 10036: Herbert L. Burklund, 11 W. 42 St. (212-PE-6-1858); SCOTCH PLAINS, N.J. 07076: C. Richard Callis, 12 Unami Lane (201-889-4873); CHICAGO, ILL. 60611: Jack Ryan, Room 2107, 919 N. Michigan Ave. (312-DE-7-4973); BEVERLY HILLS, CALIF. 90211: Winn Nance, 111 N. La Cienega Blvd. (213-657-2772); DORSET, VT. 05251: Fred W. Dieffenbach, Kent Hill Rd. (802-867-5581)

ADVERTISING CORRESPONDENCE: Room 1740, 11 W. 42 St., New York, N.Y. 10036. Phone: 212-PE-6-1858.

Energy and Climate

Whenever the weather in a region departs from norms for a few weeks or more, anxious queries arise. Is the world's climate changing? When leading meteorologists are questioned they usually equivocate. At one time considerable optimism was voiced that new insights would be gained soon from modeling calculations. In the past decade much time on some of the most powerful computers has been devoted to such calculations. But success has been elusive. The best performance on weather seems to be in short-range prediction—that is, the next day or two. Even then surprises occur. In predicting weather, meteorologists can take as a point of departure current conditions, but in attempting to estimate climatic change there is little guidance. Some cyclical patterns related to the 11-year sunspot activity have been noted, and a 2- to 3-year cycle also seems to persist.

Meteorologists still hold out global modeling as the best hope for achieving climate prediction. However, optimism has been replaced by a sober realization that the problem is enormously complex. In a recent report* Verner E. Suomi listed 27 variables that must be monitored to obtain data needed for studies of climate dynamics. These include total solar flux, cloudiness, surface albedo, sea and surface temperature, thickness of polar ice sheets, water vapor, CO_2, and tropospheric aerosols. Human activity has been changing at least three of the variables—albedo, aerosols, and CO_2. The report emphasizes potential effects of increasing and long-term use of fossil fuels.

One fact about CO_2 that is known with certainty is that the concentration in the atmosphere is increasing. Charles Keeling has been conducting precise measurements of atmospheric CO_2 since 1957. In two decades the concentration at the south pole has increased from 314 to 331 parts per million. It is estimated that since the beginning of the industrial revolution the change has been about 13 percent. Roger Revelle has analyzed cogent factors. Part of the increase is due to deforestation. About half of the CO_2 that has been produced remains in the atmosphere, and the rest has been absorbed in the ocean or removed by increased photosynthesis.

What are the likely future trends? For the remainder of this century the clearing of land will continue and the use of fossil fuel will increase. As a result, by the year 2000 the CO_2 concentration will exceed preindustrial levels by about 25 percent. Ultimately, other forms of energy such as solar may come to play a more substantial role. However, humanity's appetite for energy use seems insatiable.

What will be the climatic consequences of increased CO_2? S. Manabe and R. T. Wetherald have calculated that a doubling of CO_2 would lead to an average global increase in temperature of 2.5°C. Their model was necessarily oversimplified, but it seems plausible on the basis of a greenhouse effect. However, a few scientists can be found who privately suggest that because of complex feedback phenomena the net effect of increased CO_2 might be global cooling.

The most likely trend appears to be warming, with effects considerably greater in the polar regions than at mid-latitudes. In the polar regions CO_2 can have a relatively large greenhouse effect. Changes in global circulation would also contribute to the increase.

Humanity is in the process of conducting a great global experiment. If unpleasant effects are encountered they cannot be quickly reversed. Although a comprehensive understanding of what is going on may be difficult to attain, prudence requires at least a determined and sustained effort.

Congress is considering bills aimed at improving climate monitoring, augmenting climate research, improving services related to the climate, and identifying the domestic and international impacts of changes in the climate. Such legislation should be enacted.—PHILIP H. ABELSON

**Energy and Climate* (prepublication version, National Research Council, Washington, D.C., July 1977).

Annex 27

"COAL—Bridge to the Future", *World Coal Study (WOCOL),* 1980, pages 133-135

The complete study can be accessed through the KB Nationale Biblioteek (*see* the KB Nationale Biblioteek catalogue, available at: https://webggc.oclc.org/cbs/DB=2.37/SET=1/TTL=1/SHW?FRST=1 (last accessed on 12 March 2024). The KB Nationale Biblioteek can be contacted for assistance by phone at +31 (0)70 31 40 911.

COAL

BRIDGE TO THE FUTURE

煤——望前途之桥

KUL — BRO TIL FREMTIDEN
HIILI — SILTA TULEVAISUUTEEN
LE CHARBON — PONT VERS LE FUTUR
KOHLE — BRÜCKE ZUR ZUKUNFT
कोयला – भविष्य की सीपान
BATUBARA — JEMBATAN KEMASA DEPAN
CARBONE — UN PONTE PER IL FUTURO
石炭／未来へのかけ橋
KOLEN — BRUG NAAR DE TOEKOMST
WEGIEL — MOST KU PRZYSZŁOŚCI
KOL — EN BRO TILL FRAMTIDEN

Report of the

WOCOL WORLD COAL STUDY

COAL—Bridge to the Future

This Report presents a plausible solution for the world's most acute energy need—increasing fuel supplies to support essential growth. It shows how coal can meet that need and be mined, moved and used in ways which meet stringent environmental standards. Coal already provides 25 percent of the world's energy. Reserves are abundant, technology for using it is well established, and it is relatively cheap and likely to remain so.

This analysis of the world's energy and coal prospects to the year 2000 was prepared by the World Coal Study (WOCOL), an international project involving eighty people from sixteen major coal producing and consuming countries in intensive work over eighteen months. WOCOL was directed by Carroll L. Wilson of the Massachusetts Institute of Technology. Here are some of its major conclusions:

- Even under the moderate energy growth assumptions of the Study, world coal production will have to increase 2.5 to 3 times, and the world trade in steam coal will have to grow 10 to 15 times by the end of the century.
- Coal will have to supply between one-half and two-thirds of the additional energy needed by the world during this period.
- Coal is already economically competitive in many locations for the generation of electricity and in many industrial and other uses.
- The amount of capital required to expand the production, transport, and user facilities to triple the use of coal is within the capacity of domestic and international capital markets.

This message of cautious optimism is welcome as we bump the ceiling on world oil supply and encounter increasing delays and uncertainties about nuclear energy. But this optimism is justified only if many decisions are taken very soon because of the lead-times involved. Coal is not claimed as the ultimate energy source but as an essential "bridge to the future" as the world manages the transition away from dependence on oil.

COAL—
Bridge to the Future

Report of the World Coal Study

WOCOL

Carroll L. Wilson
Project Director, Massachusetts Institute of Technology

Ballinger Publishing Company • Cambridge, Massachusetts
A subsidiary of Harper & Row, Publishers, Inc.

Cover with title in the 13 languages of WOCOL members on background color of burning coal was suggested by Susan Leland.

Copyright © 1980 by Massachusetts Institute of Technology. All rights reserved. Printed in the United States of America. No part of this book may be used or reproduced in any manner whatsoever without written consent except in the case of brief quotations embodied in critical articles and reviews. Published simultaneously in Great Britain by Harper & Row Ltd., and in Australia and New Zealand by Harper & Row (Australasia) Pty. Limited.

This material is based on research supported in part by the U.S. Department of Energy under contract No. EX-76-A-01-2295 with MIT. Any opinions, findings, conclusions or recommendations contained herein are those of the authors and do not necessarily reflect the views of the U.S. Department of Energy.

PRINTED AT THE NIMROD PRESS, BOSTON

Library of Congress Cataloging in Publication Data

World Coal Study.

Coal—bridge to the future.

Bibliography: p.

1. Coal. I. Wilson, Carroll L. II. Title.

TP325.W82 1980 333.8'22 80-13072

ISBN 0-88410-099-5

TABLE OF CONTENTS

FOREWORD vii

STUDY PARTICIPANTS, ASSOCIATES, AND STAFF xi

CONCLUSIONS xvi

ACKNOWLEDGMENTS xviii
Sponsors and Institutions xviii

THE WORLD COAL STUDY xxi

PART I: THE NEED FOR COAL 3
Introduction 3
World Energy Prospects 5
Prospects for Coal 11
Coal Markets and Prices 24
Environment, Health, and Safety 26
Coal Resources, Reserves, and Production 33
Ports and Maritime Transport 38
Technologies for Using Coal 44
Capital Investment in Coal 48
Necessary Actions 53

PART II: BUILDING THE BRIDGE
Energy Units 58

CHAPTER 1: WORLD ENERGY PROSPECTS 61
World Oil Supplies 61
Oil: A Historical Review 65
Oil Supply Prospects in the Next Few Years 67
OPEC Countries 68
OECD Countries 70
Centrally Planned Economy (CPE) Countries 70
Non-OPEC Developing Countries 71
Summary of Outlook for the Early 1980s 71
Oil Supply Prospects in the Medium and Long Terms 72
Oil Availability for Import by the OECD Countries 72
World Energy Consumption 75
Natural Gas 76
Unconventional Oil and Gas Sources 78

Page

Nuclear Energy 78
Conservation 80
Renewable Energy Sources 81
Coal 83

CHAPTER 2: ANALYSIS OF WORLD COAL PROSPECTS 87
Framework for the Analysis 87
Country and Regional Study Approach 87
Coal Projection Methodology 88
Coal Use in the OECD Countries 91
The Electric Power Market 92
The Metallurgical Coal Market 94
The Industrial Market 95
The Synthetic Fuel Market 96
The Residential/Commercial Market 97
Total Coal Use in the OECD 97
Coal's Share of Total OECD Energy Supplies 99
The Effect of Limitations on Oil Imports and Nuclear Delays on OECD Coal Needs 100
Coal's Share in the Increase in OECD Energy Supplies 103
The Acceleration of OECD Coal Demand 103
Coal Use in Countries Outside the OECD 104
Total World Coal Use 105
World Coal Import Requirements 106
Steam Coal Imports 107
Metallurgical Coal Imports 108
Effects of Limitations on Oil Imports and Nuclear Energy Delays on OECD Coal Import Requirements 108
World Coal Export Potentials 110
International Coal Trade Patterns 112
Feasibility of Importer-Exporter Trade Patterns 114
Implications for Trade Patterns 116
National and Regional Implications of the Analysis 116

CHAPTER 3: COAL MARKETS AND PRICES 119
Coal Markets 119
Geographical Markets 119
End-Use Markets 120
Coal Demand 120
Purchase Arrangements 122
Long-Term Contracts 122
Spot and Short-Term Markets 123
Other Arrangements 123
Coal Costs 123
Coal Production Costs 124

Coal Transport Costs 125
Coal Use Costs 127
National Coal Policies 127
Observations 129

CHAPTER 4: ENVIRONMENT, HEALTH, AND SAFETY 133
Reasons for Environmental Concern 133
Surface Mining 135
Underground Mining 138
Occupational Health and Safety 139
Coal Preparation and Cleaning 140
Coal Transport and Storage 141
Coal Combustion 142
National Air Quality Standards 145
Emission Limitations and Strategies 145
CO_2 and Climate Change 147
Solid Waste 150
Thermal Emissions 151
Land and Water Use 151
Costs of Pollution Control for Utilities 153
Coal Use in Industries Other Than Utilities 153
New Coal Conversion Technologies 154
The Need for Research 155

CHAPTER 5: COAL RESOURCES, RESERVES, AND PRODUCTION 157
Definition of Coal Resources and Reserves 157
Regional Distribution of Coal Resources and Reserves 159
World Coal Production 162
Coal-Mining Methods 164
Surface Mining 164
Underground Mining 165
Coal Preparation 168
Future Expansion Needs 168

CHAPTER 6: MARITIME TRANSPORTATION AND PORTS 169
Coal Trade Routes 169
Shipping Requirements 170
Freight Rates 172
Bunkers (Fuel for Ships) 174
Coal Handling 175
Ports and Terminals 177
Loading Terminals 177
Receiving Terminals 177

Transshipment Terminals 177
Terminal Costs 178
Port Requirements for Future Coal Trade 179
Australia 179
Canada 179
Republic of South Africa 179
United States 180
Western Europe 180
Japan and Other East Asian Countries 181

CHAPTER 7: COAL-USING TECHNOLOGIES 183
Established Technology for Direct Use 184
Coal Combustion 185
Fluidized Bed Combustion 185
Coal-Oil Mixtures 187
Magnetohydrodynamic (MHD) Technology 187
Coal Gasification 187
Established Gasification Procedures 189
Underground Coal Gasification 193
Coal Liquefaction 194
Pyrolysis 194
Hydrogenation 195
Fischer-Tropsch Synthesis 197
Lead Times 198
Coal Utilization Economics 199
Power Generation 199
Gasification and Liquefaction 199
Conclusions 202

CHAPTER 8: CAPITAL INVESTMENT IN COAL 203
Coal Chains 203
Ownership of Coal Facilities in the Coal Chain 210
Capital Formation 1977–2000 211
Caiptal Estimates for Coal Supply 212
Capital Estimates for Coal-Fired Electric Power Stations 214
Factors Affecting Investment in Electric Power Systems 216
Potential Impediments to Financing Expanded Coal Supply 217
Conclusions 219

APPENDIX 1: SUMMARY COAL AND ENERGY PROJECTIONS FOR WOCOL COUNTRIES 221
Standard Fuel/Energy Equivalences 246
Unit Nomenclature and Standard Abbreviations 247

CHAPTER 4

ENVIRONMENT, HEALTH, AND SAFETY

Reasons for Environmental Concern — Surface Mining — Underground Mining — Occupational Health and Safety — Coal Preparation and Cleaning — Coal Transport and Storage — Coal Combustion — National Air Quality Standards — Emission Limitations and Strategies — CO_2 and Climate Change — Solid Waste — Thermal Emissions — Land and Water Use — Costs of Pollution Control for Utilities — Coal Use in Industries Other Than Utilities — New Coal Conversion Technologies — The Need for Research

The large expansion of world coal production and use projected by the World Coal Study to the year 2000 means that each country will need to consider the resulting environmental, health, and safety issues. There is extensive experience with the mining, transportation, and use of coal and the application of environmental controls in the countries represented in this Study.[1] The major problems and issues to be considered in establishing environmental policies, standards, and laws have been identified. Research conducted over the last decade has improved the state of knowledge about both the issues and the control strategies and technologies available. By 1979 many countries had adopted detailed legislative and regulatory systems, or other less formal systems, for controlling the environmental, health, and safety effects accompanying increased coal production and use.

Reasons for Environmental Concern

Uncertainties remain about some issues. For example, the

1. In WOCOL Final Report Volume 2, *Future Coal Prospects: Country and Regional Assessments*, each of the WOCOL country teams describes the specific environmental, health, and safety standards now in effect in its country and provides indicative cost estimates for meeting these standards.

magnitude of long-term health effects of some of the emissions from coal combustion; the effects of fossil fuel combustion on global climate; and the environmental, health, and safety hazards posed by synthetic fuel plants have not yet been determined. There are trade-offs that must be made in each country among the degree of control, the resource and financial costs associated with that degree of control, and the benefits from using coal. Comparisons must also be made between coal and other energy alternatives that have environmental, health, and safety effects of their own. Although uncertainties make it difficult at this time to make universally accepted statements on environmental issues, four general observations can be made.

1. Most of the environmental risks from coal use are amenable to technological control. Emission release, noise, and other effects can be reduced to whatever level is required by applying currently available technology. Each increment of reduction increases the cost, and as one approaches total control, such costs become very large. Within what can be expected as standards we believe that coal can be produced, transported, and used cleanly at costs that leave coal competitive with other fuels. It is likely that environmental concerns or control costs will preclude the development of certain sites or certain coal resources. However, there are so many possible sites and resources remaining worldwide that such exclusions will not be a limiting factor to the expansion of coal use.

2. National perceptions of values differ on such things as exposure of the general public to health risks or visibility reduction in the atmosphere. For example, controversy continues on the extent of health effects from various emissions from coal combustion. Moreover, environmental impacts differ because of regional characteristics such as meteorology, topography, population density, and resource distribution. For such reasons, nations and regions take different positions on the kind and extent of environmental control measures they will require as coal use increases. Even though views differ widely, the countries in the World Coal Study plan large expansions of coal use and expect to apply measures that will ensure compliance with their national environmental standards.

3. There are some issues on which joint action among nations may be needed. Adequate mechanisms may not now exist for implementing international cooperation, although there are some precedents in the use of ocean resources and in the programs of OECD nations

on environmental matters. Agreement on the application of existing control technology for the interest of other nations in excess of what one nation might do solely on its own interest may be difficult but necessary. For example, the long-range transport of emissions and deposition of acid rain in several countries is receiving increased attention and may require early action. Similarly, improved understanding of the effects of pollutants requires continuing international cooperation. The need to integrate and coordinate some environmental actions at global, regional, national, and local levels is becoming more important.

4. Finally, there is concern about climate effects from the build-up of carbon dioxide (CO_2) in the atmosphere from combustion of all carbon fuels including oil, gas, coal, and wood. Currently there is uncertainty about CO_2 inputs from various sources, the absorption of CO_2 by various sinks, and the consequences of the effects of rising CO_2 content in the atmosphere. If the effects prove as serious as some researchers predict, the resulting situation would call for extraordinary kinds of international cooperation to control world fuel combustion or, alternatively, the amount of deforestation. Even though some people believe that immediate action is necessary, most expect that there are at least several decades to evaluate the CO_2 climate modification issue. We urge strong support of research to improve our understanding of the effects of CO_2 on climate and to expand studies of the impacts of climate change.

Figure 4-1 illustrates some environmental disturbances from coal-related activities. It shows only the by-products from these activities, not their possible impact on public health or on the ecosystem at large.

Surface Mining

Much of the increase in coal production to the year 2000 is expected to come from surface mines. Therefore satisfactory reclamation of land after mining becomes important in countries with large surface mineable reserves.

In some countries, such as the Federal Republic of Germany, reclamation has been practiced on a large scale for many years. Large sections of land are planned for mining many years in advance, towns are moved, and people relocated. After the land has been mined and

PARTICIPANTS IN WOCOL

Project Director, Carroll L. Wilson
Massachusetts Institute of Technology

PARTICPANTS

Australia

Dr. Donald D. Brown
Deputy General Manager and Director
CSR Limited

Dr. Robert A. Durie
Chief Scientist
R.W. Miller Co. Pty. Ltd.

Mr. Kenneth G. Wybrow
Member, Joint Coal Board

Canada

The Hon. Jack Austin Q.C.
The Senate

Mr. Garnet T. Page
President
The Coal Association of Canada

Dr. Charles H. Smith
Senior Assistant Deputy Minister
Department of Energy, Mines & Resources

China, Peoples Republic of

Mr. Liu Huanmin[1]
Director, China Coal Society
Advisor, China Coal Industry Technical Installation Corporation

Denmark

Mr. Poul Sachmann
Executive Vice President
ELSAM

Finland

Mr. Kaarlo K. Kirvelä
Vice President and Director of the Energy Sector
Ekono Oy

France

Dr. Thierry de Montbrial
Director, Institut Français des Relations Internationales
Professor, L'Ecole Polytechnique

M. Jean-Claude Sore
Deputy Managing Director
Charbonnages de France

M. Albert Viala
Vice President
A.T.I.C.

Germany, Federal Republic of

Dr. rer. oec. Harald B. Giesel
Member of the Board
Gesamtverband des deutschen Steinkohlenbergbaus

Dr. H-D. Schilling
Head, Department of Coal Utilization
Bergbau-Forschung GmbH

Professor Hans K. Schneider
Director
Institute of Energy Economics
University of Koeln

India

Shri S.K. Bose
Joint Secretary
Ministry of Energy

Indonesia

Mr. S. Sigit
Secretary General
Department of Mines & Energy

Italy

Dr. Marcello Colitti
General Manager
ENI

Professor Umberto Colombo
Chairman, Comitato Nazionale per l'Energia Nucleare (CNEN)

Japan

Mr. Toyoaki Ikuta
President
Institute of Energy Economics

Mr. Hidezo Inaba
Vice Chairman
Committee for Energy Policy Promotion

Dr. Saburo Okita[2]
Chairman
Japan Economic Research Center

Mr. Setsuo Takagaki
Director of Research Affairs
Institute of Energy Economics

Netherlands

Dr. A.A.T. van Rhijn
Deputy Director-General for Energy
Ministry of Economic Affairs

Netherlands/UK

Mr. Frank Pecchioli
Managing Director
Shell Coal International Ltd.

Poland

Mr. Eugeniusz Ciszak
Deputy Managing Director, Director Tech.
Chief Mining Studies & Design Office (Ministry of Mining)

Sweden

Mr. Arne S. Lundberg
The Royal Swedish Academy of Engineering Sciences

United Kingdom

Mr. Robert Belgrave
Director, BP Trading Ltd.
Policy Adviser to Board of Directors, British Petroleum Co.

Sir Derek Ezra
Chairman
National Coal Board

Professor Sir William Hawthorne
Chairman, Advisory Council on Energy Conservation (1974-1979)
Master, Churchill College

Sir Ronald McIntosh
Executive Director
S.G. Warburg & Co. Ltd.
Former Director General of National Economic Development Office

United States

Mr. Thornton F. Bradshaw
President
Atlantic Richfield Co.

Mr. Gordon R. Corey
Vice Chairman
Commonwealth Edison Co.

Mr. W. Kenneth Davis
Vice President
Bechtel Power Corp.

Mr. Pierre Gousseland
Chairman and Chief Executive Officer
AMAX Inc.

Prof. Robert C. Seamans, Jr.
Dean, School of Engineering
Massachusetts Institute of Technology
Former Administrator, Energy Research & Development Admin. (ERDA)

Mr. Russell E. Train
President, World Wildlife Fund—U.S.
Former Administrator, Environmental Protection Agency (EPA)

International Institute of Applied Systems Analysis

Prof. Wolf Häfele
Deputy Director
Program Leader, Energy Systems

---

1 Observer

2 Until appointed Foreign Minister November 1979

0-88410-099-5

Carroll Wilson was appointed the first General Manager of the U.S. Atomic Energy Commission in 1947 and later held senior management positions in several companies involved in uranium mining and nuclear fuels fabrication. Since becoming a Professor in the Sloan School of Management at the Massachusetts Institute of Technology (M.I.T.) in 1960, he has organized and directed several global studies including: A Study of Critical Environmental Problems (*Man's Impact on the Global Environment, Assessment and Recommendations for Action*, SCEP Report, Cambridge, MA, M.I.T. Press, 1970), A Study of Man's Impact on Climate (*Inadvertent Climate Modification*, SMIC Report, Cambridge, MA, M.I.T. Press, 1971), and a world energy assessment by the Workshop on Alternative Energy Strategies (*ENERGY: Global Prospects 1985-2000*, WAES Report, New York, McGraw-Hill Book Co., 1977). He is now Mitsui Professor in Problems of Contemporary Technology (Emeritus) in the M.I.T. School of Engineering.

FUTURE COAL PROSPECTS: Country and Regional Assessments is a companion volume containing the full texts of the country reports prepared by teams from each of the sixteen countries participating in WOCOL as well as studies for other regions of the world. These reports describe the levels of coal production and use that each country has projected, where that coal would be used, and the policy and infrastructure actions required to reach such levels.

To order copies in the United States, contact Ballinger Publishing Company, 17 Dunster Street, Cambridge, MA 02138—telephone: (617) 492-0670. Outside the United States, contact any of the 17 Harper & Row Publishing offices around the world.

BALLINGER PUBLISHING COMPANY
17 Dunster Street
Cambridge, MA 02138

Annex 28

R. Madden & V. Ramanathan, “Detecting Climatic Change due to Increasing Carbon Dioxide”, *Science,* 1980, pp. 763-768

15 August 1980, Volume 209, Number 4458 SCIENCE

Detecting Climate Change due to Increasing Carbon Dioxide

Roland A. Madden and V. Ramanathan

Summary. The observed interannual variability of temperature at 60°N has been investigated. The results indicate that the surface warming due to increased carbon dioxide which is predicted by three-dimensional climate models should be detectable now. It is not, possibly because the predicted warming is being delayed more than a decade by ocean thermal inertia, or because there is a compensating cooling due to other factors. Further consideration of the uncertainties in model predictions and of the likely delays introduced by ocean thermal inertia extends the range of time for the detection of warming, if it occurs, to the year 2000. The effects of increasing carbon dioxide should be looked for in several variables simultaneously in order to minimize the ambiguities that could result from unrecognized compensating cooling.

The possible climatic effects of large increases in atmospheric CO_2 due to burning of fossil fuels may constitute one of the important environmental problems of the coming decades. Research efforts are being made to reduce the large uncertainties in estimates of future levels of CO_2 in the atmosphere and in corresponding model predictions of the climatic effects of these new levels. Another important aspect of the problem is our ability to detect climatic effects of increased CO_2, if and when they occur. The inherent variability of climate will make detection of changes due to increasing CO_2 difficult (*1*). If we consider climate changes due to CO_2 as a "signal," then the inherent variability acts as a "noise." It is our intention in this article to provide some quantitative estimates of this noise and to examine the feasibility of detecting a CO_2 signal.

The authors are staff scientists at the National Center for Atmospheric Research, Boulder, Colorado 80307.

We first discuss a long time series of surface temperatures and the rationale on which our estimates of the inherent variability or noise are based. Next we present the model results for surface warming due to the CO_2 increase. By comparing the estimated noise to the largest and the smallest signals predicted by models, we obtain a range of time within which we might expect to detect the effect of increasing CO_2 with some degree of statistical reliability. Uncertainties remain because our current knowledge of climate does not allow us to distinguish between changes due to CO_2 and those not due to CO_2 (*2*). However, the analysis places the problem in perspective. In order to prove or disprove the existence of the theoretically predicted effects of increasing levels of CO_2, it may be necessary to monitor several variables and formulate arguments based on physical as well as statistical grounds to minimize the effect of the many uncertainties involved.

Data Analysis

Data description. We estimated the noise on the basis of nearly continuous records of observed monthly mean temperatures from 1906 through 1977 for the 12 stations indicated in Fig. 1. Less than 1 percent of the possible 10,368 ($12 \times 12 \times 72$) monthly mean temperatures is missing. Values from the 12 stations were averaged to produce zonal mean temperatures that we assume to be representative of 60°N. This latitudinal zone was chosen because long time series of zonal means are more difficult to determine at other latitudes. The number of available stations with long records is more limited farther north and the geographic distribution of stations is less favorable farther south because of the larger percentage of oceans there.

Estimates of the noise. For the time being, we assume that the observed variance in the 72-year record results from factors other than possible effects of increasing CO_2 and, for the purpose of this analysis, is therefore noise (*3*). Later we will consider the contribution that a CO_2 signal, if it exists, might have made to the total variance over the 72 years. The noise can be reduced by time averaging. Jones (*4*) pointed out that the variance of time averages depends mainly on the spectral density near zero frequency and not on the total variance of the time series. For that reason, we first estimated the spectrum of the zonal mean temperature values, or their variance as a function of frequency. The data were broken up into five time series: one for each 3-month season (spring corresponds to March, April, and May, and so on) and one 12-month annual mean time series. Autocovariance functions were computed for each series out to a maximum of M lags. The autocovariances were then filtered with a Parzen filter (*5*) and the spectra estimated from the Fourier transform of the filtered autocovariances. The selection of M, the maximum lag, involves a compromise between minimizing the variance and minimizing the bias in our spectral estimates. By choosing a small M one obtains a small variance or range of statistical confidence limits about the estimated spectra, but

0036-8075/80/0815-0763$01.50/0 Copyright © 1980 AAAS

the bias is correspondingly large. Since it is likely that the true spectra fall off with increasing frequency (*6*), a choice of small M to minimize the confidence limits about the spectral estimates could seriously bias our near-zero spectral estimates downward. We chose $M = 27$, which results in approximately 9.5 degrees of freedom and a standardized bandwidth of 0.069 cycle per year (*5*). We discuss a likely consequence of bias for this choice of M in a later section.

The resulting spectra are presented in Fig. 2. It is important to note that the variance of 3-month summer means is less than that of 12-month annual means. This is because the variance of winter seasons is so much larger than that of summer seasons. Our basis for estimating the effect of longer time averages on the variance is the relationship between the input and output spectral density functions of a linear system (*7*); that is,

$$s(f)_N = S(f)|H(f)_N|^2$$

where $s(f)_N$ is, in this case, the power spectral density function of an N-year average of spring, summer, autumn, winter, or annual mean temperatures at frequency f, $H(f)_N$ is the amplitude response of an N-year average, and $S(f)$ is the power spectral density function of the corresponding seasonal or annual mean temperature.

The variance of an N-year average is given by

$$\sigma_N^2 = \int_{-\infty}^{\infty} s(f)_N df$$

or

$$\sigma_N^2 = \int_{-\infty}^{\infty} S(f)|H(f)_N|^2 \, df \qquad (1)$$

Figure 3 shows $|H(f)_N|^2$ for $N = 2$, 10, and 30. The importance of the low-frequency estimates of $S(f)$ in determining σ_N^2 is evident from Eq. 1 and Fig. 3.

From Eq. 1 we estimated σ_N^2 for the four seasonal and annual means for various times N. The results are indicated in Fig. 4, where $2\sigma_N$ is plotted against N. The curves for the four seasons resemble ones with an $N^{-1/2}$ dependence but they do not fall off quite as fast. This is because the seasonal spectra are approximately constant with frequency; that is, they are similar to spectra of uncorrelated data. The spectrum of annual means differs the most from this behavior, having relatively more variance at low frequencies than at high ones. The resulting decrease in variance with increasing averaging time is correspondingly less rapid than that for the seasonal means.

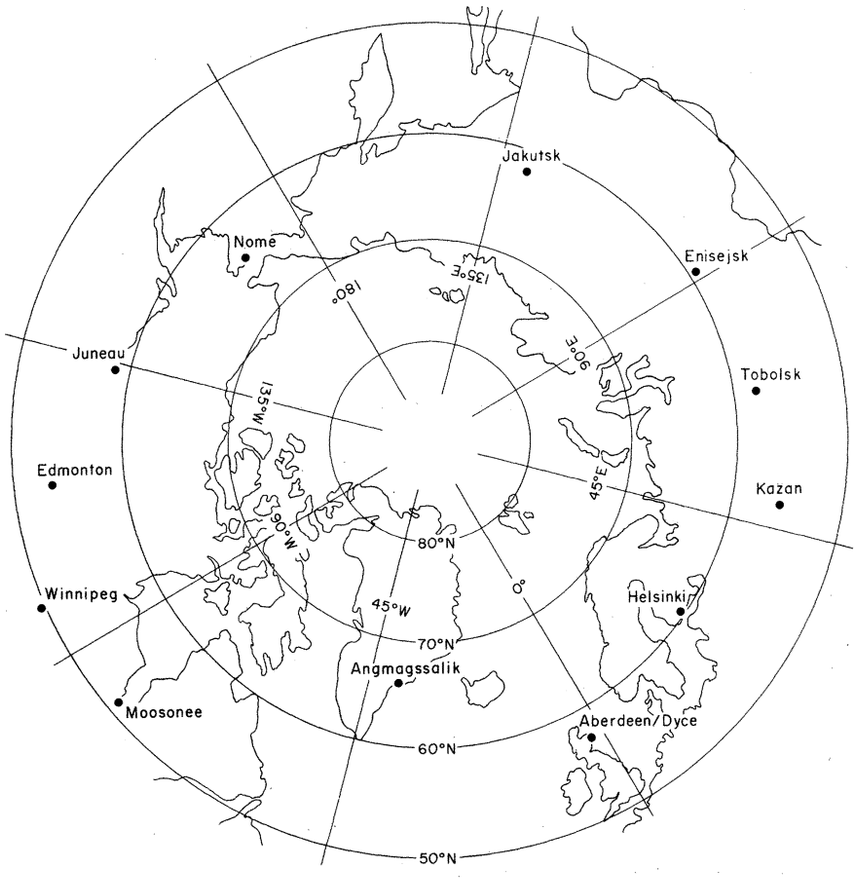


Fig. 1. Stations from which 72-year surface temperature records were taken to compute the approximate 60°N zonal mean.

Predicted Climatic Effects and Estimates of Uncertainty

Radiative heating. Increasing CO_2, while holding fixed all the other climate parameters that influence the radiation budget, will cause radiative heating of the surface-troposphere system. The hemispheric mean of this radiative heating $\langle \Delta q \rangle$ (angle brackets designate hemispheric mean) due to increased CO_2 can be approximately expressed as (*8*)

$$\langle \Delta q(\text{W m}^{-2}) \rangle = (5.9 \pm 1) \ln g; \quad 1 \le g \le 2 \qquad (2)$$

$$g = CO_2/CO_2{}^0; \quad 250 \le CO_2{}^0 \le 330 \text{ ppm} \qquad (3)$$

where g is the fractional increase of CO_2 over the reference atmospheric concentration, $CO_2{}^0$. The uncertainty of $\pm$ 1 watt per square meter for the constant 5.9 in Eq. 2 is due to possible errors in radiation model calculations (*9*).

The surface temperature signal. Climate models predict that CO_2 radiative heating warms the surface and troposphere. The increase in hemispheric mean surface temperature $\langle T_s \rangle$ can be expressed as

$$\langle \Delta T_s(\text{K}) \rangle = \frac{\langle \Delta q(\text{W m}^{-2}) \rangle}{\lambda_0(\text{W m}^{-2}\ \text{K}^{-1})} \qquad (4)$$

where the parameter λ_0 is determined by the feedback processes in the climate system, and has been the subject of considerable research in the last decade. We estimate a reasonable range for λ_0 to be

$$1 \le \lambda_0 \le 4 \text{ W m}^{-2}\ \text{K}^{-1} \qquad (5)$$

Most current climate model studies yield λ_0 values ranging from approximately 1 to 2 W m^{-2} K^{-1}. We consider 4 W m^{-2} K^{-1} to be an upper limit because (i) in current climate models mainly positive feedbacks are identified, and (ii) we obtain $\lambda_0 = 4$ W m^{-2} K^{-1} if we assume that the positive feedbacks are exactly canceled by as yet unidentified negative feedbacks or that the climate system is actually devoid of positive feedbacks (*10*). Hence in this analysis we will obtain the lower limit for the signal from Eq. 4 with $\lambda_0 = 4$ W m^{-2} K^{-1} and substituting the lower limit of Δq from Eq. 2. Hereafter, this lower limit will be referred to as the zero-feedback case.

Our interest is in high latitudes, for which we have estimated the noise and where, it turns out, the predicted ΔT_s is much larger than $\langle \Delta T_s \rangle$ (*8, 11*). The high-latitude amplification is triggered by the coupling between T_s and ice or snow cover—that is, the so-called ice/snow-albedo feedback (*11*). This amplification is significantly enhanced by the interac-

tions between T_s, atmospheric humidity, lapse rate, and radiative cooling to space (*11*, *12*). For this analysis, we adopt Manabe and Wetherald's (*11*) general circulation model (GCM) results for high-latitude ΔT_s. For a doubling of CO_2, their results can be approximately parameterized as

$$\Delta T_s(\theta) \approx 14(1 - 1.4 \cos \theta); \quad \theta > 55° \tag{6}$$

where θ is latitude. Because of the logarithmic dependence of $\langle \Delta q \rangle$ on g (Eq. 2), we can express Eq. 6 as

$$\Delta T_s(\theta) = 20 \ln g(1 - 1.4 \cos \theta); \quad \theta > 55° \tag{7}$$

We adopt Eq. 7 as an upper limit for the signal and refer to it as the positive-feedback case. Manabe and Wetherald's (*11*) study is for annual mean conditions and hence ignores the seasonal dependence of ΔT_s, which is shown to be significant by Ramanathan *et al.* (*8*). Using a seasonal energy balance climate model, Ramanathan *et al.* (*8*) indicated that the polar amplification occurs mainly during late spring and early summer and the spring-summer maximum in the computed ΔT_s agrees closely with Eq. 7. However, because of the simplified nature of their model, these results should be considered tentative and the expected seasonal variation uncertain.

Our estimate for the range of $\Delta T_s(\theta)$ is given by

$$1.2 \ln g \leq \Delta T_s(\theta) \leq 20 \ln g(1 - 1.4 \cos \theta); \quad \theta > 55° \tag{8}$$

The lower limit is for the zero-feedback case and the upper limit for the positive-feedback case. In using Eq. 4 to obtain the lower limit, we have tacitly assumed that ΔT_s is independent of season and latitude for the zero-feedback case.

Equation 8, relating g to ΔT_s, applies to the equilibrium (or steady-state) response of T_s to g. Since g is a function of time, ΔT_s as given by Eq. 8 should lag in time behind g because of the inertia of the climate system, which is primarily controlled by the thermal inertia of the oceans. This important question has received little attention in the literature, and recent studies employing simplified models of the ocean mixed layer indicate that ocean thermal inertia could delay the surface warming by periods ranging from a few years to a few decades (*13*).

Scenario for CO_2 increase. To estimate the range of the CO_2 signal we first need an estimate for the time history of g. With respect to the future increase in CO_2 concentrations, we adopt the projections of Baes *et al.* (*14*). Those authors considered two scenarios, one in which fossil fuel consumption corresponding to the present-day growth rate of 4 percent is continued indefinitely, the second in which there is a 2 percent growth rate up to the year 2025 and a symmetrical decrease in growth rate thereafter. We will refer to the first as the fast growth and the second as the slow growth scenario. In addition, Baes *et al.* considered uncertainties about the percentage of the additional CO_2 that remains airborne. To estimate the range of CO_2 signal due to the resulting uncertainty in future airborne levels, we will consider as an upper limit the fast growth case with 60 percent airborne and as a lower limit the slow growth case with 40 percent airborne. Resulting CO_2 concentrations and values of g are shown in Table 1. It is assumed that CO_2 concentrations are known to 1975.

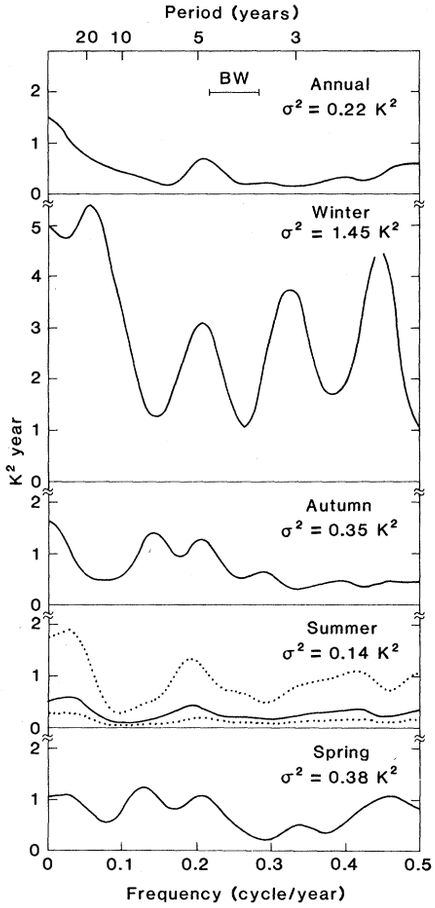


Fig. 2. Spectra $S(f)$ of the seasonal and annual zonal mean temperatures for 60°N. Areas under the spectra are proportional to variance in a given frequency range. The total variance σ^2 is indicated at the upper right, the bandwidth (*BW*) in the center. Spring, summer, autumn, and annual spectra are based on 72-year records, winter spectra on a 71-year record. Spectra have approximately 9.5 degrees of freedom. The 95 percent limits are indicated by dotted lines for the summer spectra.

Comparing Signal and Noise

Although the positive-feedback models indicate that there is a seasonal variation in the strength of the predicted signal, the nature of this variation is not certain. Therefore we examine two possibilities: (i) the predicted maximum in signal occurs during summer and (ii) this maximum occurs during winter. First we consider the summer maximum case, for which the largest signal-to-noise ratios would be likely (*15*).

Before proceeding to compare signals with noise, it is important to consider the likely effect of bias in our estimates of this noise. Our time series consists of 72 years of data. We cannot adequately estimate variability on longer time scales, yet from Eq. 1 and Fig. 3 it is evident that the low-frequency variability becomes a major contributor to the variance for very long time averages. With admitted uncertainty, Kutzbach and Bryson (*16*) have attempted to mesh both instrumental and noninstrumental records in order to describe the low-fre-

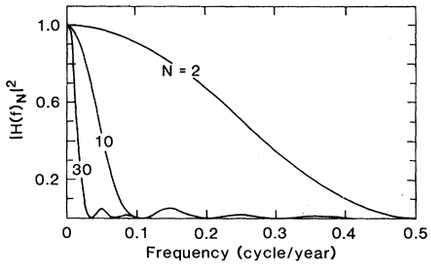


Fig. 3. Square of the amplitude response $|H(f)_N|^2$ for averages over N=2, 10, and 30 years.

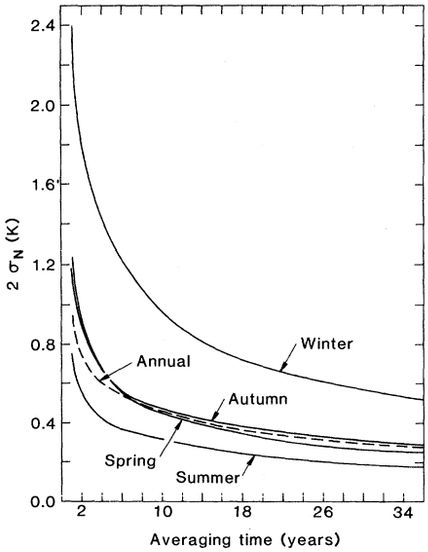


Fig. 4. Twice the expected standard deviations ($2\sigma_N$) for various averaging times N for each season and for annual averages. This is the estimated noise.

quency variance of winter temperature spectra. They found that the average spectral value between 100- and 1000-year periods is about twice that observed for periods near but shorter than 100 years. This gives us a basis for assessing the effect of bias on the summer curve of Fig. 4. If we were to model the summer spectrum between 0.01 and 0.001 cycle per year by twice the value shown in Fig. 2 in that frequency range, the level of $2\sigma_N$ shown in Fig. 4 would increase for 30-year averages ($N = 30$) by about 26 percent, from 0.19° to 0.24°C. The percentage increase would be less for shorter time averages and greater for longer time averages. The corresponding value of $2\sigma_{30}$ computed for the upper 95 percent limit of the summer spectrum shown in Fig. 2 is 0.34°C, nearly 80 percent larger than the 0.19°C computed from the spectrum itself. We tentatively conclude that, although our estimates of $2\sigma_N$ are probably biased downward, the effect is considerably smaller than that of the uncertainty due to sampling variability. This should be true for N on the order of 30 years, but bias probably becomes a more serious problem for N much larger than 30.

Figure 5, where Eq. 8 is combined with the summer curve from Fig. 4 (the summer noise), provides an estimate of when the predicted signal due to increasing CO_2 (obtained from Table 1) would exceed twice the estimated noise. The summer noise curve is taken directly from Fig. 4; the averaging time in years is indicated at the bottom, along with a date which is based on the assumption that averages begin in 1956 (*17*). The signal for the positive-feedback models is taken from the maximum value of $\Delta T_s(\theta)$ indicated in Eq. 8 for $\theta = 60°N$. The signal for the zero-feedback models is taken from the corresponding minimum value indicated in Eq. 8. The signals are plotted against the time scale at the top of Fig. 5, neglecting any delays that might arise from the inertia of the climate system. Displacement of the signal scale (top) with respect to the noise scale (bottom) is necessary since, for example, a 20-year average from 1956 to 1975 would be an estimate of the 1965 signal. The two signal curves fan out after 1975 as a result of the uncertainty in future levels of airborne CO_2. The upper limit reflects the fast growth, 60 percent airborne estimates and the lower limit the slow growth, 40 percent airborne estimates. The 95 percent limits about the noise curve (dotted lines) were determined from Eq. 1, with $S(f)$ taken from the 95 percent limits on the summer spectrum that are indicated in Fig. 2.

Table 1. CO_2 increase estimated from projections in (*14*). For 1985 and 1995 the upper limit (first value) is obtained from the fast growth (60 percent airborne) assumption and the lower limit (second value) is obtained from the slow growth (40 percent airborne) assumption.

Year	$[CO_2]$ (ppm)	$g = [CO_2]/300$
Before 1930	300	1.0
1955	315	1.05
1965	321	1.07
1975	333	1.11
1985	360, 339	1.20, 1.13
1995	393, 348	1.31, 1.16

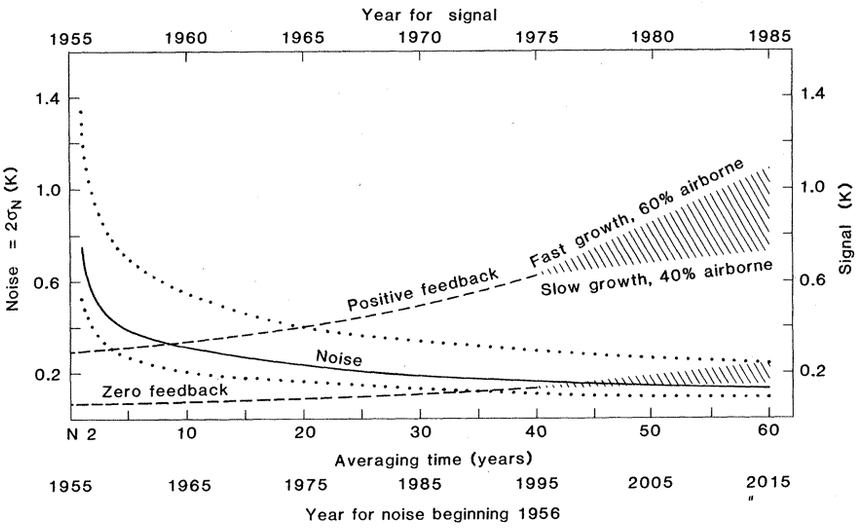


Fig. 5. Summer season $2\sigma_N$ from Fig. 4 (solid line) and 95 percent limits (dotted lines) plotted against averaging time and year beginning in 1956. Positive-feedback signal (upper dashed line) and zero-feedback signal (lower dashed line) are plotted against the year indicated at the top (see text for explanation of upper and lower year scales). Possible delays due to inertia of the climate system are not accounted for in the signal. Fanning out of the signal curves indicates the uncertainty of future CO_2 levels in the atmosphere; the upper values are based on fast growth with 60 percent CO_2 airborne and the lower values on slow growth with 40 percent airborne.

To interpret Fig. 5, we first assume that we know what the no-signal zonal mean temperature (the zonal mean temperature before any effect due to increasing CO_2) was, and that the noise curve does accurately depict the variability of time-averaged temperature that is not due to increasing CO_2. Under these circumstances, we would conclude that a 9-year average of summer temperatures computed from 1956 through 1964 should come from a distribution with a mean that is displaced 2 standard deviations toward higher temperatures from the no-signal zonal mean if the positive-feedback models predict the effects of increasing CO_2 correctly. If the zero-feedback models are correct, it would require a 45-year average from 1956 through 2000 for a similar situation to occur. We interpret Fig. 5 as giving an approximate range of time when we might expect to be able to establish statistically that model predictions are correct. That range extends from the present if the positive-feedback models are correct to near the year 2000 if the zero-feedback models are correct. As it turns out, a 20-year average temperature from 1956 through 1975 is not higher than a 20-year average temperature from 1906 through 1925; in fact, it is slightly lower (14.2°C compared to 14.42°C). Therefore, we cannot provide statistical evidence that there has been an effect due to increasing CO_2 on the present mean zonal temperature at 60°N.

These results are summarized in Fig. 6 in the form of signal-to-noise ratios (signal/$2\sigma_N$). Curves 1 and 5 come directly from Fig. 5 and depict the ratios for summer noise and the positive-feedback and zero-feedback signals, respectively. Because the seasonal dependence of positive-feedback signals is not adequately understood, we include three other curves in Fig. 6. Curve 4 is the positive-feedback signal from Fig. 5 divided by $2\sigma_N$ for winter seasons. This provides an estimate of the signal-to-noise ratio for winter if it turns out that the seasonal dependence is such that the maximum signal occurs in that season. If that proved to be the case, the corresponding signal for the other three seasons should be approximately given by (*18*)

$$\Delta T_s \approx 3 \ln g \qquad (9)$$

Curve 2 is the signal-to-noise ratio for the resulting signal given by Eq. 9 and the summer noise. It is meant to approximate the signal-to-noise ratio for summer, for the case in which the seasonal dependence results in a maximum signal occurring not in summer, as in curve 1, but in winter. A comparison of curves 2 and 4 illustrates that, even in this case,

the signal-to-noise ratios would be larger in summer. Finally, curve 3 is based on an annual average signal given by

$$\Delta T_s = \frac{9 \ln g + 20 \ln g\,(1 - 1.4 \cos \theta)}{4} \quad (10)$$

Equation 10 is based on the assumption that the signal for three seasons is given by Eq. 9 and that for the fourth is given by Eq. 8. The noise is that determined for the annual averages. Since for $N > 6$ curves 1 and 2 fall above curves 3 and 4, we conclude that a CO_2 signal will be easiest to detect in summer unless its seasonal variation is significantly different from those considered here.

Like Fig. 5, Fig. 6 is based on the assumption that the thermal inertia of the climate system is zero. Thermal inertia would displace the curves to the right through a distance that depends on how much the signal in the surface temperature is delayed. For example, for a delay of 10 years, the signal-to-noise ratio for the signal from Eq. 9 and the summer noise would equal one around 1988 instead of 1977 as indicated by curve 2 in Fig. 6.

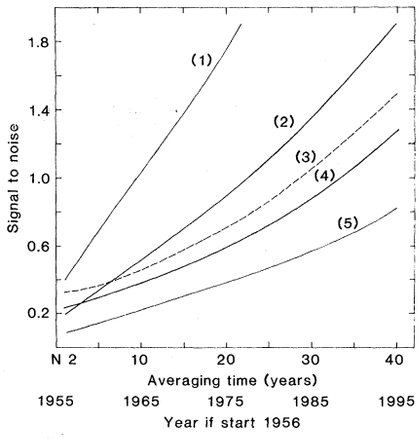


Fig. 6. Predicted signal divided by $2\sigma_N$ for (curve 1) feedback signal from Fig. 5 and $2\sigma_N$ for summer season from Fig. 4, (curve 2) signal from Eq. 9 and $2\sigma_N$ for summer season, (curve 3) average annual signal (see text) and $2\sigma_N$ for annual averages from Fig. 4, (curve 4) feedback signal from Fig. 5 and $2\sigma_N$ for winter season from Fig. 4, and (curve 5) zero-feedback signal from Fig. 5 and $2\sigma_N$ for summer season from Fig. 4. In computing signals we have neglected possible delays due to inertia of the climate system.

Discussion

The analysis of observed temperature variability at 60°N indicates that the surface warming predicted by current general circulation models of climate (*19*) should be evident now or at least within the next decade, depending on the seasonal dependence of the warming and on the ocean thermal inertia of the climate system. If the ocean thermal inertia does not delay the signal by more than a decade and the warming peaks in spring or summer, the surface warming should be detectable now. Since a recent 20-year average is not higher than a 20-year average from 1906 through 1925, we conclude that either such models overpredict the signal, or other compensatory climate changes are occurring. If the latter is not a serious problem and the warming is occurring at a rate lower than that predicted by GCM's but higher than that predicted by zero-feedback models, then it should be detectable anytime from the present to about the year 2000. In addition, we conclude that it will be easiest to detect effects in summer data.

We have assumed that all of the observed variance in the 72-year record is due to noise. The signal, if present in the data, would also contribute to the variance. Considering the positive-feedback signal to be very nearly a linear function of time, then it would contribute about 0.04 K^2 to the total variances of the time series (*20*) or 29 percent of the estimated summer noise of 0.14 K^2. This percentage would be larger for time-averaged data since the predicted slow temperature increase is essentially a low-frequency signal. However, attempting to isolate the noise by subtracting the predicted signal from the data beforehand increases the variance of the time series since there is no upward trend present. This brings us back to an important facet of the problem that cannot be neglected. Because our present knowledge of the causes of climate change is limited, it is difficult to distinguish between change that may be due to increasing CO_2 and change that is not. While it is reasonable to attempt to account for changes not due to CO_2 by looking at past records as we have done, we cannot be certain that such changes have not masked a CO_2 effect, or conversely that they may not indicate in the future that there is an observable effect of CO_2 when there is none. Because of this, as well as uncertainties in model predictions, unambiguous statistical proofs regarding the effects of CO_2 based on observations of a single variable will always be difficult. It may be necessary to look for physical as well as statistical evidence in order to adequately isolate and monitor possible effects of increasing CO_2. Physical evidence might be found in certain consistent relationships between two or more variables.

For example, as indicated by model studies, the increase in tropospheric temperature caused by CO_2 increase should be accompanied by a relatively large cooling within the middle and upper stratosphere. Hence, we can look for out-of-phase changes between troposphere and stratosphere. However, the decrease in O_3 that is predicted due to continued use of chlorofluoromethanes (CFM's) can cause a stratospheric cooling of the same order of magnitude as the estimated CO_2 cooling (*21*), and this possibility must not be neglected.

Another approach would involve monitoring the radiation budget data obtained by satellites. Satellites measure the outgoing infrared flux (both integrated and spectral) and the solar flux reflected by the earth-atmosphere system. The predicted Δq should be seen as a reduction in the outgoing infrared flux between 13 and 17 micrometers, while the predicted increase in T_s caused by Δq would increase the outgoing flux in the rest of the infrared spectrum. If, on the other hand, the effect of CO_2 increase is compensated by other effects such as an increase in aerosols or low clouds, then the decrease in infrared flux between 13 and 17 will be compensated by an equivalent increase in the reflected solar flux. Conversely, if other anthropogenic effects (*2*) contribute appreciably to a future warming, such as increases in N_2O, CH_4, CFM's, and tropospheric O_3 (all of which have bands in the 8- to 12-μm "window" region), there will be a corresponding decrease in the outgoing infrared flux in the window region.

Satellite measurements of adequate spectral resolution are available but, because of their limited accuracy and time history, they can only be used to detect effects of large CO_2 changes such as those expected to occur during the next century. We need to develop adequate strategies for summarizing and saving these valuable data for future use.

References and Notes

1. J. M. Mitchell, in *Workshop on the Global Effects of Carbon Dioxide from Fossil Fuels*, W. P. Elliott and L. Machta, Eds. (CONF-770385, UC-11, Department of Energy, Washington, D.C., 1979).
2. Some other potential causes of climate change are the following. (i) Anthropogenic sources: increases in CFM's enhance the atmospheric greenhouse effect in the spectral region 8 to 12 μm. In addition, the CFM's may cause a reduction in O_3, which in turn can affect the climate. An increase in tropospheric O_3 due to CO and hydrocarbons, an increase in N_2O due to fertilizer use, and modification of the surface albedo by overgrazing and deforestation are among the important man-made forces that may affect climate. (ii) External boundary conditions: change in the solar constant and changes in stratospheric aerosol loading due to volcanic activity. By definition, one might consider any process whose time scale is long relative to daily weather fluctuations, such as sea-surface temperature and ice cover, to be external. (iii) Intransitivity [E. N. Lorenz, *Meteorol. Monogr.* **8**, 1 (1968)]: this arises because the governing physical laws may allow more than one set of long-term statistics.
3. Observed variance is sometimes assumed to reflect potentially predictable shifts in climate means as well as unpredictable fluctuations in finite-time average estimates of those means. The

latter component is referred to as noise [C. E. Leith, *J. Appl. Meteorol.* **12**, 1066 (1973); R. A. Madden, *Mon. Weather Rev.* **104**, 942 (1976); _____ and D. J. Shea, *ibid.* **106**, 1695 (1978)]. This distinction need not be made here, since the possible effects of increasing CO_2 must be isolated from the total interannual variability regardless of its ultimate origin.
4. R. H. Jones, *J. Appl. Meteorol.* **14**, 159 (1975).
5. G. M. Jenkins and D. G. Watts, *Spectral Analysis and Its Applications* (Holden-Day, San Francisco, 1968), pp. 244–252.
6. J. M. Mitchell, *Quat. Res. (N.Y.)* **6**, 481 (1976).
7. R. B. Blackman and J. W. Tukey, *The Measurement of Power Spectra from the Viewpoint of Communications Engineering* (Dover, New York, 1958), pp. 25 and 112.
8. V. Ramanathan, M. S. Lian, R. D. Cess, *J. Geophys. Res.* **84**, 4949 (1979).
9. T. Augustsson and V. Ramanathan [*J. Atmos. Sci.* **34**, 449 (1977)] show that the various radiative-convective model studies yield values for enhanced CO_2 radiative heating that agree with each other within 10 percent. On this basis, we conservatively assume an uncertainty of approximately ± 20 percent due to radiation model errors.
10. The upper limit for λ_0 (≈ 4 W m^{-2} K^{-1}) is obtained by assuming that the climate system is devoid of all feedbacks other than infrared radiative damping and that it emits infrared radiation like a blackbody with an equilibrium temperature of about 255 K. One-dimensional radiative-convective models yield values of λ_0 ranging from 1.25 to 2 W m^{-2} K^{-1} [V. Ramanathan and J. A. Coakley, *Rev. Geophys. Space Phys.* **16**, 465 (1978)]. Energy balance climate models yield λ_0 values ranging from 1 to 2 W m^{-2} K^{-1} [for example, see M. S. Lian and R. D. Cess, *J. Atmos. Sci.* **34**, 1058 (1977)], from which we obtain the lower limit of λ_0 shown in Eq. 4. The principal reason why the model λ_0 values are significantly smaller than 4 W m^{-2} K^{-1} is the inclusion of relative humidity feedback [see the Ramanathan and Coakley reference cited above] and the ice-albedo feedback [see the Lian and Cess reference cited above]. The effects of these two positive feedbacks may be compensated by as yet unidentified negative feedbacks involving cloud-radiative interactions and ocean-atmosphere interactions.
11. S. Manabe and R. T. Wetherald, *J. Atmos. Sci.* **32**, 3 (1975).
12. V. Ramanathan, *ibid.* **34**, 1885 (1977).
13. S. L. Thompson and S. H. Schneider, *J. Geophys. Res.* **84**, 2401 (1979); B. G. Hunt and N. C. Wells, *ibid.*, p. 787.
14. C. F. Baes, H. E. Goeller, J. S. Olson, R. M. Rotty, *Oak Ridge Natl. Lab. Rep. ORNL-5194*, (1976).
15. From Fig. 2, we saw that annual averages have larger noise than summer averages. We also computed 9-month averages from March through November, excluding the winter months. The resulting variance is slightly less than that for the 3-month summer averages (0.13 compared to 0.14 K^2); however, the spectrum of the 9-month averaged data has relatively more variance at low frequencies than that of the summer-averaged data, so that averaging several summers together decreases the noise variance faster than averaging several 9-month means together. As a result, we believe that the 3-month summer seasons provide the data set with the least noise.
16. J. E. Kutzbach and R. A. Bryson, *J. Atmos. Sci.* **31**, 1958 (1974).
17. Results did not appear to be particularly sensitive to assumed starting date. For example, when averages are computed from 1930, the positive-feedback signal crosses the $2\sigma_N$ noise line in 1960 (30-year average) and the zero-feedback signal is still below the line in 1990 (50-year average). By beginning averages in 1956, we can avoid some of the uncertainties which bias in the near-zero frequency spectral estimates introduce into longer time averages with virtually no change in the result.
18. In this case, since we have assumed that the ΔT_s amplification due to ice-albedo feedback is manifested during winter, the summer signal is that given by the positive-feedback models without the ice-albedo feedback. The λ_0 for the positive-feedback models without ice-albedo feedback is approximately 2 W m^{-2} K^{-1}, and hence Eq. 9 is obtained by combining Eqs. 2 and 4 with $\lambda_0 = 2$ W m^{-2} K^{-1}. Also, the results for this case closely resemble those obtained by S. Manabe and R. J. Stouffer [*Nature (London)* **282**, 491 (1979)]. In their coupled GCM-simple mixed-layer ocean model, Manabe and Stouffer found, at 60°N for $g = 4$, a winter warming of about 10 K and a summer warming of 4 K. Equations 7 and 9 give similar values of 8.3 and 4.2 K.
19. Several unpublished GCM studies of the CO_2 climate problem are summarized in a recent report [Ad Hoc Study Group on Carbon Dioxide and Climate, *Carbon Dioxide and Climate: A Scientific Assessment* (Climate Research Board, National Research Council, Washington, D.C., 1979)]. As seen from this report, the high-latitude surface warming predicted by the GCM's is of the same magnitude or larger than the upper limit for ΔT_s given in Eq. 8.
20. From Fig. 5 the positive-feedback signal is about 0.70 K in 1977. Since the signal is nearly a linear function of time, it would contribute (0.7 K)^2/12 to the variance.
21. V. Ramanathan and R. E. Dickinson, *J. Atmos. Sci.* **36**, 1084 (1979).
22. We thank S. Schneider and H. van Loon for their helpful comments on an earlier version of this article.

Teratocarcinomas and Mammalian Embryogenesis

Gail R. Martin

Teratomas have always intrigued pathologists because they contain a grotesque array of diverse tissues, sometimes including highly organized structures such as teeth, fingers, and hair. Thanks to the pioneering work of Stevens (*1*), these rare tumors have become more than a curiosity of human pathology. Stevens observed that mice of certain inbred strains frequently develop tumors analogous to human teratomas. His subsequent studies provided a clear understanding of how teratomas arise in mice and perhaps in man as well. As cell lines were established from the mouse tumors that Stevens made available, it became apparent that these cultured cells (known as embryonal carcinoma cells or teratocarcinoma stem cells) are remarkably similar to the cells of the early embryo. The use of these tumor cells as a model system for the study of mammalian development in vitro circumvents many of the difficulties of working with embryonic material. Interest was further stimulated by the demonstration that embryonal carcinoma cells taken from the tissue culture dish can participate in the formation of a normal mouse. Such results have raised the hope that teratocarcinoma cells will be useful in creating mouse models of human genetic diseases. The discussion in this article centers on what teratocarcinoma stem cells are and on some of the ways in which their potential uses have been exploited.

Pluripotency and origin of teratocarcinoma stem cells. A typical mouse teratoma or teratocarcinoma contains a mixture of differentiated cell types (Fig. 1A). This complexity is accounted for by the fact that these tumors arise from stem cells that are pluripotent (*2*); that is, they are capable of forming derivatives of all three primary germ layers, namely, endoderm, mesoderm, and ectoderm. The random array of differentiated tissues forms as some stem cells differentiate into cartilage, and others into nerve, muscle, glandular tissue, or other cell types. It is not yet known what triggers such differentiation, but in general the differentiated derivatives of the stem cells are normal, nonmalignant cells (*3*).

Some stem cells, instead of differentiating, continue to proliferate in the undifferentiated state. They thus form nests of pluripotent embryonal carcinoma cells interspersed in the disorganized mixture of differentiated derivatives (Fig. 1B). The continued proliferation of this undifferentiated stem-cell population is responsible for the malignant properties of teratocarcinomas such as progressive growth and transplantability, but not metastasis (*4*). In cases where the stem cells cease to proliferate because they differentiate or die, the tumors become benign and are known as teratomas. Strictly speaking, "teratocarcinoma" refers to a malignant tumor, and "teratoma" refers to a benign one. The latter term, however, is often used to designate either type of tumor.

The author is an assistant professor in the Department of Anatomy, School of Medicine, University of California, San Francisco 94143.

0036-8075/80/0815-0768$02.00/0 Copyright © 1980 AAAS

Annex 29

Minutes of the Meeting of American Petroleum Institute CO2 and Climate Task Force (AQ-9), 29 February 1980

American Petroleum Institute
2101 L Street, Northwest
Washington, D.C. 20037
202-457-7000

J. J. Nelson
(202) 457-6381

March 18, 1980

To: AQ-9 Task Force

Attached please find a copy of the minutes of the February 9, 1980 AQ-9 Task Force meeting. Please inform me of any errors or omissions.

Cordially,

J. J. Nelson

Attachment--minutes

/mi

An equal opportunity employer

CO_2 AND CLIMATE TASK FORCE (AQ-9)

Minutes of Meeting

9:15 a.m.
Friday, February 29, 1980

Manhatten Room
LaGuardia Airport
New York City, New York

MEMBERS PRESENT

K. Blower, Chairman	SOHIO
B. Bailey	Texaco
H. Shaw	Exxon R&E

OTHERS PRESENT

J. Laurman	Consultant
J. Nelson	API/EAD
C. Showers	SOHIO

OPENING REMARKS

K. Blower, Chairman, opened the meeting by listing the following goals of this meeting:

1. Increase industry's understanding of the CO_2 and climate problem.

2. Determine if there are feasibile and valuable research projects that could be accomplished by API.

3. Establish a mechanism to prepare any needed issue papers.

B. Bailey added the following items for consideration:

1. This Task Force should be the focal point and establish a basis for providing API comments on CO_2 and climate matters.

2. An overall goal of the Task Force should be to help develop ground rules for energy release of fuels and the cleanup of fuels as they relate to CO_2 creation.

CONSULTANT REPORT

Dr. J. A. Laurman, a consultant and a recognized expert in the field of CO_2 and climate, made a presentation to the Task Force entitled, "The CO_2 Problem; Addressing Research Agenda Development."

An outline is included as Attachment A.

In addition, a complete technical discussion, led by Dr. Laurman identified the problem, discussed the scientific basis and technical evidence of CO_2 buildup, impact on society, methods of modeling and their consequences, uncertainties, policy implications, and conclusions that can be drawn from present knowledge. A series of summary charts are attached as Attachment B.

API RESEARCH NEEDS

One area of possible API research was identified: Preparatory research to be able to answer questions dealing with the CO_2 problem and synthetic fuels.

COMMENTS ON DOE TECHNICAL PAPER

K. Blower and Bruce Bailey will modify the draft API letter back to DOE concerning an article submitted to the Task Force for comment. When the Task Force has approved the letter, it will be coordinated within API staff.

OTHER BUSINESS

The Task Force should set up a rationale and system for review of technical articles and responses to inquiries.

One potential area for R&D was discussed by the Task Force: "Investigate the Market Penetration Requirements of Introducing A New Energy Source into World Wide Use." This would include the technical implications of energy source changeover, research timing and requirements.

The meeting was adjourned at 4:25 p.m.

Prepared by:

Jimmie J. Nelson

THE CO_2 PROBLEM; ADDRESSING RESEARCH AGENDA DEVELOPMENT

The difficulties of dealing with the pragmatic questions related to the CO_2/fossil fuel problem all relate to certain general features, these having A) high impact cost, B) large uncertainty, and being C) far distant and D) global. The problem is interdisciplinary in its scientific aspects and it has ramifications in many economic sectors and in most nations. Therefore, not only is addressing it difficult in anlytic terms, but the mulitiplicity of possible interest groups that can be affected means that choice of what constitute the critical research issues depends on the user. In the most general terms we can subdivide the motivational aspect into those who see the need as to

A) better understand the CO_2/climate system, resulting in an ability to predict a) short range and b) long range effects.

or to

B) assess the present day importance of the future impact, as viewed
   i) from a world viewpoint
   ii) by national entities
   iii) by specific industrial sectors or interest groups

Highest priority investigations depend on which of these groups is involved. In particular, a highly relevant aspect for all of these groups is the influence of present and future information on public perception and governmental attitudes regarding the problem and the resultant effect on energy policy.

Instead of attempting to research all aspects of the CO_2 problem that bear on the concern of any particular group, we may select a feature that appears to be particularly important to that sector - for example, nuclear energy proponents might wish to address the problem of market penetration time lags as the most critical for making their case.

A) Reducing uncertainty in projections

CO_2 input

a) deforestation, past present and future.

b) effect of various energy use policies - coal, oil shale, nuclear, biomass, solar, synthetics.

c) turn-around scenarios for non-carbon based fuel use, impact calculations.

d) remedial measures: biomass, scrubbing, bacterial enzymes, fertilizing oceans.

Carbon cycle

a) CO_2 growth and photosynthesis

b) missing CO_2 since - detritus, humus, regrowth of deforested areas, oceans, non-stationary biosphere.

c) validity of box-model projections in short (50 yr) range.

d) organic material in oceans (detritus, dissolution, nutriant limitations)

e) estuarian regions

f) ground water

g) carbonate distribution

h) use of tracers

i) cataloguing on the biosphere

j) climatic change feedback effects - ocean temperature, plant growth.

Climate modeling

a) ocean dynamics

b) simplifying models

c) feedback effects : clouds, sea ice, vegitation change(albedo).

d) regional climatic change

B) Impact of climatic change

Socio-economic

I) General problems:

a) how to make estimates of costs of large perturbations, even assuming climatic changes are known?

b) how do we discount the future?

c) geopolitical problems, either from climatic change or from remediation measures

d) building in resilience. Can severity be versed in terms of critical rates of change of forcing of the societal system? Is a generic non-specific formulation possible?

II) Immediate policy questions. The physical facts agree on the probability of large effects 50 years away, but with large probable error. Source of the uncertainty arises from deforestation, poor climate models and uncertainty in CO_2 input (energy projections). The first may be settled in a year or two; the second will not. Hence we have to treat an unsure situation, which may be possible via decision analysis if error distribution can be quantified. This has not been done for impact costs, so first

a) can it be? If yes, there still remain two major difficulties:

b) what are market penetration times for new energy sources? and

c) what future (social) discounting rate should be used?

If fossil fuel use rates are reduced to 2% p.a. or under, it looks as if the immediate problem is considerably eased (but needs checking). So another question is

d) what is the 50 year future of fossil fuel use?

Of more parochial interest is

e) what roles do the different catagories of fossil or synthetic fuel play in future projections?

The Natural Biosphere

The Managed Biosphere

REASONS FOR INCREASED CONCERN WITH THE CO_2 PROBLEM

- DEVELOPMENT OF RELIABLE ATMOSPHERIC CO_2 GROWTH RATE MEASUREMENTS
- ITS CORRELATION WITH GLOBAL INDUSTRIAL CO_2 EMISSIONS, MOSTLY FROM FOSSIL FUEL COMBUSTION
- SCIENTIFIC CONSENSUS ON THE POTENTIAL FOR LARGE FUTURE CLIMATIC RESPONSE TO INCREASED CO_2 LEVELS
- REALIZATION THAT REMEDIAL ACTIONS WOULD TAKE A LONG TIME TO BECOME EFFECTIVE

ATTACHMENT B

OBSERVATIONAL EVIDENCE - CONCLUSIONS

- TWENTY YEARS OF GOOD CO_2 DATA, BUT ESSENTIALLY FROM ONE SOURCE
- PRESENT ATMOSPHERIC CO_2 CONCENTRATION = 335 ppm
  PRE-INDUSTRIAL (1860)" " ≈ 290 ppm
- CURRENT GROWTH RATE = 4.3% p.a. OF INCREASE SINCE 1860
- STRONG EMPIRICAL EVIDENCE THAT RISE CAUSED BY ANTHROPOGENIC RELEASE OF CO_2, MAINLY FROM FOSSIL FUEL BURNING
- ATMOSPHERIC RETENTION IS 56% OF RELEASE, ASSUMING NO EFFECTS FROM DEFORESTATION

ENERGY USE PROJECTIONS - CONCLUSIONS

- AVERAGE GROWTH RATE 3-4% p.a. FOR NEXT FIFTY YEARS, FOSSIL FUEL SLIGHTLY LESS
- THIS IS NOT CONSISTANT WITH LONG TERM PAST TREND
- PROJECTED CO_2 RELEASE ~~RATE~~ INCREASE (PROPORTIONAL TO INTEGRATED FOSSIL FUEL OUTPUT)
  CLOSE TO 3% p.a. UNTIL MID-21ST CENTURY; SUBJECT TO ERROR OF
  ABOUT ± 1% p.a.
- EFFECT OF FOSSIL FUEL DEPLETION MINOR IN NEXT FIFTY YEARS

CARBON CYCLE - CONCLUSIONS

- POSSIBLE CO_2 RELEASE CONTRIBUTION FROM DEFORESTATION, PERHAPS RIVALLING FOSSIL FUEL SOURCE
- ALL CARBON CYCLE MODELS BEHAVE LINEARLY UP TO 3-4 TIMES PRE-INDUSTRIAL ATMOSPHERIC CO_2 LEVELS
- HENCE GIVE THE SAME PROJECTED ATMOSPHERIC CO_2 LEVELS FOR THE SAME INPUT
- FOSSIL FUEL DEPLETION EFFECTS SMALL
- DEFORESTATION EFFECT ON PROJECTIONS ONLY SIGNIFICANT IF IT BECOMES DEPLETED
- CO_2 "DOUBLING" DATE IS 2038 AT A 3% p.a. GROWTH OF ATMOSPHERIC RELEASE RATE
- ERROR IN THIS ESTIMATE IS SMALL COMPARED WITH OTHER SOURCES OF ERROR

CLIMATE MODELING - CONCLUSIONS

- GLOBAL AVERAGED 2.5°C RISE EXPECTED BY 2038 AT A 3% p.a. GROWTH RATE OF ATMOSPHERIC CO_2 CONCENTRATION
- LARGE ERROR IN THIS ESTIMATE - 1 IN 10 CHANCE OF THIS CHANGE BY 2005
- NO REGIONAL CLIMATE CHANGE ESTIMATES YET POSSIBLE
- LIKELY IMPACTS:

  1°C RISE (2005): BARELY NOTICEABLE

  2.5°C RISE (2038): MAJOR ECONOMIC CONSEQUENCES, STRONG REGIONAL DEPENDENCE

  5°C RISE (2067): GLOBALLY CATASTROPHIC EFFECTS

UNCERTAINTY IN ESTIMATES

1) CARBON CYCLE MODELING - MINOR

2) DEFORESTATION - MAJOR EFFECT ONLY IF RATE IS LARGE AND DEPLETION SETS IN

3) NATURAL CLIMATE VARIABILITY - SMALL, ABOUT 0.5° C IN 50 YEARS

4) OTHER ANTHROPOGENIC SOURCES - LESS THAN CO_2, BUT POTENTIALLY MAJOR IF CONSIDERED IN TOTO

5) EFFECT OF A ± 1% VARIATION IN FOSSIL FUEL GROWTH RATE RELATIVELY MINOR

6) CLIMATE MODELING ERROR VERY LARGE; ALLOWANCE IN POLICY ANALYSIS ESSENTIAL

POLICY IMPLICATIONS

- GLOBAL PROBLEM, BOTH IN SOURCE AND FOR REMEDIES
- TIME SCALE FOR SIGNIFICANT IMPACT, VERY ROUGHLY 50 YRS
- HIGH RISK, HIGH UNCERTAINTY SITUATION, RELATIVELY FAR AWAY
- TIME FOR ACTION ? MARKET PENETRATION TIME THEORY SAYS THERE IS NO LEEWAY

CONCLUSIONS

- AT A 3% PER ANNUM GROWTH RATE OF CO_2, A 2.5°C RISE BRINGS WORLD ECONOMIC GROWTH TO A HALT IN ABOUT 2025.

Even if this estimate is grossly wrong it is still probable that

- WHETHER THERE ARE GROUNDS FOR IMMEDIATE RESPONSE TO THE THREAT DEPENDS ON THE VALIDITY OF THE LONG MARKET PENETRATION TIME CONCEPT.
- EVEN IF THE LATTER IS APPLICABLE, PRESENT DAY SIGNIFICANCE OF THE IMPACT DEPENDS STRONGLY ON CHOICE OF A FUTURE DISCOUNTING FACTOR.
- NEED FOR IMMEDIATE POLICY ACTION HINGES ON THESE LAST TWO FEATURES.

Annex 30

J. Hummel & R. Reck, "Carbon Dioxide and Climate: The Effects of Water Transport in Radiative-Convective Models", *Journal of Geophysical Research,* 1981, pp. 12,035-12,038

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 86, NO. C12, PAGES 12,035–12,038, DECEMBER 20, 1981

Carbon Dioxide and Climate: The Effects of Water Transport in Radiative-Convective Models

JOHN R. HUMMEL AND RUTH A. RECK

Physics Department, General Motors Research Laboratories, Warren, Michigan 48090

Considerable attention is being focused on the possible climatic effects resulting from increases in the concentration of atmospheric carbon dioxide. In calculating CO_2 influence on the thermal structure of the atmosphere, the role of clouds is critically important. Not only are the cloud properties, such as amount, numbers of clouds, altitudes, and optical properties important but also whether or not these properties are fixed or coupled to model temperatures. The transport of water vapor determines whether or not a region has clouds, the cloud properites, and the water vapor profiles appropriate for clear and cloudy skies. Results are presented of the change in surface temperature with changes in carbon dioxide content for two radiative-convective models with three different cloud coverages. We used (1) the Manabe-Wetherald radiative-convective model in which three clouds with fixed pressures, thicknesses, and optical properties and a single water vapor profile are inputed and (2) the Hummel-Kuhn model, which couples radiative heating, convection, and water vapor transport in order to calculate locations and thicknesses. The Hummel-Kuhn model yields temperature increases for doubled CO_2 larger than the Manabe-Wetherald model for various assumed total cloud cover amounts. For assumed standard cloud cover amounts the Hummel-Kuhn estimate is 20% larger than the Manabe-Wetherald estimate. For reduced and enhanced cloud cover amounts the Hummel-Kuhn estimates are 37% and 17% larger, respectively. The calculated cloud locations and thicknesses did not change in the calculations; therefore the increased sensitivity in the Hummel-Kuhn model is due to the larger water vapor amounts in the Hummel-Kuhn model and the added infrared absorption by the water vapor dimer.

INTRODUCTION

Numerous calculations concerning speculated surface temperature increases following changes in the atmospheric carbon dioxide content have been made with radiative-convective models. Calculations of a surface temperature increase of from 0.7 K to about 3 K have been reported by various researchers, as summarized by *Schneider* [1975]. These one-dimensional models have used different sets of input data, which, therefore, makes a direct comparison of the results rather difficult. Calculations have been made with a general circulation model (GCM) [*Manabe and Wetherald,* 1975] that indicate larger surface temperature increases could occur in the polar regions as a result of ice-albedo feedback, thereby leading to a partial melting of the polar ice caps.

Atmospheric cloud processes depend on the presence and transport of water vapor. These factors determine what the water vapor profiles will be, whether or not clouds will form, at what altitudes and how thick the clouds will be, and what the cloud optical properties will be. These factors affect and are affected by the atmospheric temperature profile. The radiative-convective models used in making the various calculations include cloud effects but do not permit the various cloud properties such as altitude, thickness, abundance, number of cloud layers, or radiation properties to vary during the course of the calculations. As noted by *Hummel* [1978, 1980] and *Hummel and Kuhn* [1981], neglecting the variations in cloud altitude and thickness that occur with changes in the temperature profile can lead to large differences in surface temperature sensitivity to physical parameter changes. In addition, most radiative-convective models employ a single, mean water vapor profile instead of separate clear and cloudy region profiles.

Results will now be presented comparing calculations of surface temperature increases resulting from increases in the atmospheric carbon dioxide content. The calculations will be from the Manabe-Wetherald radiative-convective model [*Reck,* 1979], in which three clouds are assumed with fixed pressures, thicknesses, and optical properties, and the Hummel-Kuhn radiative-convective model coupled to a one-dimensional water vapor model that calculated cloud locations and thicknesses [*Hummel,* 1978, 1980]. In both models cloud cover amount is fixed. In addition to containing fixed clouds, the Manabe-Wetherald model uses a single water vapor profile based on a constant distribution of relative humidity. The Hummel-Kuhn cloud model calculates cloud altitudes and thickness with a vertical transport model for water vapor. The transport model includes idealized large- and small-scale vertical motions. Cloud locations are determined by the altitude where saturation occurs. Condensate within clouds is also transported. The transport calculations are conceptually similar to the model of *Weare and Snell* [1974]. Whereas in Weare and Snell the entire atmosphere is structured as a diffuse thin cloud, Hummel and Kuhn divide the atmosphere into separate clear and cloudy regions with different water vapor profiles and radiative properties. The radiative fluxes from each part of the sky are then averaged together, weighted by the effective cloud cover, to give a mean radiative flux. The multiple cloud layers included in the Manabe-Wetherald model are representative of horizontal variations in temperature and moisture fields. Therefore, keeping the cloud amount and altitudes fixed implicitly assumes that the circulation processes in the atmosphere do not change as the temperature profile changes.

ANALYSIS PROCEDURE

The input data used in this study are listed in Table 1. For each of the three cloud conditions listed, steady state temperature profiles were computed for carbon dioxide contents of

Copyright © 1981 by the American Geophysical Union.

Paper number 1C1257.
0148-0227/81/001C-1257$01.00

TABLE 1. Input Parameters

Surface albedo, ω_s	14%
Rayleigh scattering, ω_R	7%
Aerosols	None
Lapse Rate, Γ	6.5 K/km

Cloud Properties	Manabe-Wetherald Model			Hummel-Kuhn Model
	High	Middle	Low	
Pressure levels, mb	336 (thin)	664 (thin)	664–811	calculated
Fractional cloud cover, α_c				
Case 1	0.091	0.040	0.151	0.261*
Case 2 (standard)	0.181	0.079	0.302	0.473*
Case 3	0.272	0.119	0.453	0.649*
Cloud reflectivities	0.210	0.480	0.690	0.320†
Cloud absorptivities	0.005	0.020	0.035	···‡
Water vapor dimer		not included		included

*This is the effective total cloud cover of the three clouds used in the Manabe-Wetherald model. For the parameters used in this paper only one layer existed in the steady state atmosphere.

†This is the total reflectivity based on the total effective cloud cover. Individual cloud reflectivities are not needed [e.g., *Hummel*, 1978, 1980].

‡The cloud absorptivity is currently not included [e.g., *Hummel and Kuhn*, 1981].

300, 450, and 600 ppmv. The surface temperature changes relative to that obtained for an atmosphere with 300 ppmv CO_2 were then computed. The surface temperature changes obtained are given in Table 2.

Discussion of Results

For each of the cloud and CO_2 conditions listed in Table 2, the Hummel-Kuhn model produces a steady state atmosphere with one cloud with a top at 500 mb and base at 650 mb. While the steady state cloud in the cases studied was found to be at 500–650 mb, it should not be concluded that cloud height is insensitive to changes in temperature or moisture. As discussed by *Hummel* [1980] and *Hummel and Kuhn* [1981], cloud heights do change when other physical parameters change, such as relative humidity, especially when pressure dependent moist adiabatic critical lapse rates are used rather than a constant 6.5 K/km critical lapse rate. The effective cloud cover $\alpha_c = 0.473$ represents the postulated standard cloud conditions. The effective cloud cover $\alpha_c = 0.261$ represents a halving of the individual cloud amounts in the Manabe-Wetherald model, while the effective cloud cover $\alpha_c = 0.649$ represents an increase of 50% in the individual cloud amounts in the Manabe-Wetherald model.

For increases in CO_2 content, the Hummel-Kuhn model displays in inverse relationship between surface temperature change and cloud cover, i.e., the maximum change in surface temperature with the smallest cloud cover amount. This occurs because the planetary albedo is less and the surface temperature is higher with a smaller amount of cloud cover. The higher temperature increases the atmospheric water vapor content in the model, and the calculated CO_2-H_2O greenhouse effect increases.

The Manabe-Wetherald cloud treatment leads to a more complicated relationship between cloud cover amount and CO_2. Fortunately, the model allows the individual flux components to be followed, and it is possible to resolve what has happened within the model. As the cloud cover increases the downward infrared flux from the thick, low-lying cloud increases, while the solar absorption of CO_2 decreases owing to less net solar radiation. For a 50% CO_2 increase the magnitudes of these two fluxes are similar, and for the largest cloud cover amount the increase in the infrared flux from the low-lying cloud is greater than the decrease in CO_2 solar absorption. For the 100% CO_2 increase the decreased solar absorption is a considerably larger effect, and we obtain the inverse relationship obtained in the Hummel-Kuhn model. This competition between solar absorption by carbon dioxide and downward infrared flux from clouds again stresses the importance of accurate cloud descriptions and optical properties.

In all cases the Hummel-Kuhn model is more sensitive to CO_2 increases than is the Manabe-Wetherald model. For an increase in CO_2 of 50%, the Hummel-Kuhn model gives 30.8, 20.7, and 9.3% larger increases in surface temperature than the Manabe-Wetherald model for the cloud coverages 0.473,

TABLE 2. Surface Temperature Increases Calculated by the Manabe-Wetherald and Hummel-Kuhn Radiative-Convective Models for Carbon Dioxide Increases Under Three Effective Cloud Cover α_c Conditions

Model	$\alpha_c = 0.473$ (Standard) ΔCO_2 Increase*		$\alpha_c = 0.261$ CO_2 Increase*		$\alpha_c = 0.649$ CO_2 Increase*	
	50%	100%	50%	100%	50%	100%
Manabe-Wetherald	0.78	1.71	1.16	1.87	0.86	1.62
Hummel-Kuhn	1.02	2.05	1.40	2.56	0.94	1.89

In degrees Kelvin.

* Increase from 300 ppmv.

TABLE 3. Precipitable Water Amounts

Model	$\alpha_c = 0.473$ (Standard) ΔCO_2 Increase*			$\alpha_c = 0.261$ ΔCO_2 Increase*			$\alpha_c = 0.649$ ΔCO_2 Increase*		
	0	50%	100%	0	50%	100%	0	50%	100%
Manabe-Wetherald	1.19	1.26	1.35	2.01	2.16	2.28	0.62	0.66	0.71
Hummel-Kuhn	2.83	3.03	3.24	2.76	3.03	3.27	2.88	3.07	3.27

*Increase from 300 ppmv, in centimeters.

0.261, and 0.649, respectively. For the doubled CO_2 case the relative increases are 19.9, 36.9, and 16.7, respectively. The reasons for the increased sensitivity to increases in amounts of CO_2 are the increased water vapor in the Hummel-Kuhn model because of the inclusion of separate clear and cloudy sky water vapor profiles and the water vapor dimer. The difference in sensitivities due to the different radiative parameterizations and numerical procedures is less than about 6%.

Table 3 gives the precipitable water amounts for the two models and for the conditions given in Table 1. For the standard cloud and CO_2 conditions the Manabe-Wetherald model gives a precipitable water amount more than a factor of 2 below the global average value of 2.6 cm [*Sellers*, 1965]. As a result, the 'greenhouse' effect of water vapor is underestimated. Since the water vapor amounts are coupled to the temperature profile, the 'greenhouse' effect of carbon dioxide is also underestimated. The Hummel-Kuhn results are much closer to the global average, and because of the larger amounts of water vapor the surface temperature sensitivities are larger than those from the Manabe-Wetherald model.

The water vapor profile in the Manabe-Wetherald model is based on the fixed distribution of relative humidity. Therefore, as the cloud cover amount increases, the temperature decreases and so does the precipitable water amount. In the Hummel-Kuhn model this inverse relationship between cloud cover amount and precipitable water amount is generally absent. The mean atmospheric water vapor profile in the Hummel-Kuhn model is the cloud cover amount weighted average of the separate clear and cloudy sky water vapor profiles [e.g., *Hummel*, 1980; *Hummel and Kuhn*, 1981]. The cloudy sky water vapor profile must have a region of saturation where the clouds exist, and so the cloudy sky profile is larger than the clear sky profile (by a factor of 2 or more at the levels where clouds exist). The contributions from the cloudy sky profile to the mean water vapor profile increase as the cloud cover amount increases, therefore, giving rise to the nearly direct relationship between cloud cover amount and precipitable water amount.

The other contributing factor to the increased sensitivity is the water vapor dimer. The water vapor dimer is included in the spectral region 18.0–100 μm. As stated in Table 1, the Hummel-Kuhn model includes the additional absorption by the water vapor dimer, while the Manabe-Wetherald model does not. The water vapor dimer is two water molecules linked together by a weak hydrogen bond. The absorption by the dimer occurs in the water vapor continuum [*Bignell*, 1970]. The concentration of the dimers is proportional to the square of the water vapor partial pressure, and when the mixing ratio of water vapor exceeds 10^{-2} g/g, as it may in the lowest levels of the atmosphere, the additional infrared absorption may be significant enough to further reduce the longwave emission to space, thereby further increasing the surface temperature [*Cox*, 1973; *Ramanathan*, 1976] in order to maintain flux balance. Dimer contributions are largest under high moisture conditions. Therefore, for an effective cloud of 0.261 the large difference between the Manabe-Wetherald and Hummel-Kuhn estimates is due primarily to the dimer contributions. (A detailed discussion of dimer effects on radiative-convective model calculations is contained in the work of *Hummel* [1981].)

SUMMARY

Estimates of surface temperature changes from increases in atmospheric carbon dioxide are shown to depend on how cloud processes (i.e., cloud locations, amounts, optical properites, and water vapor profiles) are treated in radiative-convective models. We have compared surface temperature sensitivity calculations to changes in carbon dioxide for two cloud specifications. We used (1) the standard Manabe-Wetherald radiative-convective model, in which all cloud properties are fixed and a single water vapor profile is used, and (2) the Hummel-Kuhn model, in which vertical water vapor transport is included, cloud locations and thicknesses are calculated, and separate clear and cloudy sky water vapor profiles are included. The calculations were performed for three assumed cloud cover conditions.

For the three cloud cover conditions, the surface temperature sensitivities to a doubling of CO_2 were larger for the Hummel-Kuhn model. The increased sensitivity in the Hummel and Kuhn model is due primarily to the larger, more realistic, water vapor profiles found in the model. Increased sensitivity also results from the effects of the water vapor dimer.

While these results indicate that the direct contribution for CO_2 increases to surface heating may be larger than previously calculated, the question of indirect influences of the CO_2 is still far from resolved. As noted by *Reck* [1979], changes in cloud amount in fixed cloud models can compensate for surface temperature increases caused by carbon dioxide increases. Clearly, then, research must be continued to develop models that can interactively predict cloud locations, thickness, and amounts.

REFERENCES

Bignell, K. J., The water-vapour infrared continuum, *Q. J. R. Meteorol. Soc., 96*, 390–403, 1970.

Cox, S. K., Infra-red heating calculations with a water vapour pressure broadened continuum, *Q. J. R. Meteorol. Soc., 99*, 669–679, 1973.

Hummel, J. R., An atmospheric radiative-convective model with interactive water vapor transport and cloud development, PhD. Thesis, Univ. of Mich., Ann Arbor, 1978.

Hummel, J. R., Importance of separate clear and cloudy sky water vapor profiles in radiative convective models, in *Atmospheric Water Vapor*, edited by A. Deepak et al., Academic, New York, 575–586, 1980.

Hummel, J. R., Anomalous water vapor absorption: Implications for radiative-convective models, submitted to *J. Atmos. Sci.*, 1981.

Hummel, J. R., and W. R. Kuhn, An atmospheric radiative-con-

vective model with interactive water vapor transport and cloud development, *Tellus*, in press, 1981.

Manabe, S., and R. T. Wetherald, The effects of doubling the CO_2 concentration on the climate of a general circulation model, *J. Atmos. Sci., 32,* 3–15, 1975.

Ramanathan, V., Radiative transfer within the earth's troposphere and stratosphere: A simplified radiative-convective model, *J. Atmos. Sci., 33,* 1330–1346, 1976.

Reck, R. A., Carbon dioxide and climate: Comparison of one-dimensional and three-dimensional models, *Environ. Int., 2,* 387–391, 1979.

Schneider, S. H., On the carbon dioxide-climate confusion, *J. Atmos. Sci., 32,* 2060–2066, 1975.

Sellers, W. D., *Physical Climatology,* 272 pp., University of Chicago Press, Chicago, Ill., 1965.

Weare, B. C., and F. M. Snell, A diffuse thin cloud structure as a feedback mechanism in global climatic modeling, *J. Atmos. Sci., 31,* 1725–1734, 1974.

(Received September 22, 1980;
revised July 31, 1981;
accepted August 3, 1981.)

Annex 31

T. Wigley, *Energy production and climatic change: an assessment,* in URANIUM AND NUCLEAR ENERGY: 1981, The Uranium Institute, (Butterworth Scientific Limited, 1981), pages 291-307

The complete book can be accessed through the TU Delft Library (*see* TU Delft Library catalogue, available at: https://tudelft.on.worldcat.org/search/detail/839390679?queryString=%22Uranium%20and%20nuclear%20energy%22%201981&clusterResults=false&groupVariantRecords=false (last accessed on 12 March 2024). The TU Delft Library can be contacted for assistance by phone (at +31 (0)15 27 85678) or email (at Library@tudelft.nl).



URANIUM
INSTITUTE

URANIUM AND NUCLEAR ENERGY: 1981

Proceedings of the Sixth International
Symposium held by the Uranium Institute
London, September 1981

Uranium and Nuclear Energy: 1981

Proceedings of the Sixth International Symposium held by The Uranium Institute

London, 2 — 4 September, 1981

Butterworth Scientific Limited

in co-operation with The Uranium Institute

NAPIER COLLEGE OF COMMERCE AND TECHNOLOGY
AC 83/076147 101
RC 193
MERCHISTON
333.7924 URA
CAT M.Q. X
CON 0408221518
INV B.B. 27.50

All rights reserved. No part of this publication may be reproduced, or transmitted in any form or by any means, including photocopying and recording, without the written permission of the copyright holder, application for which should be addressed to the Publishers. Such written permission must also be obtained before any part of this publication is stored in a retrieval system of any nature.

This book is sold subject to the Standard Conditions of Sale of Net Books and may not be re-sold in the UK below the net price given by the Publishers in their current price list.

First published 1982

© The Uranium Institute, 1982

British Library Cataloguing in Publication Data

Uranium and nuclear energy: 1981: proceedings of the Sixth International Symposium held at the Uranium Institute.
1. Atomic power—Congresses
1. Uranium Institute
621.48 TK9006

ISBN 0-408-22151-8

Printed in Great Britain

The Uranium Institute

Members*

AUSTRALIA
Energy Resources of Australia Limited
Pancontinental Mining Limited
Western Mining Corporation Limited

BELGIUM
Synatom SA

CANADA
Denison Mines Limited
Eldorado Nuclear Limited
Rio Algom Limited
Saskatchewan Mining Development Corporation
Uranerz Canada Limited

EUROPE
Euratom Supply Agency

FEDERAL REPUBLIC OF GERMANY
Nukem GmbH
Rheinisch-Westfälisches Elektrizitätswerk AG
Saarberg-Interplan Uran GmbH
Urangesellschaft mbH and Co. KG

FRANCE
Commissariat à l'Energie Atomique
Compagnie Française de Mokta
Compagnie Minière Dong-Trieu
Comurhex
Electricité de France
Eurodif SA
Minatome SA
Pechiney Ugine Kuhlmann

ITALY
Ente Nazionale per l'Energia Elettrica
Ente Nazionale Idrocarburi

*This listing of the membership and Council refers to the position at the time of the Institute's Sixth Annual Symposium, 2-4 September 1981.

JAPAN
C. Itoh and Co. Limited
Japan Atomic Power Company
Kanematsu-Gosho Limited
Kansai Electric Power Company Incorporated
Marubeni Corporation
Mitsubishi Corporation
Mitsui and Company Limited
Nichimen Company Limited
Nissho-Iwai Company Limited
Power Reactor and Nuclear Fuel Development Corporation
Sumitomo Corporation
Tokyo Electric Power Company Incorporated

SOUTH AFRICA
Atomic Energy Board
Buffelsfontein Gold Mining Company Limited
Electricity Supply Commission
Uranium Enrichment Corporation of South Africa Limited
Vaal Reefs Exploration and Mining Company Limited

SOUTH WEST AFRICA/NAMIBIA
Rössing Uranium Limited

SPAIN
Empresa Nacional del Uranio SA

SWEDEN
Luossavaara-Kiirunavaara AB
Swedish Nuclear Fuel Supply Company

SWITZERLAND
Gruppe der Kernkraftwerkbetreiber und -projekten

TAIWAN
Taiwan Power Company

UNITED KINGDOM
British Nuclear Fuels Limited
Central Electricity Generating Board
Rio Tinto-Zinc Corporation Limited
United Kingdom Atomic Energy Authority
Urenco Limited

UNITED STATES
Florida Power and Light Company

HONORARY MEMBERS
J.W. Shilling
P. Taranger

Officers

CHAIRMAN

J. Féron
Inspecteur Général, Electricité de France

VICE CHAIRMAN

R.E. Worroll
Uranium Adviser, Chamber of Mines of South Africa

COUNCIL

G.R. Albino
President, Rio Algom Limited

Dr U. Belelli
Manager, Nuclear Department, Ente Nazionale per l'Energia Elettrica

Dr W. Casper
Chairman, Supervisory Board, Urangesellschaft mbH & Co. KG

J-L. Dherse
Director, Rio Tinto-Zinc Corporation Limited

N.M. Ediger
President, Eldorado Nuclear Limited

P. Erkès
Director General, Synatom SA

D.A. Etheredge
Chairman, Gold and Uranium Division, Anglo American Corporation of South Africa Limited

B.G. Fisk
Chief Executive, Energy Resources of Australia Limited

C.A. Gibson
Chief Executive and Deputy Chairman, Rössing Uranium Limited

A.J. Grey
Chairman, Pancontinental Mining Limited

I. Hori
Managing Director, Tokyo Electric Power Company Incorporated

J. Hudiburg
President, Florida Power and Light Company

K. Ito
Senior Managing Director, Kansai Electric Power Company Incorporated

J. Kostuik
President, Denison Mines Limited

H.M. Morgan
Executive Director, Western Mining Corporation Limited

G.A. Park
Production Assets Manager, Electricity Supply Commission of South Africa

A. Petit
Directeur Adjoint des Relations Internationales, Commissariat à l'Energie Atomique

P. Reynaud
Council Manager, Compagnie Française de Mokta

M. Segawa
President, Power Reactor and Nuclear Fuel Development Corporation

Dr G.M. Sfligiotti
Vice-President, AGIP SpA, Ente Nazionale Idrocarburi

J-P. Silve
Marketing and International Relations Manager, Uranium Pechiney Ugine Kuhlmann

F-J. Spalthoff
Director, Rheinisch-Westfälisches Elektrizitätswerk AG

Dr E. Svenke
Managing Director, Swedish Nuclear Fuel Supply Company

M. Townsend
Head, British Civil Uranium Procurement Organization Central Electricity Generating Board

Dr E. Trümpy
President, Gruppe der Kernkraftwerkbetreiber und -projekanten

Dr P. Young
President, Uranerz Canada Limited

SECRETARY GENERAL

B.T. Price

Energy production and climatic change: an assessment

Tom M.L. Wigley

In recent years the subject of climatic change has become popular both with the scientific community and with the media. The reason for this is two-fold. First, it has become abundantly clear that the Earth's climate is not static, but is constantly changing on all time scales. Only a few decades ago many scientists, particularly those outside meteorology, believed that the state of the atmosphere could be described by reference to a so-called 'normal' period, and climate was supposed to be well-defined by average conditions over, say, a 30 year span. We now know that this is not correct, and that the reference period used in the past (1931-60) was, in fact, rather unusual. Secondly, although the idea is certainly not new, it is highly likely that man has the ability to alter the climate significantly.

Figure 1 gives an illustration of the variability of climate on annual to decadal time scales. The climate parameter here is the average surface air temperature of the Northern Hemisphere, taken from Jones *et al.*[1] Two things should be noticed: the marked year-to-year variability, which makes even this large-area average quantity a rather 'noisy' record; and the marked warming trend in the early part of this century. The period 1931-60 can be seen to be unusually warm relative to the record as a whole. After reaching a peak around 1940, Northern Hemisphere temperatures fell to the mid-1960s and have shown a slight warming since then, especially in recent years.

The magnitudes of the changes shown in Figure 1 may seem small, but they are, nevertheless, of considerable importance. The changes themselves

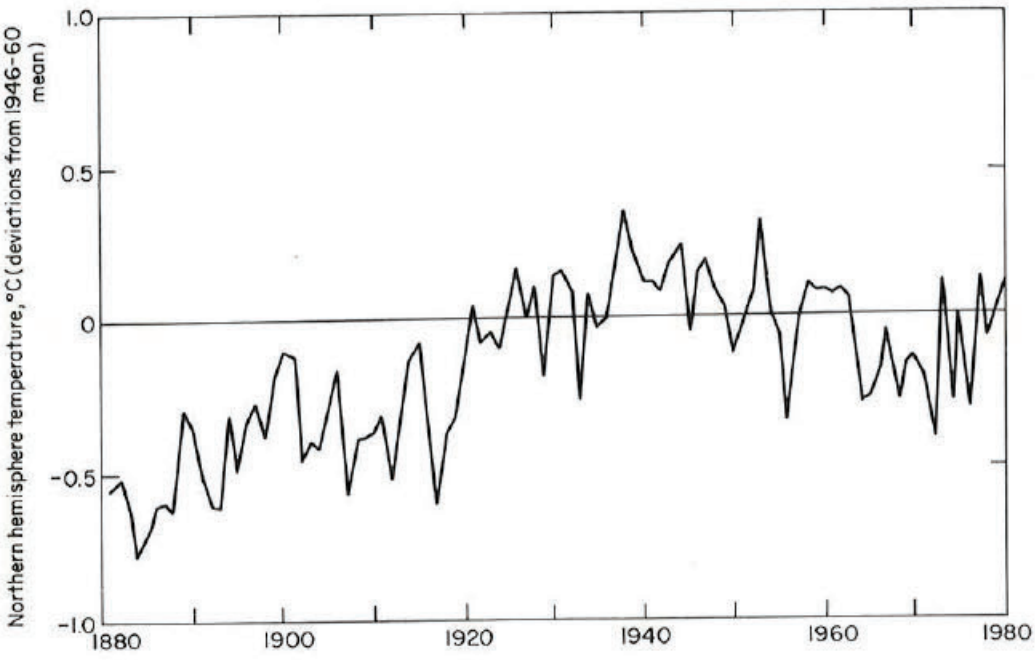


Figure 1. Variations in Northern Hemisphere average surface air temperature relative to 1946-60 as a reference period (from Jones et al.[1]). The warming of the 1970s has continued into the 1980s, with the winter of 1980-81 being equal warmest on record (Wigley *et al.*[2]) and the spring of 1981 being the warmest on record (Jones[3])

are similar in magnitude to changes which have occurred over past millennia. One has to go back more than 10 000 years, to the last Ice Age, before substantially larger variations can be detected. *Regional*-scale variations accompanying these changes have been much larger in magnitude (areal averaging reduces the variance considerably). To illustrate this point, Figure 2 (from Kelly *et al.*[4]) shows variations in Arctic (65 – 85°N) winter temperatures. The change from the late 1910s to the late 1930s here is around 3°C compared with 0.7°C for the hemisphere as a whole.

The trends in Figures 1 and 2 are broadly parallel, but this parallel does not necessarily extend to smaller spatial scales nor to other climate parameters. This is because the large-scale changes shown in Figure 1 are themselves manifestations of significant changes in the climate system *as a whole*: the atmospheric circulation system, the oceans, and the high-latitude snow and ice cover. The climate system is extremely complex and spatially variable with numerous feedback mechanisms. Regional fluctuations, although part of the overall picture, can differ widely from fluctuations in global or hemispheric averages.

Figure 3 gives as an example variations in *regional* climate in Africa: rainfall in the Sahel. The recent drought, longer lasting and more severe

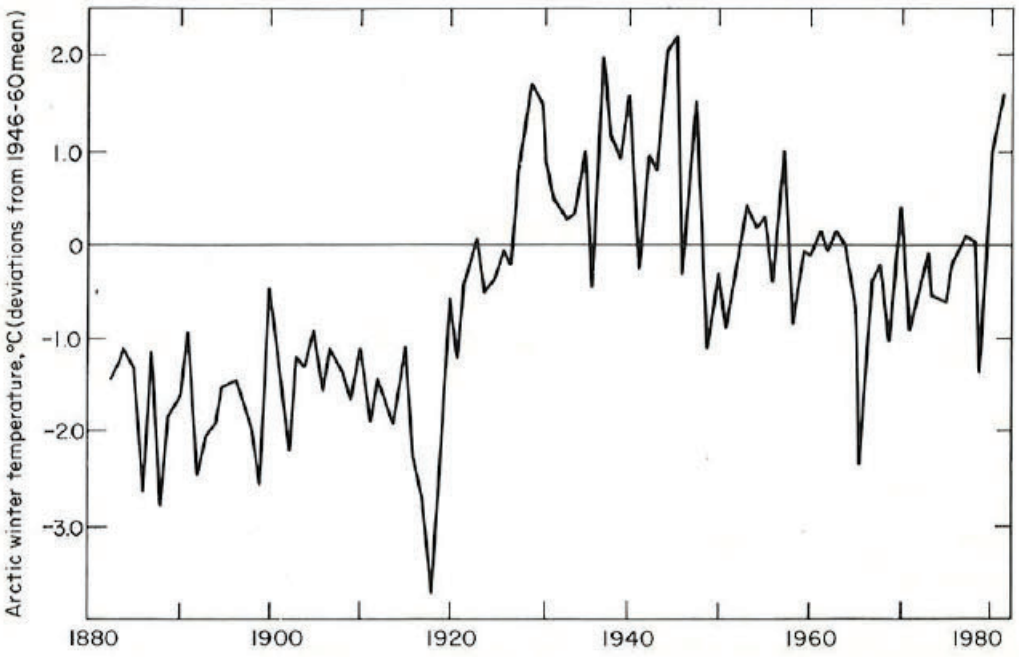


Figure 2. Arctic winter temperature variations: average over the latitude band 65 - 85°N; winters are dated by the January (after Kelly et al.[4])

than earlier droughts of this century, has been linked to larger-scale changes in the atmospheric circulation and to changes in sea surface temperatures in the Atlantic. The links are not simple: there is, for example, no obvious relationship between Northern Hemisphere mean temperature (Figure 1) and Sahel rainfall (Figure 3), but they are real, and important in understanding the causes of regional climatic change and how regional changes relate to the broader-scale picture.

These items are particularly significant now because man's activities may produce changes in climate that exceed any which have occurred naturally in the past 10 000 years. The cause is atmospheric carbon dioxide. By burning fossil fuels and, most probably, by deforestation and changing land-use, man has upset the balance in the global carbon dioxide budget and produced, over the past century, a considerable increase in atmospheric CO_2 concentration. Future changes will almost certainly occur at an accelerating rate. These changes are important because CO_2 is a radiatively active gas. It participates strongly in the radiation balance of the atmosphere, effectively trapping out-going long-wave radiation in the lower layers of the atmosphere and producing a warming by the 'greenhouse' effect.

The carbon dioxide issue is generally considered as a series of linked research areas: studies of the global carbon budget, studies of the effects of changing atmospheric carbon dioxide levels on global climate, and studies

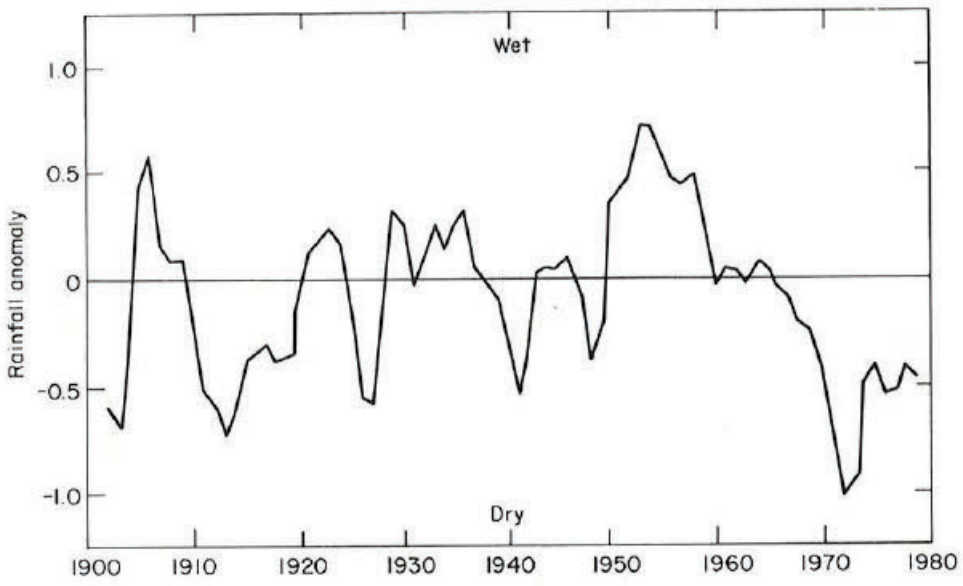


Figure 3. Rainfall variations in the Sahel. The values shown are an index based on the average of a large number of rainfall stations calculated by Nicholson[5], and updated by J.M. Lough (Climatic Research Unit). The extreme year-to-year variability has been smoothed out using a 1–2–1 binomial filter. Although the recent drought is the most severe this century, drought is not an uncommon occurrence in this part of the world and the impact of past droughts has also been severe (Bowden *et al.*[6])

of the impact of CO_2-induced climatic change on man and society. In each of these three areas the ability to predict future changes (in carbon dioxide levels, climate, or impact) depends on the ability to model physical, biological and social processes, and on knowledge of the basic data to put into these models. For example, in carbon budget studies, where the prime concern is to predict future atmospheric CO_2 levels, it is necessary to know not only how any anthropogenic input of carbon into the system will be redistributed among the various carbon reservoirs (the oceans, the atmosphere and the biosphere), but also just what the anthropogenic input is likely to be. Of course, it is impossible to know this input precisely (it may well depend on future climate, in fact), so scientists researching in this area use a range of realistic scenarios of energy demand and land-use changes to predict a range of possible atmospheric carbon dioxide futures. In climate studies, the results of carbon budget studies can, ideally, be fed into climate models to determine the subsequent details of climatic change. However, present-day climate models are not capable of predicting CO_2-induced climatic changes in any great detail, certainly not in sufficient detail to be able to estimate the possible impact on man on a regional scale. As a consequence the results of climate models must themselves be

considered as physically realistic scenarios and combined with scenarios derived by other means to give a composite picture of *possible* future climatic conditions. The results, while they can not yet be labelled as forecasts or predictions, nevertheless form an important basis for estimating the future impact of climatic change on man. This paper provides a brief review of estimates of future carbon dioxide levels, their possible effect on global climate, and the subsequent impact on man.

Changes in atmospheric carbon dioxide

With increasing industrialization, the growth in the use of fossil fuels over the past century has been dramatic. In terms of the amount of carbon in the carbon dioxide released by the burning of fossil fuels the rate of consumption has risen from about 0.1 GtC/year (1 GtC/year = 10^9 tonnes of carbon per year) to the current level of 5.5 GtC/year (i.e. 38 000 tonnes of CO_2 per minute!). The changes, using data from Rotty[7], are shown in Figure 4. Except for periods during the two World Wars and during the great economic depression around 1930, the rate of increase in CO_2

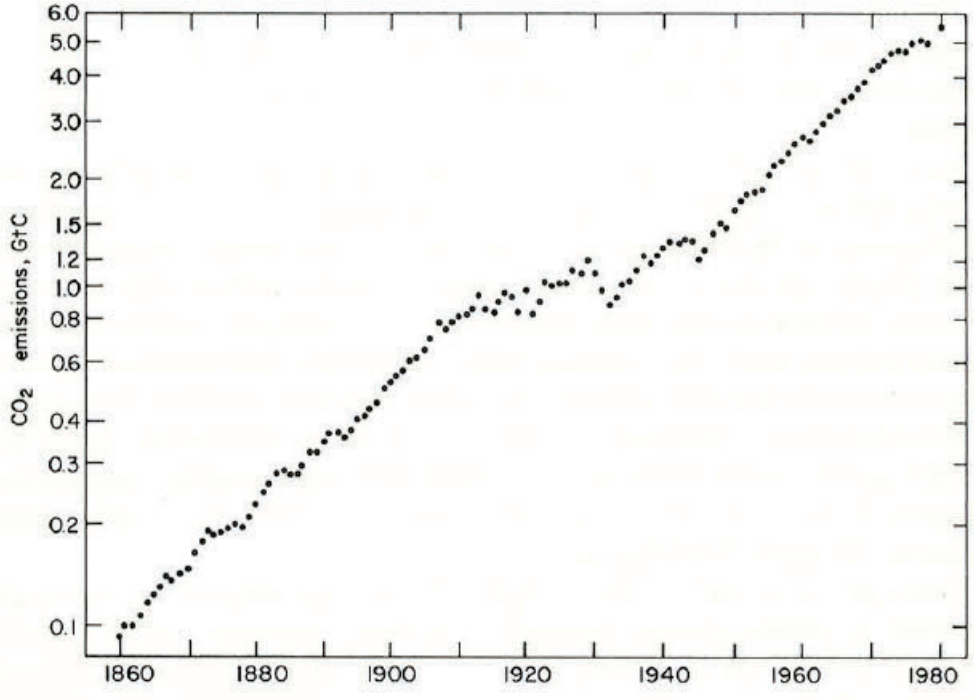


Figure 4. Increasing use of fossil fuels as evidenced by global emissions of carbon dioxide (Rotty[7]). Prior to 1973 growth was remarkably steady at 4.3% per year, except during the World Wars and the depression of the early 1930s. Since the oil 'crisis', growth has slowed to around 2% per year

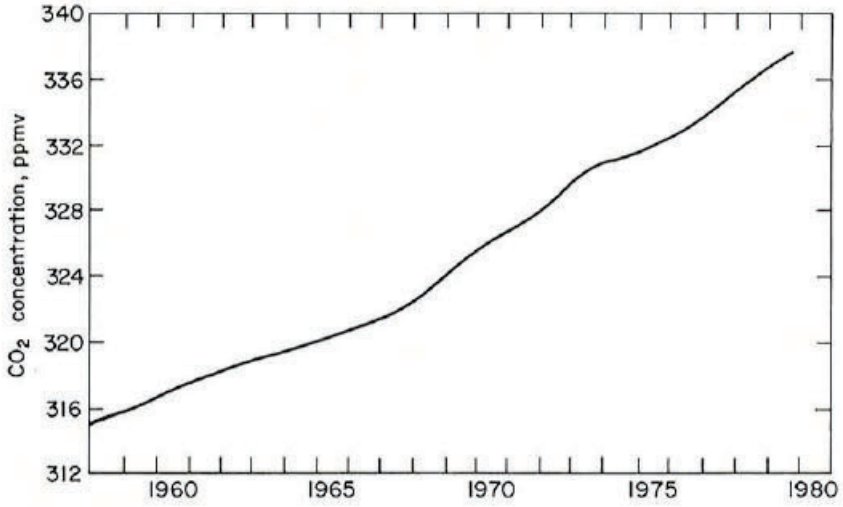


Figure 5. Variations in atmospheric carbon dioxide concentration since 198 at Mauna Loa, Hawaii (from CEQ[13], quoting data from Keeling and co-workers, Scripps Institution of Oceanography). There is a strong seasonal cycle of about 3 ppmv amplitude which has been removed to show the trend more clearly. All other monitoring stations, from the South Pole to high northern latitudes, show the same trend

production has been exponential, increasing at around 4.3% per year. In recent years, since the oil 'crisis' of 1973, growth has slowed to around 2% per year.

Accompanying this increasing output of CO_2 has been a steady increase in atmospheric CO_2 concentration. Regular measurements of atmospheric CO_2 began only in 1958;[8,9] at this time the free atmospheric concentration at the South Pole or on the top of Mauna Loa in Hawaii, far from the influence of local effects from industry, was around 315 ppmv (parts per million by volume). The preindustrial (or natural background) level is believed to have been about 280-290 ppmv. Indirect evidence from deep-ocean chemistry[10,11] indicates a preindustrial level of between about 260 and 290 ppmv, while measurements made late last century, compiled by Callendar,[12] are in the range 288 – 297 ppmv. Since 1958 the level has risen to almost 340 ppmv (See Figure 5).

From the data used to derive Figure 4, the total amount of carbon in the form of carbon dioxide released from fossil fuels since 1860 is about 160 GtC. Yet the rise in atmospheric CO_2, from about 280 to 338 ppmv is only equivalent to 120 GtC (or even less if the preindustrial level were higher). This is because the carbon dioxide released is redistributed among the three main carbon reservoirs: the oceans and the biosphere as well as the atmosphere. The oceans are believed to be the major sink for this excess carbon. The biosphere, although potentially a sink, is believed to

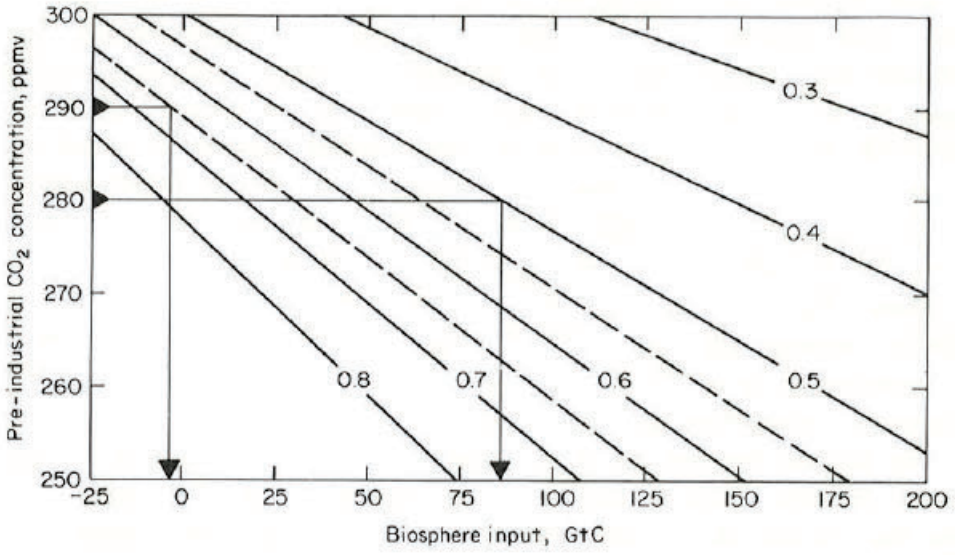


Figure 6. Airborne fraction for the period 1960-1980 as a function of initial carbon dioxide concentration and total input due to biosphere changes (deforestation and changing land use). Theoretical carbon budget models predict an airborne fraction of 0.50 – 0.65 which is consistent with the best available estimates of the initial atmospheric level (280 – 290 ppmv) and the total biospheric input (75 GtC)

have been an additional source of carbon dioxide over much of the past century as a result of land-use changes and deforestation.

To predict future changes in CO_2 we need to know how the released carbon is redistributed. An important parameter here is the 'airborne fraction', the amount from fossil fuels and from the biosphere which remains in the atmosphere. If ΔM_a is the increase in atmospheric carbon dioxide, ΔM_f is the amount of CO_2 produced by the consumption of fossil fuel and ΔM_b is the CO_2 contribution from the biosphere (which may be negative if the biosphere acts as a sink), all measured over the same time interval Δt, then the airborne fraction α is

$$\alpha = \frac{\Delta M_a}{\Delta M_f + \Delta M_b} \qquad (1)$$

In terms of changes in atmospheric carbon dioxide concentration, this equation may be written as

$$\alpha = \frac{2.13\Delta\text{ppmv}}{\Delta M_f + \Delta M_b} \qquad (2)$$

provided ΔM_f and ΔM_b are expressed in GtC.

The airborne fraction can be calculated in two independent ways: either from observations, or by using a theoretical carbon budget model. Consider the period 1860 to the present day. Since we know ΔM_f (see Figure 4) and Δppmv, at least approximately, all we need is the biosphere term ΔM_b to find α. Figure 6 shows the airborne fraction as a function of the two least certain parameters in equation (2), the pre-industrial CO_2 concentration and the biospheric term. The best estimate of the latter[14,15] is about 75GtC, although some researchers[16,17] believe it could be higher. Compare this with the contribution from fossil fuels of approximately 160GtC between 1860 and 1980. The preindustrial CO_2 level is thought to be between 280 and 290 ppmv. The corresponding range for the airborne fraction, α, is between 0.44 and 0.53.

The second method for calculating α is to use a model of the global carbon budget. Such models must describe in simple but realistic terms how the oceans take up the excess carbon: essentially they describe how CO_2 produced from fossil fuels and from deforestation etc., is distributed between the atmosphere and the oceans. To do this requires a knowledge of ocean chemistry and ocean mixing processes. At present, although the chemistry aspects are well understood,[18,19] there is some uncertainty in our understanding of the mixing processes, and these carbon budget models are still being improved. The best models available today[20] give an airborne fraction of between 0.50 and 0.65. If the preindustrial CO_2 level is taken as 280 – 290 ppmv, then the carbon budget model estimates of α would imply a biospheric contribution of – 3 to 87 GtC, nicely bracketing the current WMO estimate quoted above.[15]

These results, and the current situation, are summarized in Figure 7. Note that by far the biggest 'store' of carbon is in the deep oceans, but oceanic mixing here is so slow that this part of the system is relatively inert on time scales of decades to centuries. Fossil fuel reserves (mostly coal) are large relative to the present atmospheric level so there is considerable potential for future changes in atmospheric CO_2. The uncertainty in our knowledge of changes in the biosphere is indicated by the flux range of 110 – 114 GtC/year *into* the atmosphere, an excess over the assimilation due to photosynthesis of between 0 and 4 GtC/year. The fossil fuel input today is around 5 GtC/year, so the total input to the atmosphere is between 5 and 9 GtC/year. Some ocean areas are a source of CO_2 while other areas are a sink; the net oceanic influence is to act as a sink for between 2 and 6 GtC/year. The balance of sources and sinks is shown as an increase in atmospheric loading of around 2.8 GtC/year. In terms of concentration change, this is equivalent to a build-up of CO_2 at the rate of about 1.3 ppmv/year (c.f. Figure 5).

The agreement between models and observation gives some confidence in our ability to predict future atmospheric CO_2 levels. To do this, however, future energy demands and the future level of reliance on fossil

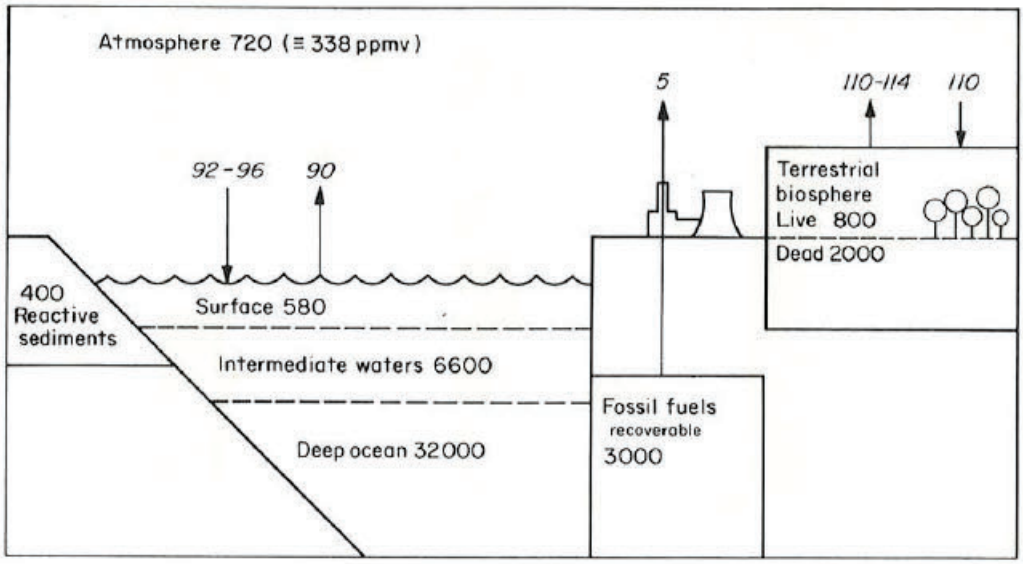


Figure 7. Simplified diagram of global carbon cycle showing sizes of main active or potentially active reservoirs (in GtC) and estimates of important fluxes between these reservoirs (in GtC/year). The present imbalance can be explained by the 5 GtC/year fossil fuel contribution, of which approximately 3 GtC/year is accumulating in the atmosphere, resulting in an increase in concentration of about 1.3 ppmv/year

fuels have to be estimated. Since different fossil fuels produce different amounts of CO_2 per unit of energy, the split between different fossil fuels must also be known, although this is not a crucial factor in the calculations. The details of future energy demand are not known, so we must rely on what are considered realistic scenarios.

Numerous estimates of future energy demand have been published in recent years.[21,24] Present fossil fuel energy consumption is estimated at 8.2 TWyear/year (1 TWyear = 8.76 x 10^{15} watt h = 2.989 10^{16} Btu = 29.89 quads). This is equivalent to a continuous increase of over 3.5% per year since the 19th century. Estimates of total energy demand for the year 2025 range between 18 and 50 TWyear/year. A value of 27 TWyear/year with an uncertainty of ±25% seems appropriate for assessing the CO_2 problem.[15] This corresponds to a growth rate for total energy demand of around 2.4% per year over the next 45 years; the growth rate for fossil fuel contribution is somewhat less.

The CO_2 production rate depends on the fraction of energy demand satisfied by fossil fuel use. Figure 8 (derived from Rogner and Sassin[22], and Häfele[24]) shows one projection of future energy distribution with a decline in the fossil fuel fraction from 91% in 1975 to 70% in 2025. The latter figure, substantially lower than some estimates[21] implies a fossil fuel

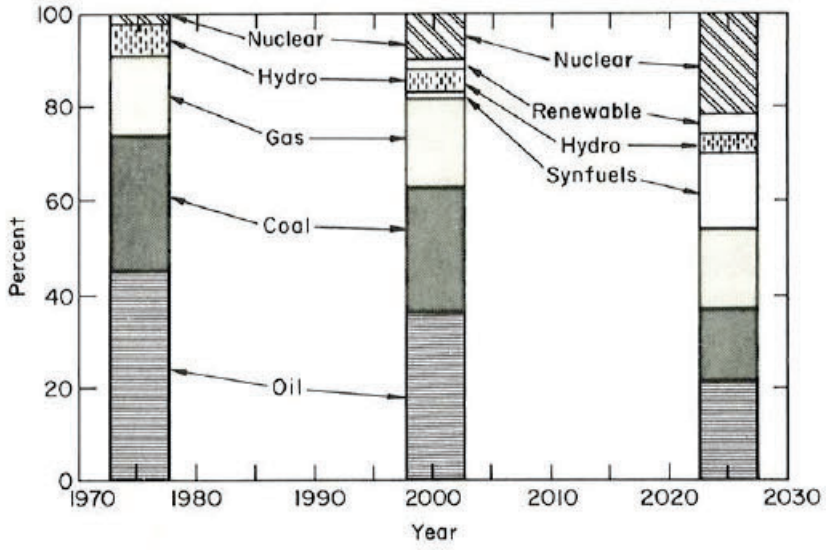


Figure 8. Present and projected distribution of energy sources

contribution to total energy use of 18.9 TWyear/year in 2025. This is similar to the recent WMO estimate[15] of 21.25 TWyear/year.

The CO_2 production rate depends on the proportional usage of different fossil fuels (see Figure 8), but it can be estimated reasonably well using the 1980 figures of 8.2 TWyear/year, equivalent to an output of 5.5 GtC/year of CO_2. On this basis, a fossil fuel energy consumption of 18.9 TWyear/year would yield 12.7 GtC/year carbon dioxide. This value is very similar to the WMO estimate of 13.6 GtC/year. These figures are considerably less than some other results given in the literature (values quoted by Kellogg and Schware[25] range from 16 to 29 GtC/year in 2025), and they therefore represent fairly conservative estimates of future CO_2 production rate. They agree well with Rotty's recent[7] 'low energy use scenario'. Possible contributions from the biosphere have been ignored, but if these continue at the same rate indicated earlier, their total contribution to atmospheric carbon dioxide over the next 45 years is unlikely to exceed 10% of the fossil fuel contribution. In fact, as indicated above, the biosphere could act as a *sink* for CO_2 in future years, as a result of planned reforestation and/or because of the effect of increasing CO_2 on primary productivity (plants produce more dry matter in high CO_2 environments[26,27]).

These estimates of around 13 GtC/year as the production rate for CO_2 correspond to an increase over the next 45 years of around 2% per year, much less than the average over the past century, but similar to the value prevailing since 1973.

What does this future energy use scenario mean in terms of future

atmospheric CO_2 levels? A simple calculation can answer this question. If $M_f(t)$ is the accumulated fossil fuel input in GtC up to year t after 1980, and if CO_2 production rate increases at 2% per year, then

$$M_f(t) = \frac{5.5}{0.02}(e^{0.02t} - 1) \qquad (3)$$

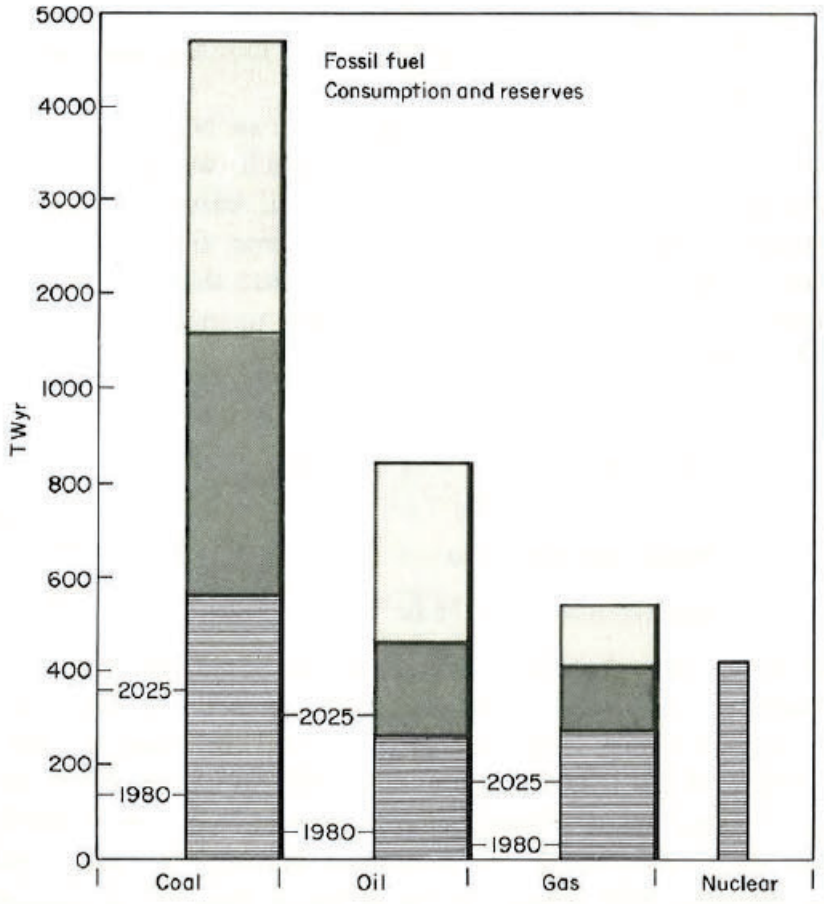


Figure 9. Recoverable fossil fuel reserves compared with use up to 1980 and projected use to 2025. Reserves are from Häfele[24] and are divided into sections according to recovery costs. Lower sections are economically recoverable with present-day technology. Oil reserves include conventional sources such as tar sands, heavy crudes, etc. Upper limit to coal reserves is from Rotty and Marland.[23] Häfele considers 1580 TWyear to be the ultimately recoverable resource limit. Projected consumption values are consistent with the scenario outlined in the text (i.e. approximately 20 TWyear/year by 2025). Projected coal usage includes coal converted to synliquids (see Figure 8). Nuclear reserves (from Häfele[24]) are shown to the same scale for comparison

By the year 2025 ($t = 45$), the total amount of CO_2 produced by fossil fuel burning after 1980 will be around 400 GtC, much larger than the amount produced to date (about 160 GtC): in fact, the next 160 GtC would come in 23 years.

Present fossil fuel reserves are more than adequate to maintain a 2% growth rate. Figure 9 shows the reserves of different fossil fuels, together with the usage to 1980 and projected use to 2025, based on the partitioning of Figure 8 and an assumed 2% growth rate. Although the scenario predicts substantial depletion of easily recovered oil reserves by 2025, coal reserves are still substantial and provide the potential for much greater increases in atmospheric CO_2.

Changes in atmospheric CO_2 concentration can be estimated directly from equation (3). A more rigorous approach would be to use a sophisticated carbon budget model, but instead a realistic estimate can be obtained from equation (3) by using an airborne fraction of 55% and simply converting from GtC to ppmv (note that this is a conservative estimate since the airborne fraction is expected to increase as CO_2 levels increase). This gives

$$\text{ppmv}(t) = 338 + \frac{0.55\ (5.5)}{2.13\ (0.02)}(e^{0.02t} - 1)$$

which simplifies to

$$\text{ppmv}(t) = 338 + 71\ (e^{0.02t} - 1) \qquad (4)$$

Figure 10 shows projected CO_2 changes based on this equation, together with the changes corresponding to growth at 2.8% per year (similar to Rotty's intermediate energy use scenario):[7] changes only up to 2050 are shown. If the results of climate models, to be discussed later, are correct, then a significant climatic change will have occurred before that time. Since this may result in a radical change in energy policies, projections beyond 2050 based on the scenario and simple calculations used here are of doubtful value.

To summarize, future atmospheric CO_2 levels are dependent on future fossil fuel usage, and on the way in which emitted CO_2 is redistributed between the oceans, the atmosphere and the biosphere. Fossil fuel consumption depends on energy demand, energy use strategies, and available resources. Even the most conservative estimates, involving future growth at rates much below those of recent decades, predict that CO_2 production rates will more than double over the next 45 years. These values can be converted to changes in atmospheric CO_2 concentration using carbon budget models. Predicted levels for *low* energy use scenarios are around 440-450 ppmv in 2025, roughly 50% higher than the preindustrial level. Higher energy use scenarios predict CO_2 levels up to around 600

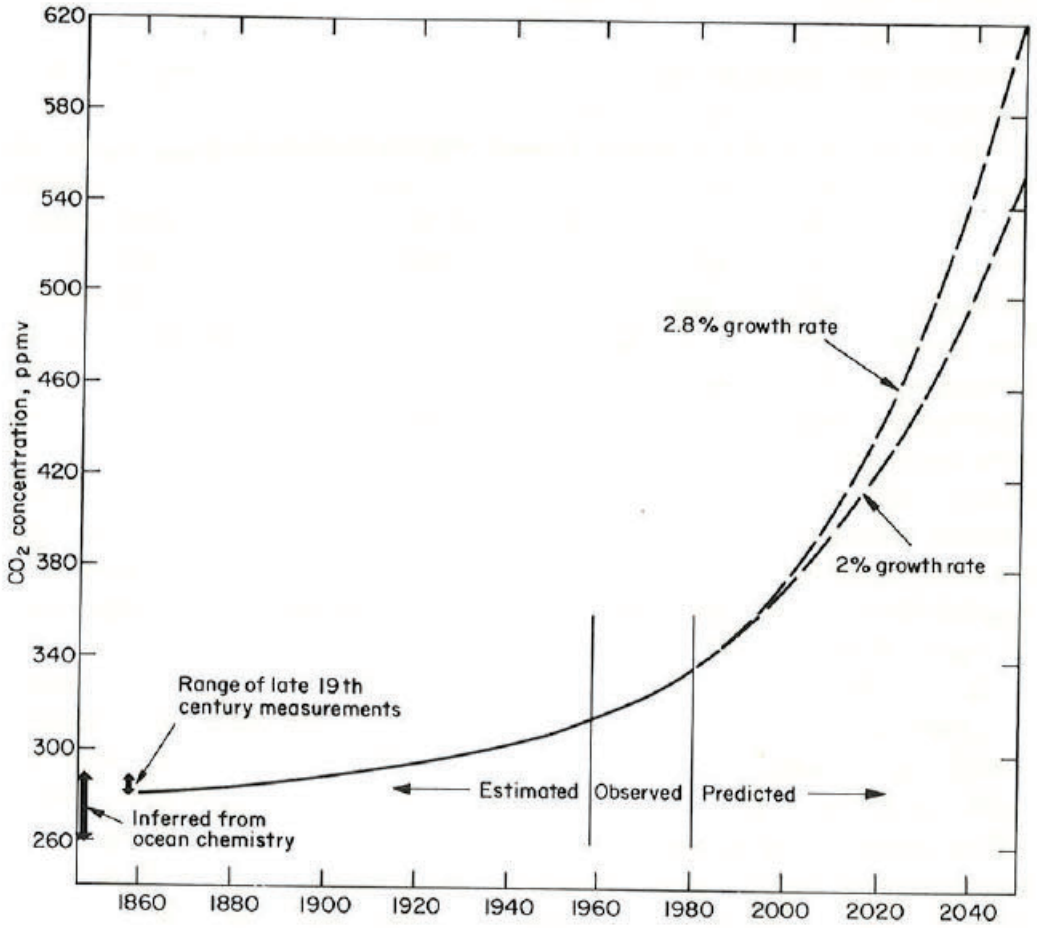


Figure 10. Past and projected future changes in atmospheric carbon dioxide concentration

ppmv by 2025, but these values are less likely because of constraints on fuel demand.[23]

It is salutory to consider the results of an energy use scenario deliberately designed to keep the maximum level *below* 450 ppmv. Such a scenario has been considered by Siegenthaler and Oeschger.[28,29] It would require fossil fuel energy production rate to increase only very little above the present value and to decrease rapidly soon after 2000. They state[29] that it 'seems probable that the actual CO_2 input rates during the next several decades will exceed those of this scenario, because the growing energy demand cannot be sufficiently satisfied by other resources'. Future levels in excess of 450 ppmv appear to be inevitable.

Impact of carbon dioxide on climate

The underlying issue is that increased levels of atmospheric carbon dioxide will cause an increase in mean global surface temperature. The commonly quoted figure is that a doubling of CO_2 will by a 'greenhouse' effect, raise temperatures by between 2 and 3°C. I will begin by discussing the degree of confidence with which this estimate can be made. But first I must point out that any temperature increase will certainly not be evenly distributed, neither geographically nor seasonally. If the global mean annual surface temperatures rose by 2°C, then some places would warm more (some, much more), others less; some places might even get cooler; and the pattern of warming would differ from season to season. These are necessary consequences, because increased CO_2 will perturb the whole climate system, and will do so in quite complex ways. Furthermore, CO_2-induced changes will occur not only in temperature, but also in other meteorological and oceanographic parameters, pressure patterns, prevailing winds, rainfall, ocean temperatures and currents, sea-ice distribution, etc. All these are interlinked facets of the global climate system.

How sure can we be that doubling of CO_2 levels will warm the globe by *on average* 2–3°C? The answer is that we can have considerable confidence in this estimate. It is based on the results of a variety of different methods of mathematically modelling the so-called greenhouse effect (reviewed by Gates[30]). The simplest of these are one-dimensional energy balance models which are called radiative-convective models. These treat the whole atmosphere as a single vertical column of air in which the temperature profile is determined by two main processes, the net absorption of radiation and the redistribution of the heat so produced by thermal convection. Changes in CO_2 act essentially by changing the amount of absorbed and reradiated long wave radiation in the lower layers of the atmosphere. This has other important consequences, which the models also consider, the most significant of these being the effect of water vapour. Water vapour is also a radiatively active gas, producing a greenhouse effect. Since warmer temperatures imply more evaporation and hence more water vapour in the atmosphere, due allowance must be made for the subsequent enhanced impact of increasing CO_2 on the atmospheric heat balance. This is known as the water-vapour feedback effect. Water-vapour feedback roughly doubles the response of atmospheric temperature to CO_2 changes.[31]

The earliest realistic radiative-convective model[32] handled this feedback in a relatively simple way. Depending on how this was done, and how clouds were modelled, the response to a doubling of CO_2 was a warming of 1.4–2.9°C at the Earth's surface. More sophisticated, one-dimensional radiative-convective models[33] give very nearly the same response.

The next level of sophistication is to consider horizontal variations, but

in the north – south direction only. Of these, the simplest models (surface energy balance models) have no vertical co-ordinate. They do, however, model the important driving force for the weather machine, the imbalance between solar energy input at the equator and at the poles. When formulated correctly,[34] such models produce a warming of about 2°C for a doubling of CO_2. An important new aspect which these models are able to consider is the ice-albedo feedback: warmer temperatures in high latitudes imply less snow and ice cover, less direct reflection of incoming radiation (i.e. lower albedo) and hence still higher temperatures. This results in an amplification of the CO_2 effect in high latitudes.

Beyond these two types of one-dimensional model are two-dimensional models which can be either hybrids of the radiative-convective and surface energy balance models (e.g. Ramanathan *et al.*[35]) or reduced, 'zonally-averaged' versions of more complex three-dimensional models (e.g. Potter[36]). Potter found a warming of 2°C for a CO_2 doubling; Ramanathan *et al.* obtained a warming of 3.2°C for a CO_2 doubling.

All these relatively simple models have their advantages in that they allow single aspects of the response to changes in CO_2 (such as the ice-albedo feedback) to be factored out and studied in detail. The most realistic models, however, are those which consider the time-dependent three-dimensional circulation of the whole atmosphere: general circulation models (GMCs). The general method here is first to run the model with a preindustrial CO_2 level of say 300 ppmv (the 'standard' run) and then with a higher CO_2 level of say, 600 ppmv. The differences between the runs provide the effects of CO_2.

Although GCMs used for climate studies are similar in many ways to those used and proven in routine weather forecasting, there are important differences. The changes being studied are on a time scale of decades or centuries; and on these time scales significant variations in the oceans and Arctic and Antarctic sea-ice distributions can occur. Thus, CO_2-climate models must include the oceans and sea ice as interactive factors. In *weather* prediction, on the day-to-day time scale, these factors vary so slowly that their changes can be ignored. The need to include oceans and sea ice greatly increases the complexity of GCMs, so much so that considerable development work remains to be done. Furthermore, bigger computing systems are required, and at present compromises must be made. Thus, in order to model ocean and ice changes realistically, it is often necessary to simplify other factors. All GCMs used for CO_2 studies involve compromises of some kind: simplifications in the way the ocean is modelled; in the way sea-ice variations are modelled; simplified geography; a simplified, or non-existent seasonal solar radiation cycle; and/or simplifications in the way small-scale atmospheric processes such as clouds are modelled. I will elaborate on only two of these: oceans and clouds.

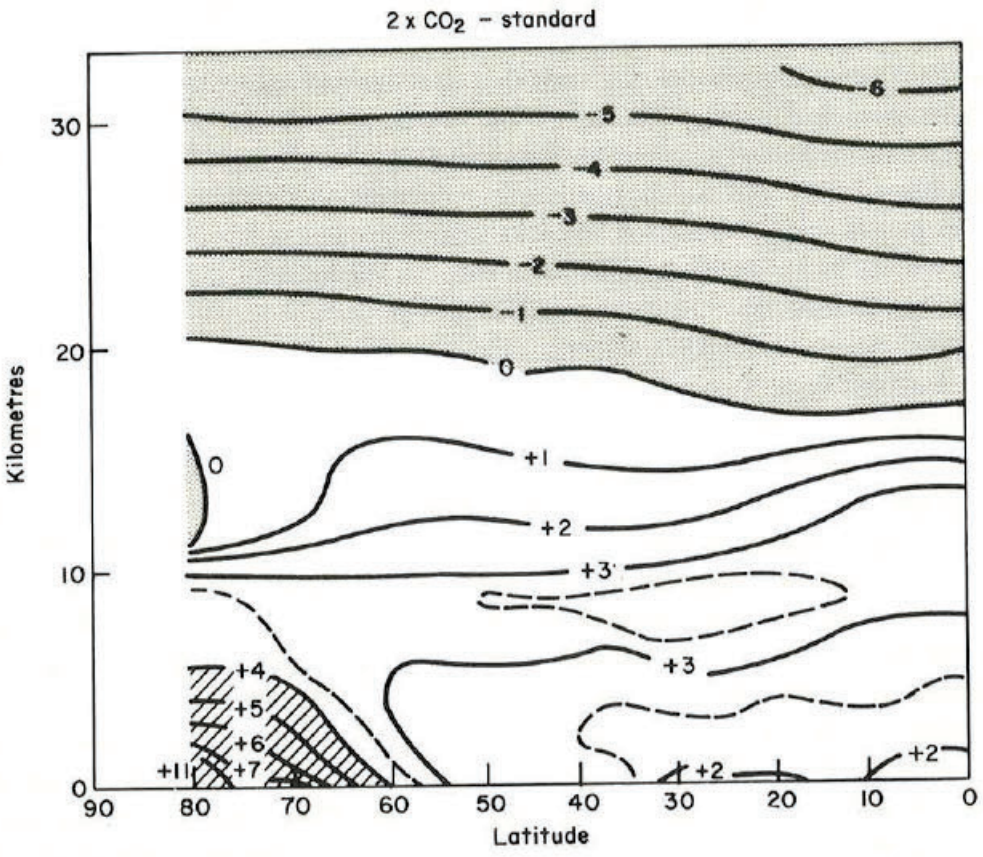


Figure 11. Latitudinal and vertical distribution of mean annual temperature increase due to doubling of atmospheric carbon dioxide concentration (from Manabe and Wetherald[39], using a GCM with a 'swamp' ocean, fixed cloud cover no seasonal insolation cycle, and highly idealized geography)

Simplified oceans

The simplest ocean is one which is pre-set either to be similar to the present, or to be arbitrarily warmer than the present. For example, the 5-level global GCM of the UK Meteorological Office[37] and the 2-level Oregon State University GCM[38] have both been run with a non-interactive, infinite heat-capacity ocean (i.e., unaffected by any CO_2-induced atmospheric warming). In this extremely unrealistic mode (the important water-vapour and ice-albedo feedbacks are effectively short-circuited), a doubling of CO_2 produces a warming of only 0.2°C, compared with a warming of 2.3°C when the ocean is allowed to respond.

At the opposite extreme, and physically much more realistic, are models with a so-called 'swamp' ocean, which has zero heat-capacity and so can respond instantly to atmospheric temperature changes. The important advance here is to allow realistic heat and moisture exchanges between

the oceans and the atmosphere. The first such model used was that of Manabe and Wetherald.[39] Their model still has a number of simplifications: highly idealized geography, fixed cloudiness, and no seasonal cycle. The estimate of global average warming for a doubling of CO_2 based on this model is 2.9°C, but the signal is greatly amplified at high latitudes. The surface warming is shown to be balanced by cooling at high elevations. A latitudinal cross-section of Manabe and Wetherald's results is shown in Figure 11. An improved version of this model, with variable cloudiness and a larger computational domain[40] produces very similar results: a warming of 3.0°C for a doubling of CO_2. Although these models have no seasonal insolation cycle, and so give only annual average values, the effect of adding a seasonal cycle is relatively small.[41]

The next improvement is to use a shallow, finite heat-capacity model ocean, simulating the upper mixed layer of the real ocean, as in the GCM of Manabe and Stouffer.[42,43] The influence of the ocean can, in fact, be studied using simpler models. For example, Hunt and Wells[44] have coupled a 300m oceanic mixed layer to a radiative-convective model. They found the effect on the *magnitude* of the CO_2-induced temperature change to be small, but the oceans caused a lag in the response of the atmosphere by around 8 years. Other coupled ocean-atmosphere models point to lags of up to 20 years, so that *present* changes in CO_2 might be expected to take up to a decade or so before their effects on the whole climate system were fully felt. The importance of this lag effect, or transient response aspect, has been discussed in detail by Schneider and Thompson[45]. It has both good and bad aspects. It may give us more leeway to prepare for the effects of increasing CO_2; but it also means that, by the time the effects are unequivocally detected, a further period of CO_2 increase will have already and irrevocably occurred.

Simplified small-scale atmospheric processes

The most important aspect here is the modelling of clouds. Cloud processes (evaporation, condensation, precipitation, reflectivity) play a very important part in the atmospheric energy balance, yet they obviously cannot be modelled on an individual basis. All models (including weather forecasting models) try to aggregate the effects of clouds in some way: the procedure is called 'cloud parameterization'. Many CO_2 – climate models use fixed cloudiness. More complex models have demonstrated that the way clouds are parameterized is not particularly important; widely differing schemes give roughly the same warming for a doubling of CO_2. The suggestion that cloud changes might provide a significant negative feedback mechanism (higher temperatures imply more evaporation and more cloud cover, which might offset the warming) has been examined intensively. These detailed analyses (see, for example, Cess[46], Wetherald and Manabe[47] and Charlock[48]) expose the weaknesses in this simplistic argument and indicate that

Annex 32

"Projecting Future Sea Level Rise. Methodology, Estimates to the Year 2100, and Research Notes", *U.S. Environmental Protection Agency*, 24 October 1983, pages iii-vii

96.6
M3

United States
Environmental Protection
Agency

Office of Policy
& Resource Management
Washington, DC 20460

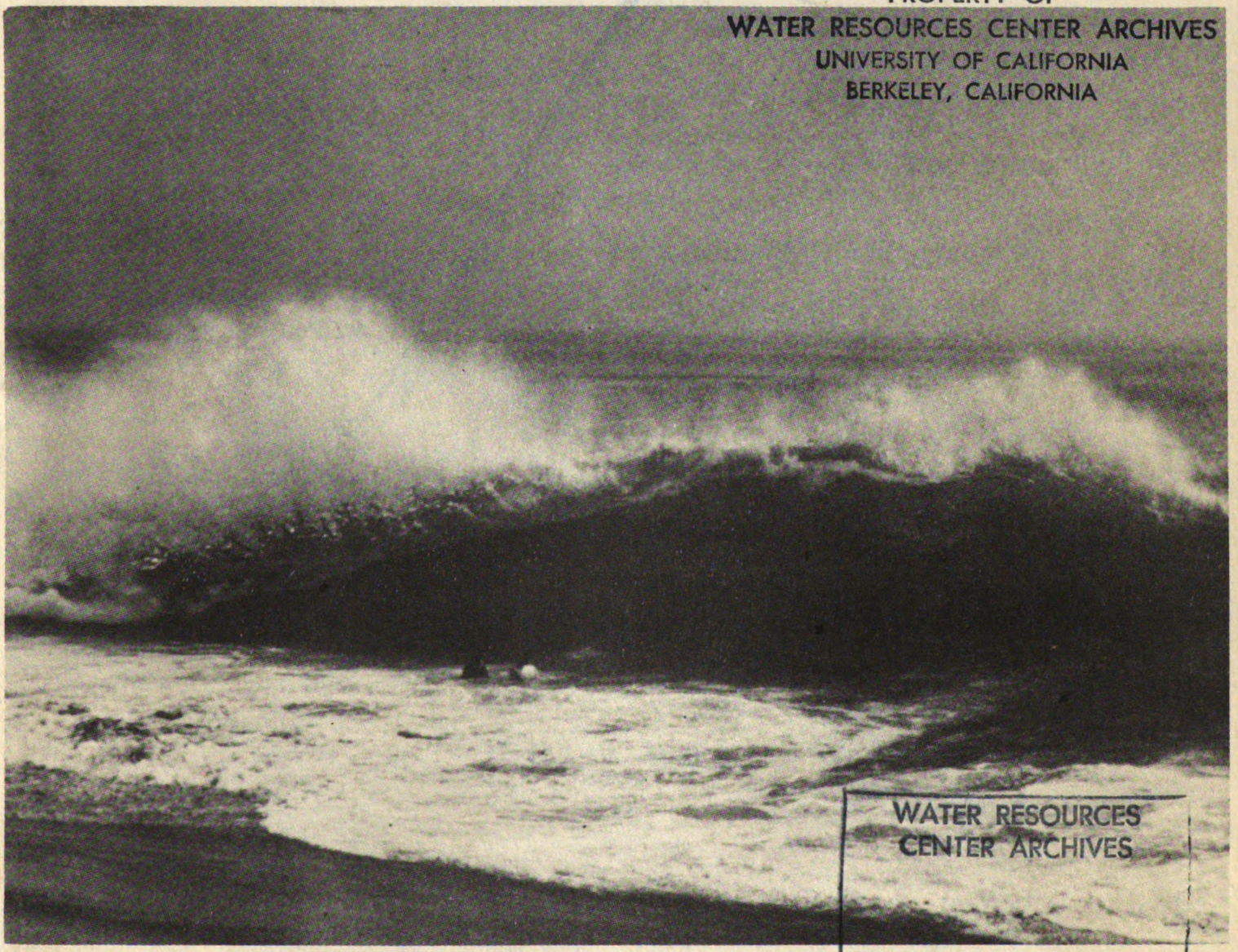
October 1983
EPA 230-09-007
Revised

EPA
UNIVERSITY OF CA RIVERSIDE, LIBRARY
3 1210 02502 2128

Projecting Future Sea Level Rise

Methodology, Estimates to the Year 2100, & Research Needs

PROPERTY OF
WATER RESOURCES CENTER ARCHIVES
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA



WATER RESOURCES
CENTER ARCHIVES
UNIVERSITY OF CALIFORNIA
BERKELEY

PROJECTING FUTURE SEA LEVEL RISE

Methodology, Estimates to the Year 2100, and Research Needs

By

John S. Hoffman, EPA
Dale Keyes, Consultant
James G. Titus, EPA

A Report of:

The Strategic Studies Staff
Office of Policy Analysis
Office of Policy and Resource Management
U.S. Environmental Protection Agency
401 M Street, S.W. (PM-221)
Washington, D.C. 20460
(202) 382-5484

2nd Edition, Revised

October 24, 1983

TABLE OF CONTENTS

	Page
PREFACE	iii
ACKNOWLEDGMENTS	v
REPORT SUMMARY AND FINDINGS	vi
CHAPTER 1 INTRODUCTION	1
CHAPTER 2 THE SCIENTIFIC BASIS FOR PROJECTING SEA LEVEL RISE	4
CHAPTER 3 THE APPROACH, ASSUMPTIONS, AND MODELS USED TO ESTIMATE SEA LEVEL RISE	13
CHAPTER 4 SEA LEVEL SCENARIOS TO THE YEAR 2100	38
CHAPTER 5 IMPACTS OF SEA LEVEL RISE	41
CHAPTER 6 RESEARCH NEEDED TO IMPROVE ESTIMATES OF SEA LEVEL RISE	51
APPENDIX A -- SUMMARY OF SEA LEVEL RISE SCENARIOS, INCLUDING SPECIAL CASES OF INCREASED VOLCANIC ACTVITY AND CHANGES IN SOLAR IRRADIATION	59
APPENDIX B -- MODELS, ANALYTICAL METHODS, AND ASSUMPTIONS USED FOR ESTIMATING THE SCENARIOS OF SEA LEVEL RISE	63
APPENDIX C -- METHODS OF ESTIMATING SNOW AND ICE CONTRIBUTION	101
BIBLIOGRAPHY	115

PREFACE

The primary objective of this report is to estimate the range of future sea level rise. This information should help coastal engineers, planners, coastal zone managers, water supply and quality planners, and site planners to make better decisions in coastal areas. Scientists and federal research policy makers can use this report in choosing research to improve sea level rise estimates.

This report has undergone an extensive peer review to ensure its accuracy and completeness. Nevertheless better estimates of sea level rise will be forthcoming as scientific knowledge improves.

No EPA policy is implied in this document. Comments are welcome and should be sent to John Hoffman, PM-221, Strategic Studies Staff, EPA, Washington, D.C. 20460.

ACKNOWLEDGMENTS

Several people made valuable contributions to this study. Dr. Alan Truelove of Pechan and Associates did much of the early computer programming. Dr. Sergej Lebedeff, Dr. Gary Russell, Dr. Andrew Lacis, and Dr. James Hansen of the Goddard Institute for Space Studies (GISS) provided computer programs and technical advice on the temperature-flux equations, thermal-expansion model, and ice-sheet melting. Dr. Robert Thomas and Dr. David Thompson of the Jet Propulsion Laboratory provided information on glacial processes. Dr. William Emanuel of Oak Ridge National Laboratories provided the computer program and technical advice on the carbon-cycle model. CO_2 projections were derived from runs of a modified version of the World Energy Model provided by the Institute of Energy Analysis, Oak Ridge Associated Universities. Loren Dunn of EPA made valuable contributions to earlier versions of this effort. Wynne Cougill and Steven Seidel made editorial suggestions. Tom Glover provided graphics and Carolyn Acklin typed numerous drafts.

We would like to thank more than one hundred peer reviewers, too numerous to name, who took time to comment on this report. All errors, omissions and inaccuracies, however, are the responsibilities of the authors.

REPORT SUMMARY AND FINDINGS

Concentrations of atmospheric CO_2 and other greenhouse gases will continue to increase in coming decades. Two National Academy of Sciences panels have concluded that higher levels of these gases will almost certainly produce a large global warming. That warming, by thermally expanding the oceans and by causing the transfer of ice and snow resting on land to the oceans, should raise sea level substantially faster than the rise that has taken place during the past century.

Although current knowledge is inadequate to make a precise prediction of future sea level rise, it is sufficient to predict the likely range. Many factors were considered in generating the estimates of sea level rise contained in this report: population and productivity growth, atmospheric and climatic change, and oceanic and glacial response. High and low assumptions for these principal determinants of sea level rise were derived from the literature. When linked together the various assumptions allowed the estimation of high and low paths of future sea level rise. Based on this work, the following findings can be stated:

(1) GLOBAL SEA LEVEL WILL ALMOST CERTAINLY RISE IN COMING DECADES.

- A global rise of between 144 cm (4.8 feet) and 217 cm (7 feet) by 2100 is most likely.
- A global rise as low as 56 cm (1.9 feet) or as high as 345 cm (11 feet) by 2100 cannot be ruled out.
- Along most of the Atlantic and Gulf Coasts of the United States, the rise will be 18 to 24 cm (0.6 to 0.8 feet) more than the global average.

(2) ESTIMATES OF FUTURE SEA LEVEL RISE CAN BE USED TO REDUCE ITS ADVERSE IMPACTS.

- Sea level rise will increase shoreline retreat, erosion, flooding, and saltwater intrusion in coastal areas. Important economic impacts could result.
- Many, if not most of the adverse economic impacts of sea level rise can be avoided if timely actions are taken in anticipation of these effects.
- Professionals and policymakers need to assess the vulnerability of forthcoming decisions and the existing infrastructure to sea level rise.

(3) THE RANGE OF FUTURE SEA LEVEL RISE ESTIMATES COULD BE NARROWED BY ACCELERATING RESEARCH.

- Differences in estimates of sea level rise are due to deficiencies in scientific knowledge and in the methods used for constructing estimates. These deficiencies can be corrected.

- The most important research opportunities for improving sea level rise estimates are in estimating the transfer of ice and snow from land to sea, understanding the growth of the minor trace gases, and narrowing estimates of the sensitivity of the climate system to increased greenhouse gases. Many opportunities exist for improving knowledge in these areas.

- Under current funding, estimates of sea level rise will improve very slowly.

- Greater and more secure funding of interdisciplinary teams could produce a more rapid improvement in estimates.

Annex 33

B. Flannery et al., *Energy Balance Models Incorporating Evaporative Buffering of Equatorial Thermal Response,* in CLIMATE PROCESSES AND CLIMATE SENSITIVITY, eds. J. Hansen & T. Takahashi (American Geophysical Union, 1984)

The complete book can be accessed through the Vrije Universiteit Amsterdam Library (*see* Vrije Universiteit Amsterdam Library catalogue, available at: https://vu.on.worldcat.org/search/detail/898777674?queryString=Climate%20processes%20and%20climate%20sensitivity&clusterResults=true&groupVariantRecords=false (last accessed on 12 March 2024). The Vrije Universiteit Amsterdam Library can be contacted for assistance by phone at +31 (020) 59 85020.

Geophysical Monograph 29
Maurice Ewing Volume 5

Climate Processes and Climate Sensitivity

Edited by

James E. Hansen
Taro Takahashi

American Geophysical Union
Washington, D.C.
1984

Published under the aegis of the Geophysical Monograph Board: Sean Solomon, Chairman; Francis Boyd, Merle Henderschott, Janet Luhmann, James Papike, and John Schaake, members.

Climate Processes and Climate Sensitivity

Library of Congress Cataloging in Publication Data

Maurice Ewing Symposium (4th : 1982 : Palisades, N.Y.)
Climate processes and climate sensitivity.

(Maurice Ewing series ; 5) (Geophysical monograph, ISSN 0065-8448 ; v. 29)
"Based on papers presented at the Fourth Biennial Maurice Ewing Symposium held at Palisades, New York, October 25-27, 1982"
Includes bibliographies.
1. Climatology—Congresses. 2. Geophysics—Congresses. 3. Ocean-atmosphere interaction--Congresses. I. Hansen, James E. (James Edward), 1941- . II. Takahashi, Taro. III. American Geophysical Union. IV. Title. V. Series. VI. Series: Geophysical monograph ; v. 29.

QC980.M38 1982 551.5 84-6256
ISBN 0-87590-404-1

Copyright 1984 American Geophysical Union
2000 Florida Avenue, NW
Washington, D.C. 20009

Figures, tables, and short excerpts may be reprinted in scientific books and journals if the source is properly cited.

Authorization to photocopy items for internal or personal use, or the internal or personal use of specific clients, is granted by the American Geophysical Union for libraries and other users registered with the Copyright Clearance Center (CCC) Transactional Reporting Service, provided that the base fee is $1.00 per copy, plus $.(10) is paid directly to CCC, 21 Congress St., Salem, MA 01970. 0065-8448/84/$01.00 + .10.
This consent does not extend to other kinds of copying, such as copying for creating new collective works or for resale. The reproduction of multiple copies and the use of full articles or the use of extracts, including figures and tables, for commercial purposes requires specific permission from AGU.

Printed in the United States of America

CONTENTS

PREFACE vii

INVENTING THE FUTURE: ENERGY AND THE CO_2 "GREENHOUSE" EFFECT
E. E. David Jr. 1

ATMOSPHERE AND OCEAN DYNAMICS

FEEDBACKS BETWEEN DYNAMICAL HEAT FLUXES AND TEMPERATURE STRUCTURE IN THE ATMOSPHERE
Peter H. Stone 6

ON THE ROLE OF GLOBAL-SCALE WAVES IN ICE-ALBEDO AND VEGETATION-ALBEDO FEEDBACK
Dennis L. Hartmann 18

THE OCEAN'S TRANSIENT RESPONSE TO GLOBAL SURFACE TEMPERATURE ANOMALIES
K. Bryan, F. G. Komro, and C. Rooth 29

A RECENT Θ-S SHIFT IN THE DEEP WATER OF THE NORTHERN NORTH ATLANTIC
James H. Swift 39

VARIATION OF MONSOONAL UPWELLING: A RESPONSE TO CHANGING SOLAR RADIATION
Warren L. Prell 48

HYDROLOGIC CYCLE AND CLOUDS

MODELING EVAPOTRANSPIRATION FOR THREE-DIMENSIONAL GLOBAL CLIMATE MODELS
Robert E. Dickinson 58

THE INFLUENCE OF VEGETATION ON THE HYDROLOGIC CYCLE IN A GLOBAL CLIMATE MODEL
D. Rind 73

CLOUD/CLIMATE SENSITIVITY EXPERIMENTS
John O. Roads, Geoffrey K. Vallis, and Lorraine Remer 92

ENERGY BALANCE MODELS INCORPORATING EVAPORATIVE BUFFERING OF EQUATORIAL THERMAL RESPONSE
Brian P. Flannery, Andrew J. Callegari, and Martin I. Hoffert 108

TEMPORAL VARIATIONS IN LAKE LEVELS SINCE 30,000 YR BP - AN INDEX OF THE GLOBAL HYDROLOGICAL CYCLE
F. Alayne Street-Perrott and Sandra P. Harrison 118

ALBEDO AND RADIATION PROCESSES

CLIMATE SENSITIVITY: ANALYSIS OF FEEDBACK MECHANISMS
J. Hansen, A. Lacis, D. Rind, G. Russell, P. Stone, I. Fung, R. Ruedy, and J. Lerner 130

ON THE TRANSIENT RESPONSE PATTERNS OF CLIMATE TO TIME DEPENDENT CONCENTRATIONS OF ATMOSPHERIC CO_2
G. R. North, J. G. Mengel, and D. A. Short 164

SYSTEMATIC ANALYSIS OF CLIMATIC MODEL SENSITIVITY TO PARAMETERS AND PROCESSES
Matthew C. G. Hall and Dan G. Cacuci 171

VEGETATION-ALBEDO FEEDBACKS
Robert E. Dicksinson and Brian Hanson 180

ON THE EMPIRICAL VERIFICATION OF MODEL-PREDICTED CO_2-INDUCED CLIMATIC EFFECTS
Stephen H. Schneider 187

SOLAR VARIABILITY AS A SOURCE OF CLIMATE CHANGE
Sabatino Sofia 202

CRYOSPHERIC PROCESSES

SOME ASPECTS OF THE CRYOSPHERE AND ITS ROLE IN CLIMATIC CHANGE
Charles R. Bentley 207

CLIMATE SENSITIVITY AND THE MARGINAL CRYOSPHERE
R. G. Barry, A. Henderson-Sellers, and K. P. Shine 221

THE ROLE OF SEA ICE DYNAMICS IN MODELING CO_2 INCREASES
W. D. Hibler III 238

RESPONSE OF ANTARCTIC SEA ICE TO UNIFORM ATMOSPHERIC TEMPERATURE INCREASES
Claire L. Parkinson and Robert A. Bindschadler 254

ICE SHEET MARGINS AND ICE SHELVES
Robert H. Thomas 265

WEST ANTARCTICA, THE SEA-LEVEL CONTROLLED MARINE INSTABILITY: PAST AND FUTURE
J. L. Fastook 275

ICE CORES AND GLACIAL HISTORY

NORTH ATLANTIC CLIMATIC OSCILLATIONS REVEALED BY DEEP GREENLAND ICE CORES
W. Dansgaard, S. J. Johnsen, H. B. Clausen, D. Dahl-Jensen, N. Gundestrup, C. U. Hammer, and H. Oeschger 288

LATE GLACIAL CLIMATE HISTORY FROM ICE CORES
H. Oeschger, J. Beer, U. Siegenthaler, B. Stauffer, W. Dansgaard, and C. C. Langway 299

SIMULTANEOUS CLIMATIC CHANGE IN BOTH HEMISPHERES AND SIMILAR BIPOLAR INTERGLACIAL WARMING: EVIDENCE AND IMPLICATIONS
John H. Mercer 307

OCEAN CHEMISTRY

IS THERE A TIE BETWEEN ATMOSPHERIC CO_2 CONTENT AND OCEAN CIRCULATION?
Wallace S. Broecker and Taro Takahashi 314

THE CLIMATE-CHEMISTRY CONNECTION
Wallace S. Broecker and Tsung-Hung Peng 327

GLACIAL-HOLOCENE CHANGES IN ATMOSPHERIC CO_2 AND THE DEEP-SEA RECORD
W. H. Berger and R. S. Keir 337

ON THE RELATIONSHIP BETWEEN OCEAN CHEMISTRY AND ATMOSPHERIC pCO_2 DURING THE CENOZOIC
Michael L. Bender 352

CADMIUM IN BENTHIC FORAMINIFERA AND ABYSSAL HYDROGRAPHY: EVIDENCE FOR A 41 KYR OBLIQUITY CYCLE
Edward A. Boyle 360

ENERGY BALANCE MODELS INCORPORATING EVAPORATIVE BUFFERING OF EQUATORIAL THERMAL RESPONSE

Brian P. Flannery and Andrew J. Callegari

Corporate Research Science Laboratories, Exxon Research and Engineering Co.
Linden, New Jersey 07036

Martin I. Hoffert

Department of Applied Science, New York University
New York, New York 10003

Abstract. We describe two non-standard energy balance models which include effects of latent heat on climate sensitivity, and apply them to study sensitivity to uniform variations in insolation and changes in the concentration of atmospheric CO_2. The Tropical Equatorial Constraint (TEC) model incorporates the proposal of Newell and Dopplick (1979) that evaporative losses from tropical sea surface strongly limit thermal response. The two phase model includes an approximate treatment of energy transfer both as sensible heat and as latent heat of water vapor.

We compare the mathematical and physical assumptions underlying each model, and contrast their solutions with results from a standard model in which the diffusion coefficient remains constant with forcing. Both the TEC and two phase model produce stronger thermal response in polar regions than does the standard model. The TEC model shows that the implication of Newell and Dopplick (1979), that equatorial buffering will limit climate response to increasing CO_2, is not justified when its global consequences are considered. The two phase model closely reproduces results for temperature change with latitude found by Manabe and Wetherald (1980) using a general circulation model. Polar amplification found in the two phase model is attributable to the behavior of a temperature dependent effective diffusion coefficient that increases with warming.

1. Introduction

In previous papers we developed two types of energy balance models, (EBMs): the TEC (for Tropical Equatorial Constraint), and two phase model, that incorporate different aspects of the possible influence of latent heat on climate sensitivity. The TEC model developed in Hoffert et al. (1982, hereafter referred to as Paper I) explores the consequences of the proposal of Newell and Dopplick (1979, hereafter ND) that evaporative losses from sea surface strongly limit thermal response in the tropics. That idea was incorporated as an explicit boundary condition on equatorial temperature as a function of solar constant. Here we extend the TEC model to the case of forcing by changes in the concentration of atmospheric CO_2. Flannery (1982, hereafter referred to as Paper II) developed a two phase EBM that includes the effect of energy transport in the form of latent energy of water vapor and the thermal energy of air.

Here, in section 2, we describe the physical basis and mathematical form of a standard EBM (see North et al., 1981) and of the TEC and two phase models, and in section 3 we systematically compare the behavior of these models for sensitivity to solar and CO_2 forcing. In section 4, we compare a few special cases with corresponding cases calculated using a general circulation model (GCM) (Manabe and Wetherald 1980, hereafter referred to as MW). We will especially focus on the question of the latitudinal distribution of temperature change with forcing. We discuss and summarize our results in section 5.

2. Energy Balance Models

The Standard EMB

We consider annual mean, steady state, latitudinally resolved, symmetric, EBMs which prescribe the distribution of surface temperature $T(x)$ as a function of latitude $\Theta = \sin^{-1}(x)$. The standard model equation, as discussed in North et al. (1981), describes conservation of energy on a sphere subject to solar heating $S(x)$ attenuated by

Copyright American Geophysical Union

TABLE 1. Standard EBM Coefficients, Tuned to Current Climate

INSOLATION	Q_o = 334 W m^{-2}	s_o = 1.246	s_2 = 0.738
IR RADIATION	A = 205 W m^{-2}	B = 2.23 W m^{-2} °C^{-1}	
ABSORPTION	a_o = 0.785	a_2 = 0.263	
	b_o = 0.380	T_s = -10°C	

fractional absorption a(x,T), longwave infrared cooling $I[T,F(CO_2)]$, and diffusive energy transport characterized by diffusion coefficient D

$$-D\frac{d}{dx}(1-x^2)\frac{dT}{dx} = a(x,x_s)\,S(x) - I[T,F(CO_2)]. \quad (1)$$

For a symmetric model, boundary conditions are: at the pole

$$x=1:\ \frac{dT}{dx} = \frac{a(x,x_s)\,S(x) - I[T,F(CO_2)]}{2D}, \quad (2a)$$

at the equator

$$x = 0:\ \frac{dT}{dx} = 0. \quad (2b)$$

Functionally, insolation includes a scale factor Q, which is 1/4 the solar constant, and geometrical projection factors

$$S(x) = Q(s_o - s_2x^2). \quad (3)$$

To study sensitivity to solar forcing, we vary Q from its present value Q_o. We represent longwave radiation as a linear function of surface temperature, plus a term dependent on the atmospheric concentration of CO_2,

$$I[T,F(CO_2)] = A + BT + C\ln[F(CO_2)], \quad (4)$$

where $F(CO_2)$ is the concentration of atmospheric CO_2 relative to its current value. The temperature dependence has been discussed by Warren and Schneider (1979). Satellite observations constrain A and B in order of magnitude, but they require tuning to match a prescribed temperature distribution. Following Hoffert et al. (1980), we include a logarithmic dependence on the atmospheric concentration of CO_2 relative to its present value, and we adjust C to agree with consensus values for global mean temperature rise from CO_2 doubling, $\Delta \langle T \rangle \approx 2.5$ K. Our representation of albedo comes from Hartmann and Short (1979); it includes the important non-linear effect of ice-albedo feedback when temperature falls below a critical value T_s for the formation of ice or snow cover

$$a(x,T) = a_o - a_2x^2, \text{ for } T > T_s, \quad (5)$$

$$a(x,T) = b_o, \text{ for } T < T_s. \quad (5b)$$

Table 1 lists values for the coefficients adopted here. They have been adjusted to match a current climate with T(eq) = 29°C, and an ice line at $x_s = 0.947$ ($\theta = 71°$) which also results in T(pole) = -15°C, and a global mean temperature $\langle T \rangle$ = 14.33°C. These parameterizations and coefficient values are in close agreement with values found and discussed in North et al. (1981). We refer to the model defined by these equations as the standard model. In contrast to the TEC and two phase models, the principal distinguishing features of the standard model are that (1) transport is simply proportional to the temperature gradient and (2) the diffusion coefficient D does not vary when Q or $F(CO_2)$ change.

Fortunately, the standard model can be analyzed exactly by representing the temperature and net source term as expansions in Legendre polynomials

$$a(x,x_s)S(x) = \sum_{L=0}^{\infty}\xi_L P_L(x), \quad T(x) = \sum_{L=0}^{\infty}T_L P_L(x). \quad (6)$$

The coefficients of the source term depend only on the location of the ice-line

$$\xi_L(x_s) = \int_{-1}^{1} a(x,x_s)S(x)P_L(x)dx. \quad (7)$$

The coefficients T_L are given by

$$T_o = (\xi_o - A)/B;\ T_L = \xi_L/[L(L+1)D + B], \quad (8)$$

for L > 1.

As discussed in North et al. (1980) a consistent solution for T(x) and Q can be found by iterating until $T(x_s) = T_s$. Note that the coefficient T_o is also the global mean temperature $\langle T \rangle$. Because the radiative loss term is linear with T, and diffusion only redistributes energy, losses at the mean temperature exactly compensate mean net insolation ξ_o. This is simply a restatement of global energy balance.

The TEC EBM

ND proposed that an evaporative constraint on heating of tropical seas would limit global

Copyright American Geophysical Union

warming by increases in atmospheric CO_2 to values an order of magnitude lower than previously accepted model predictions, i.e., 0.25 K compared with 2-3 K. They based their idea on seasonal and historical observations, and on quantitative analysis of surface energy balance between sea and air, identifying the strong cooling effect of evaporative losses as the controlling feature. Their proposal became the subject of several subsequent studies since it contradicted consensus ideas for global warming from CO_2. GCMs, such as those of Manabe and Wetherald (1975), do include the supposed limiting evaporative effects of ND, but do not find such constrained temperature rise: so other effects must operate that overcome the evaporative limit. The discrepancy between ND and GCM results is hardly surprising because the ND analysis neglects important contributing effects in the highly coupled climate system that are included in the GCM.

The discrepancy has been resolved by attributing the GCM rise to additional feedback from water vapor emission, calculated fully self-consistently in the numerical models (see Ramanathan, 1981; Newell and Dopplick, 1981; Kandel, 1981). However, some aspects of the problem remain controversial: ND point out that the tropical temperature and concentration of water vapor in the Manabe and Wetherald (1975) model for current climate significantly exceed observed values; Kandell notes that analyses differ substantially in the magnitude of terms in the surface energy balance; and results of line-by-line radiative transfer calculations by Wiscombe quoted in Paper I indicate that water vapor feedback is less pronounced under equatorial conditions than in mid-latitudes characteristic of global analyses--this is because water vapor bands are nearly saturated under conditions of high absolute humidity in the tropics (see also Kiehl and Ramanathan, 1982). Limited response of tropical sea surface temperature also receives support from studies of paleoclimate, e.g. Frakes (1979, page 178); Schopf (1980, page 142).

The TEC model developed in Paper I explicitly examines the consequences of the effect proposed by ND. We fixed the response of the equatorial temperature to changes in solar insolation, Q/Q_o, by imposing a boundary condition

$$T_{eq}\ (°C) = 29 + 17.3 \ln(Q/Q_o) \quad . \qquad (9)$$

This form is based on analysis of surface energy balance closely resembling that of ND. Since the standard model described by Eqs. (1-5) cannot satisfy Eq. (9), except for $Q/Q_o = 1$, an additional degree of freedom was provided by allowing D to vary with Q — mathematically D(Q) becomes an adjustable parameter. (We continued to keep D independent of latitude). However, physically plausible solutions do not exist for arbitrary values of Q. In Paper I, we showed that D becomes negative outside the limits $0.80 \leq Q/Q_o \leq 1.15$. To maintain equatorial temperatures higher than in the standard model as Q decreases so must D, until when D = 0 the model reaches local radiative equilibrium at $Q/Q_o = 0.80$. Similarly, as Q rises so does D to maintain temperatures lower than in the standard model. Ultimately, D approaches infinity, and the model becomes isothermal at $Q/Q_o = 1.15$. Thus, ND's hypothesis can only be incorporated into a standard EBM by forcing the meridional transport, as parameterized by the diffusion coefficient D, to be a function of tropical conditions.

Paper I compared the TEC and standard EBM results for changes produced by varying insolation. Relative to the standard model, the TEC constraint buffers equatorial temperature change, but it amplifies response in polar regions. The result is readily explained by global energy balance, using the analytic results in Eqs. (6-8). With increasing Q, T must rise, but the rise at the pole will be enhanced if the equatorial temperature is constrained. Consequently, imposing such a limit strongly alters the latitudinal distribution of temperature change.

Here we also apply the TEC model to variations in the concentration of atmospheric CO_2. A straight forward extension of the simplified surface energy balance analysis of Paper I to include CO_2 radiative effects does not change Eq. (9), i.e., the equatorial temperature does not change at all with rising CO_2. This occurs because we neglect variations in IR feedback under the assumption that water vapor feedback dominates, but is small, since the water vapor bands are already near saturation under tropical conditions. Clearly, such strong anchoring overestimates the buffering effect, but not materially. If mean global warming of 2 K occurs, then, for the rest of the model, it hardly matters whether equatorial temperature changes by 0 K or 0.2 K. For the same reasons as for solar forcing, the TEC model shows strong amplification of thermal response at the poles for CO_2 forcing.

The Two Phase Model

In Paper II we described an EBM formulation that includes both sensible heat of air and latent energy of water vapor as agents of diffusive energy transfer. In the two phase model, the fundamental equation

$$-D\frac{d}{dx}(1-x^2)\frac{d(1+\Psi_L)T}{dx} = a(x,x_s)S(x) - I[T,F(CO_2)], \qquad (10)$$

closely resembles the standard equation, but includes the energy associated with water vapor through the term Ψ_L, which is the ratio of latent to sensible energy,

Copyright American Geophysical Union

$$\Psi_L = \frac{r_a q_{sat}(T) L(T)}{c_p T} \quad , \qquad (11)$$

where L(t) is the latent energy of water vapor, r_a is the relative humidity, $q_{sat}(T)$ is the saturation vapor pressure and c_p is the specific heat of air at constant pressure. This expression can be obtained from physical arguments that identify the diffusive flux as arising from the exchange of parcels of air between adjacent latitudinal segments of the atmosphere with different temperature and humidity, as described in Paper II. The principal physical dependence introduced by adding latent heat to the model is the exponential variation of saturation vapor pressure with temperature given by the Clausius-Clapeyron equation

$$\ln(q_{sat}) = \text{const} - L/(RT) \qquad (12)$$

where R is the gas constant of water vapor. L/R ≈ 5300 K at 300 K.

The two phase model requires a prognostic equation for the distribution of water vapor. Paper II adopted a simple but reasonably accurate assumption for relative humidity that has the advantage of allowing one to define a useful diagnostic concept, the effective diffusion coefficient $D_{eff}(T)$. With reasonable accuracy, the mean distribution of water vapor in the atmosphere can be represented by assuming constant humidity $r_a = 0.8$, independent of latitude, and results, such as those in MW, suggest that relative humidity tends to remain constant during climate change. In that case, Ψ_L is only a function of temperature, and the latitudinal gradient of Ψ_L can be converted into an expression proportional to the temperature gradient. This results in an expression that can be interpreted as an effective diffusion coefficient $D_{eff}(T)$ characterizing the diffusive energy flux

$$F \propto -D' \frac{d(1+\Psi_L)T}{dr} = -D' \left[1+\Psi_L \frac{L}{RT}\right] \frac{dT}{dr} \qquad (13a)$$

$$D_{eff} = D' \left[1+\Psi_L \frac{L}{RT}\right] \qquad (13b)$$

In Paper II, the two phase model was tuned to reproduce T(eq) = 29°C, x_s = 0.947, as in the standard and TEC models discussed above. This required adjustment of both D', from 0.623 to 0.317 W m^{-2} K^{-1}, and the radiative loss coefficient B, from 2.23 to 1.95 W m^{-2} (deg C)$^{-1}$, because the models are slightly different in the distribution T(x). The fiducial two phase model gives a mean temperature <T> = 16.55°C, and polar temperature -17.55°C, compared with 14.33°C and -14.69°C, respectively, in the standard and TEC models.

In the sensitivity studies of Paper II, D' is held constant, as is D in the standard model, but the effective diffusion coefficient varies strongly with latitude and forcing, through its dependence on temperature. In the fiducial model of current climate obtained with the two phase model, $D_{eff}(T)$ varies from D/2 at the pole to 2D at the equator. Also, as forcing produces a warmer climate $D_{eff}(T)$ rises at all latitudes, but most rapidly in the tropics. This behavior causes temperature changes to be relatively larger at the pole than at the equator. The actual latitudinal distribution of warming with latitude agrees very well with the GCM calculations of MW for Q/Q_o = (1.02, 1.04), and $F(CO_2)$ = (2,4).

3. Results for Solar and CO_2 Forcing

We investigated sensitivity to solar and CO_2 forcing for the standard, TEC, and two phase EBMs using numerical solutions to the model equations for values of scaled insolation in the range $0.87 \leq Q/Q_o \leq 1.15$, and $0.5 \leq F(CO_2) \leq 4.0$. For all models, we used identical numerical techniques employing relaxation on a finite difference grid to solve the two point boundary value problem. This method works readily for the highly non-linear two phase model, and allows us to incorporate the adjustment of the diffusion coefficient in the TEC model in a direct fashion. In Table 2, we list the explicit differences associated with the tuned models, parameterizations, and boundary conditions in the three EBMs.

Figure 1 illustrates the major differences in sensitivity to solar forcing. We only examine those solutions closely related to the "current climate" solution, and we do not show results appropriate to the well-known alternate branches of the standard EBM formulation: the ice-covered earth branch, or the unstable branch for which $dx_s/dQ < 0$ (Held and Suarez 1974). If sensitivity is measured by the retreat of ice with increasing insolation, then the TEC model is most sensitive, with $dx_s/dQ(TEC) = 4dx_s/dQ$ (standard), and the two phase model intermediate, but much closer in response to the standard model. Figure 1(b) shows the monotonic increase of the diffusion coefficient with insolation in the TEC model. While the global mean temperature change with insolation is nearly identical in all the models, the response with latitude varies considerably, as shown in Figures 1(c) and 1(d). The TEC model constraint produces a small equatorial variation, but, since the mean temperature rise is not greatly altered, this forces large polar amplification. Again, the two phase model exhibits polar amplification and equatorial buffering intermediate between the standard and TEC models.

Polar amplification can readily be understood in terms of global energy balance and the analysis of results using Legendre expansions, as in Eqs. (6-8). Radiative losses at the global mean temperature exactly compensate for net warming at the global mean insolation rate, which only depends on the location of the ice-line. When the

Copyright American Geophysical Union

TABLE 2. Comparison Between Standard, TEC and Two Phase Models

Fiducial Model	x_s	T(eq)	T(pole)	<T>
Standard	0.947	29.00 °C	-14.69 °C	14.33 °C
TEC	0.947	29.00 °C	-14.69 °C	14.33 °C
Two Phase	0.947	29.00 °C	-17.55 °C	16.54 °C

Fiducial Parameters	Diffusion	B(in I = A + BT)
Standard	0.623 W m^{-2} K^{-1}	2.23 W m^{-2} $°C^{-1}$
TEC	0.623	2.23
Two Phase	0.317	1.95

Forcing Constraints	T(eq)	Diffusion
Standard	Free	Fixed
TEC	Prescribed	Adjusts
Two Phase	Free	Fixed

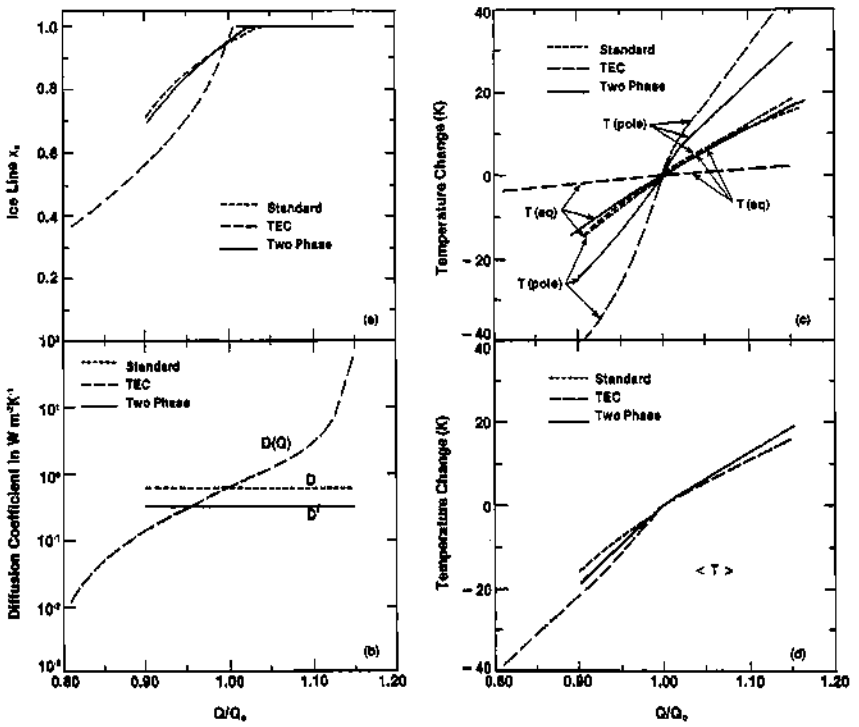


Fig. 1. Comparison of changes induced by scaled changes in insolation Q/Q_o derived from three types of EBM: (a) location of the ice-line, (b) diffusion coefficient, (c) change in equatorial and polar temperature, and (d) global mean temperature.

Copyright American Geophysical Union

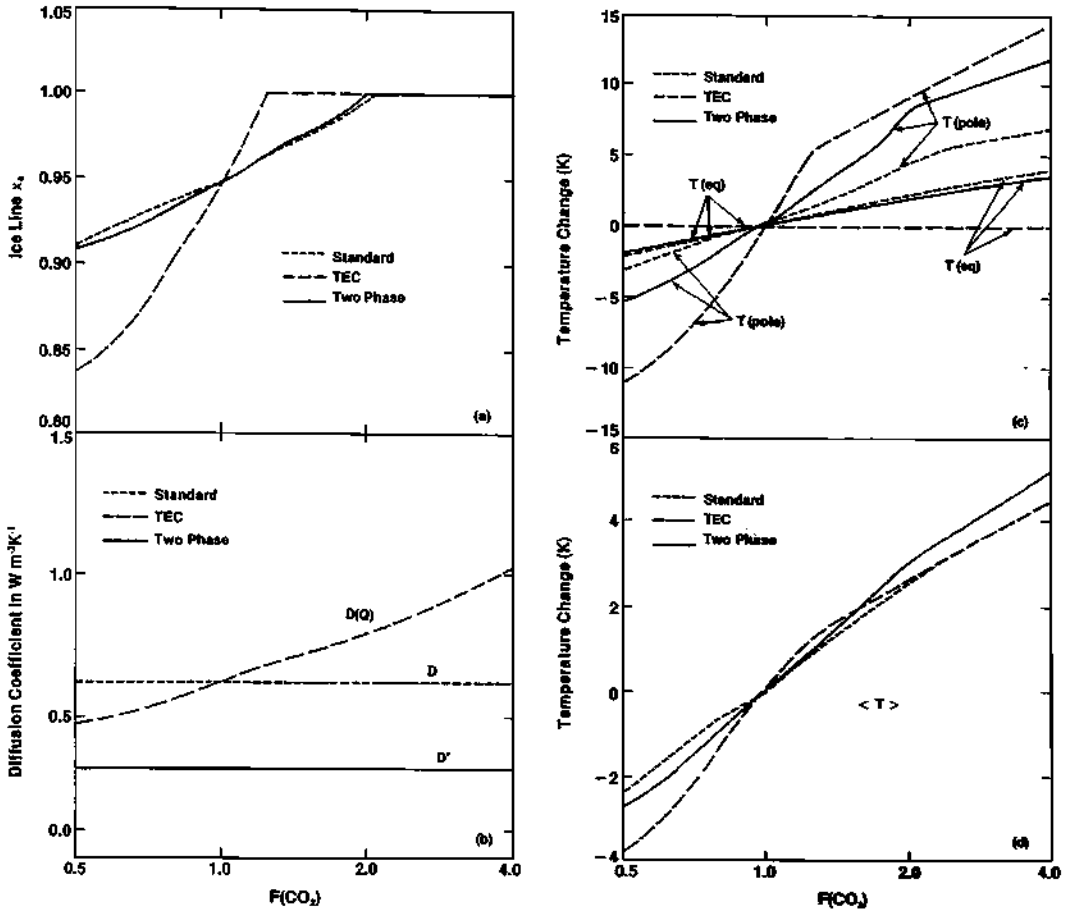


Fig. 2. Comparison of changes induced by variations in the concentration of atmospheric CO_2, relative to its current value, derived from three types of EBM: (a) location of the ice-line, (b) diffusion coefficient, (c) change in equatorial and polar temperature, and (d) global mean temperature.

ice-line coincides for any two models, then A + B <T> must agree. In particular, this happens for all models once the ice-line disappears, for Q/Q_0 > 1.03. This accounts for the common value of Δ<T> between the TEC and Standard models for large Q, and explains the slightly larger value of Δ<T> in the two phase model. Since B (two phase)/B (Standard) = 1.14, Δ<T> (two phase) = 1.14Δ<T> (Standard). Obviously, the TEC model must exhibit polar amplification, since the mean temperature rise must agree but the equatorial response is constrained. Mathematically, that rise occurs because D(Q) grows, so that more energy can be transported poleward in spite of the reduced temperature gradient. In the two phase model a similar change occurs, associated with a rise in the effective diffusion coefficient, $D_{eff}(T)$, as defined in Eq. (13b).

In fact, Figure 1(c) shows that polar amplification in the standard model only occurs because ice-albedo feedback operates. Once ice disappears in the standard model, it is easy to show analytically, using Eqs. (6-8), that $\Delta T(x) \propto T(x)$, i.e. the equator warms more than the poles in the Standard model. This explains the crossover in Figure 1(c), where equatorial warming exceeds polar warming for large Q. The TEC and two phase models continue to exhibit polar amplification even after ice vanishes.

Figure 2 illustrates the sensitivity of the EBMs to variation in the concentration of atmospheric CO_2. Behavior with increasing CO_2 is similar to that found for increasing insolation. Both models that include effects related to latent heat show polar amplification, with the strongest effects in the TEC model, and the two phase model showing intermediate amplification. Note that, for CO_2 doubling, all models produce a rise in global mean temperature of about 2.5 K, as tuned by the choice of C in the parameterization of CO_2 effects, Eq. (4). The slight differences between the models result from slightly different positions for the ice-line with doubled CO_2, and the different value of B in the two phase model.

4. Comparison with Results from GCM Simulations

In their simulations of the effects of atmospheric CO_2 increases on climate, MW calculated a set of models that compared the effects of

Copyright American Geophysical Union

increasing insolation with increasing CO_2. Their GCM considered idealized, sector geography with swamp oceans, i.e. no heat capacity, and only evaluated annual mean forcing without seasonal effects. Thus, their model is in many respects comparable to the simple EBMs of this study. Some of our results can be directly compared with the GCM simulations; we have intentionally drawn our Figures 3 and 4 to nearly the same scale as corresponding Figures 19 and 3 in MW.

MW found that insolation and CO_2 forcing produced quite similar response, i.e. 2 (and 4) X CO_2 concentration and +2% (and 4%) changes in Q/Q_o produce nearly identical patterns of temperature change with latitude, and they showed that poleward energy transport of latent heat was comparable with transport of sensible heat. A principal result from their study was the pronounced amplification of temperature rise at the poles: $\Delta T(\text{pole}) \approx 4\Delta T(\text{eq})$.

Figure 3 shows the temperature variation with latitude $\Delta T(x)$ found in the three EBM simulations for $F(CO_2) = (2,4)$ and $Q/Q_o = (+2\%, +4\%)$. The standard model produces a relatively flat distribution of temperature rise, with only slight polar amplification, while the TEC model produces strong amplification. Results for $\Delta T(x)$ from the two phase model agree nearly exactly with the GCM result (see Figure 19 of MW).

In Figure 4, we show the net poleward flux of energy for each of the three models for the cases $F(CO_2) = (1,2,4)$. The pattern of response in poleward flux is completely different in the three cases. In the standard model, the flux falls nearly everywhere with rising CO_2 while in the TEC model flux rises at nearly all latitudes. The more complex response in the two phase model agrees very well with the pattern of change in poleward flux with latitude found in the GCM study (see Figure 3 of MW).

However, the agreement of the two phase model with the GCM results cannot be carried through in complete detail, physically. The two phase EBM formulation prescribes a functional form for transport of latent heat in which flux is proportional to a temperature gradient, Eq. 13(a), and the model equations actually impose constraints only on the divergence of flux. In Figure 3 of MW, the poleward flux is separately shown for the sensible and latent heat components. While the net flux in the GCM agrees quite well with the two phase flux, the latent heat flux in tropical regions in the GCM, and in real climate, actually pumps energy against the gradient of temperature and absolute himidity. This occurs by correlations in the three dimensional motion and energy content that can be resolved in the GCM but cannot be accounted for in the simple diffusion model of this paper. Nonetheless, the divergence of latent heat flux in the GCM behaves as in the two phase model, and the variation in total flux with forcing agrees remarkably well between the GCM and two phase models.

Finally, Figure 5 shows the absolute humidity and effective diffusion coefficient, Eq. (13b), of

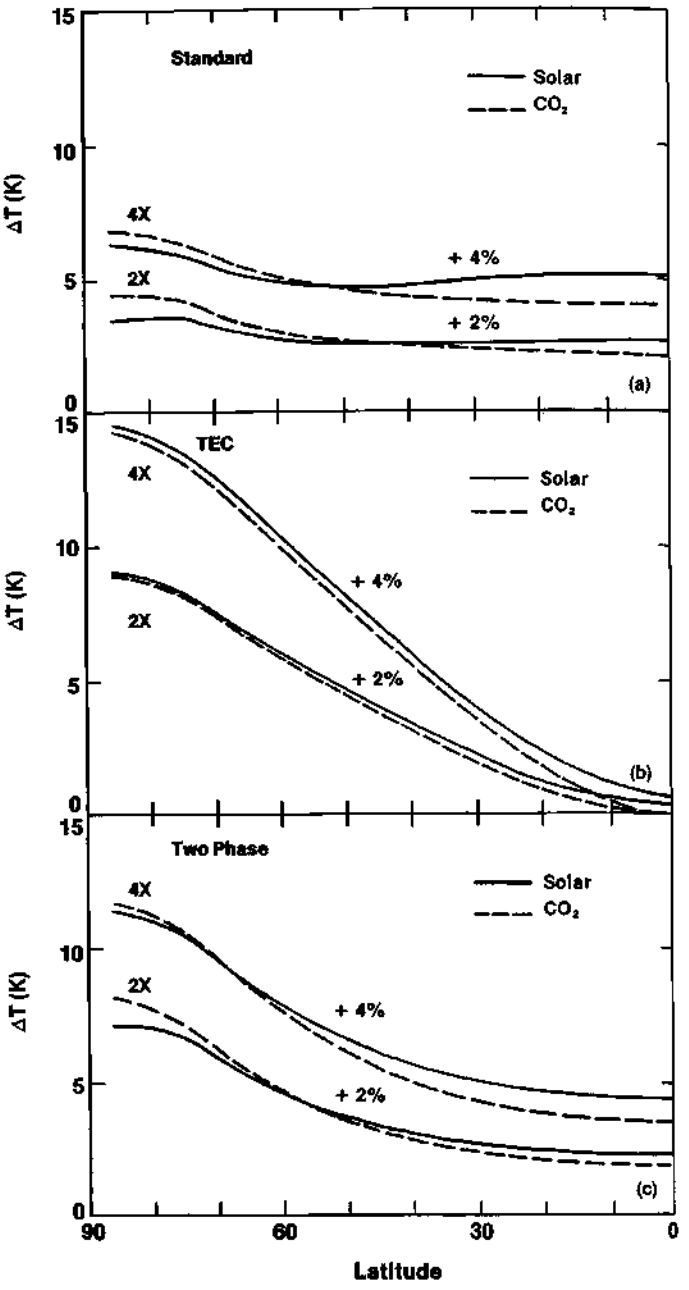


Fig. 3. The latitudinal distribution of temperature change produced by 2% and 4% increases in the solar constant, and increases in atmospheric concentration of CO_2 by factors of 2 and 4, as calculated from the standard (a), TEC (b), and two phase (c), EBM.

the two phase model as a function of latitude for the cases with CO_2 forcing. The distribution of humidity agrees quite well with that found in MW. This produces a variation in $D_{eff}(T)$ such that the mean value roughly agrees with D in the standard model, but the variation from equator to pole is substantial, with $D_{eff}(\text{eq}) = 3\ D_{eff}(\text{pole})$. Because of its exponential temperature dependence, $D_{eff}(T)$ rises at all latitudes with

Copyright American Geophysical Union

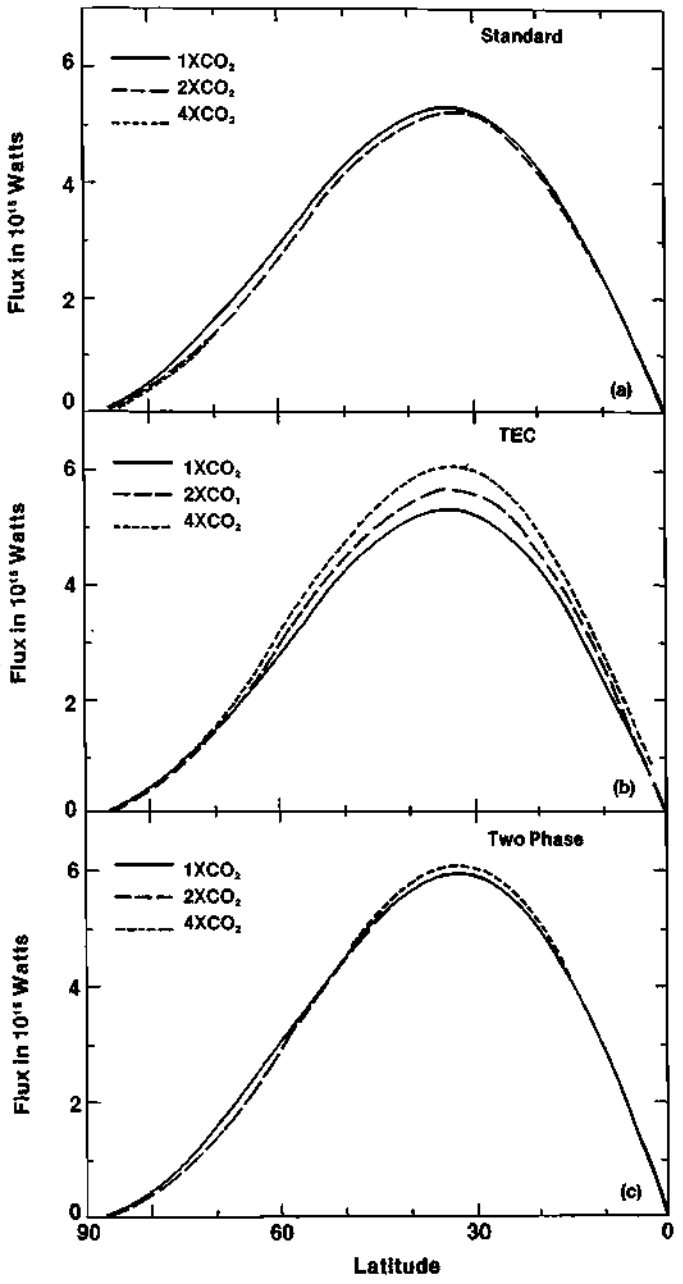


Fig. 4. The latitudinal distribution of poleward flux of energy produced by 2% and 4% increases in the solar constant, and increases in atmospheric concentration of CO_2 by factors of 2 and 4 as calculated from the standard (a), TEC (b), and two phase (c), EBM.

warming, but most rapidly at the equator. Thus, warmer climate becomes more nearly isothermal in the two phase model. With rising temperature, the ability of the system to transport energy rises because the latent heat content rises exponentially.

5. Conclusions

From these models, it is clear that effects of water vapor strongly influence climate sensitivity of EBMs. In particular, they strongly enhance polar amplification of thermal response to both solar and CO_2 forcing beyond that produced solely by ice-albedo feedback and geometrical effects. In this respect, the two phase model agrees far better with the GCM results of MW than does the standard model.

The behavior of the effective diffusion coefficient, $D_{eff}(T)$, characterizing the two phase model explains polar amplification. Since $D_{eff}(T)$ rises exponentially with temperature, the temperature distribution becomes more isothermal with warming. Of course, such an analysis applies to the behavior of the model, but extension to real climate is plausible. In a warmer climate the latent heat content of the atmosphere rises exponentially, so any form of dynamical motion is more effective at transporting energy.

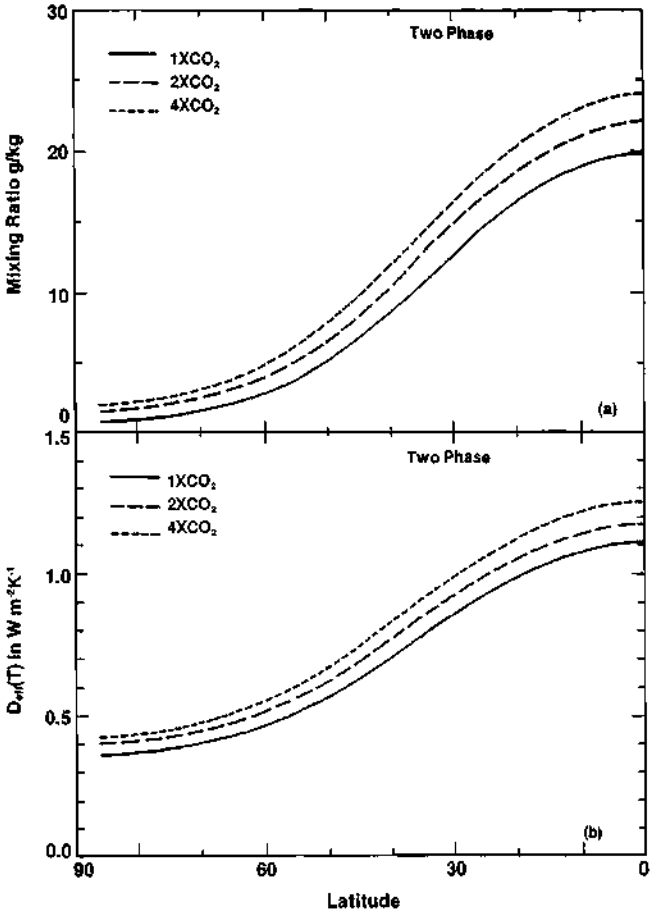


Fig. 5. The latitudinal distribution of (a) water vapor mixing ratio and (b) effective diffusion coefficient, Eq. (13b), as calculated in the two phase EBM for atmospheric concentrations of CO_2 (1, 2 and 4) times its present value.

Copyright American Geophysical Union

Of course these simple physical models serve only to highlight specific effects to the extent that they can be analyzed in an EBM; their consequences for true climate require a far more complex analysis in a more fundamental and complete model, such as a GCM. Nonetheless, they have value as understandable examples of analyzable mechanisms. Physically, such behavior produces a tendency to global isothermality with warming.

Results of the TEC model show that limiting equatorial response by evaporative buffering, as proposed by ND, does not limit global response: rather, such buffering strongly amplifies polar response. This result arises from considerations of global energy balance.

6. Comparison with the MLEBM results of Peng, Chou, and Arking

Since presentation of this paper at the Ewing Symposium, our attention has been directed to the recent work of Peng, Chou, and Arking (1982) and Chou, Peng, and Arking (1982) who have developed a Multi-layer EBM which they used to examine climate response to solar and CO_2 forcing. Their model includes highly resolved, vertical radiative transport, and parameterized dynamical energy transfer involving both horizontal and vertical transport. Their results are far more detailed in content, since they have the ability to analyze vertical components of response, and to treat the dependence of CO_2 and water vapor radiative effects as a function of changing vertical distributions with latitude. Their model treats horizontal transport in a far more non-linear fashion than ours, even in the absence of water vapor transport, since they explicitly include parameterizations modeling dependences of baroclinic instability on the solution. Also, they use an albedo prescription that is less sensitive than that used by us.

The most common grounds for comparison between Chou et al. (1982) and this work are their Figure 8, for poleward flux, with our Figure 4, and their Figure 10, for change in surface temperature, with our Figure 3. Qualitatively, the responses are very similar: both models show pronounced polar amplification. However, the magnitude of high latitude temperature change for doubled atmospheric CO_2 found by Chou et al. is about 60% that found here with the two phase model or in the GCM simulation of MW. Although it is difficult to be certain of attribution in such different models, probably the major source of discrepancy arises from the less sensitive albedo response used by them.

Overall, they find that, by comparing models with fixed and variable poleward transport by latent heat effects, only about 20% of the enhanced polar temperature response can be attributed to enhanced transport by water vapor. This is unlike earlier GCM results of MW, or our results, which suggest that enhanced poleward transport by water vapor is of comparable magnitude with ice-albedo feedback. In our models with large variation from current conditions, polar ice disappears but polar amplification persists. Again, part of that discrepancy arises from the smaller overall response found by Chou, et al. than found by us or MW, and which, probably, can be attributed to different specifications for ice-albedo variation. Nonetheless, all of these models highlight the crucial role of water's influence on climate sensitivity through its effect on ice-albedo change, radiative transfer, and meridional energy transport.

References

Chou, M. D., L. Peng and A. Arking, Climate studies with a multi-layer energy balance model. Part II: The role of feedback mechanisms in the CO_2 problem, J. Atmos. Sci., 39, 2657-2666, 1982.

Flannery, B. P., An energy balance model incorporating transport of thermal and latent energy, (preprint, Paper II), 1982.

Frakes, L. A., Climates through Geologic Time, Elsevier Scientific Publishing Company, New York, 310 pp., 1979.

Hartmann, D. L., and D. A. Short, On the role of zonal asymmetries in climate change, J. Atmos. Sci., 36, 519-528, 1979.

Held, I. M. and M. J. Suarez, Simple albedo feedback models of the icecaps, Tellus, 26, 613-629, 1974.

Hoffert, M. I., A. J. Callegari, and C. T. Hseih, The role of deep sea heat storage in the secular response to climate forcing, J. Geophys. Res., 85, 6667-6679, 1980.

Hoffert, M. I., B. P. Flannery, A. J. Callegari, C. T. Hseih, and W. Wiscombe, Evaporation-limited tropical temperatures as a constraint on climate sensitivity, J. Atmos. Sci., in press: (Paper I), 1982.

Kandel, R. S., Surface temperature sensitivity to atmospheric CO_2, Nature, 293 (5834), 634-636, 1981.

Kiehl, J. T. and V. Ramanathan, Radiative heating due to increased CO_2: The role of H_2O continuum absorption, J. Atmos. Sci., 39, 2923-2926, 1982.

Manabe, S. and R. T. Wetherald, The effects of doubling the CO_2 concentration on the climate of a general circulation model, J. Atmos. Sci., 32, 3-15, 1975.

Manabe, S. and R. T. Wetherald, On the distribution of climate change resulting from an increase in the CO_2 content of the atmosphere, J. Atmos. Sci., 37, 99-118, 1980. (MW)

Newell, R. E. and T. G. Dopplick, Questions concerning the possible influence of anthropogenic CO_2 on atmospheric temperature, J. Appl. Meteor., 18, 822-825, 1979.

Newell, R. E. and T. G. Dopplick, Reply to Robert

Copyright American Geophysical Union

G. Watts' "Discussion of questions concerning the possible influence of anthropogenic CO_2 on atmospheric temperature", J. Appl. Meteor., 20, 114-116, 1981.

North, G. R., R. F. Cahalan, and J. A. Coakley, Energy Balance Climate Models, Rev. Geophys. Space Phys., 19, 91-121, 1981.

Peng, L., M. D. Chou and A. Arking, Climate studies with a multi-layer energy balance model. Part I: Model description and sensitivity to the solar constant, J. Atmos. Sci., 39, 2639-2656, 1982.

Ramanathan, V., The role of ocean-atmosphere interactions in the CO_2 climate problem, J. Atmos. Sci., 38, 918-930, 1981.

Schopf, T. J. M., Paleoceanography, Harvard University Press, Cambridge, Massachusetts, 341 pp., 1980.

Warren, S. G. and S. H. Schneider, Seasonal simulation as a test for uncertainties in the parameterizations of a Budyko-Sellers zonal climate model, J. Atmos. Sci., 36, 1377-1391, 1979.

Copyright American Geophysical Union

Annex 34

M. Shepard, “The Greenhouse Effect: Earth’s Climate in transition”, *EPRI Journal,* 1986, pp. 4-15

The Greenhouse Effect and Global Warming

ELECTRIC POWER RESEARCH INSTITUTE

EPRI JOURNAL

JUNE
1986



EPRI JOURNAL is published nine times each year (January/February, March, April/May, June, July/August, September, October, November, and December) by the Electric Power Research Institute.

EPRI was founded in 1972 by the nation's electric utilities to develop and manage a technology program for improving electric power production, distribution, and utilization.

EPRI JOURNAL Staff and Contributors
Brent Barker, Editor in Chief
David Dietrich, Managing Editor
Ralph Whitaker, Feature Editor
Taylor Moore, Senior Feature Writer
Michael Shepard, Feature Writer
Pauline Burnett, Technical Editor
Mary Ann Garneau-Hoxsie, Production Editor
Jim Norris, Illustrator
Jean Smith, Program Secretary
Christine Lawrence (Washington)
Kathy Kaufman (Technology Transfer)

Richard G. Claeys, Director
Communications Division

Graphics Consultant: Frank A. Rodriquez

© 1986 by Electric Power Research Institute, Inc. Permission to reprint is granted by EPRI, provided credit to the EPRI JOURNAL is given. Information on bulk reprints available on request.

Electric Power Research Institute, EPRI, and EPRI JOURNAL are registered service marks or trademarks of Electric Power Research Institute, Inc.

Address correspondence to:
Editor in Chief
EPRI JOURNAL
Electric Power Research Institute
P.O. Box 10412
Palo Alto, California 94303

Cover: The buildup of CO_2 and certain trace gases in the atmosphere is blocking the natural escape of much of the earth's heat from our environment. Experts believe that the resultant warming trend could have profound implications for the earth's climate in as few as 50 years.

EPRI JOURNAL

Volume 11, Number 4 June 1986

Editorial

2 **The Scientific Unknowns of CO_2**

Features

4 **The Greenhouse Effect: Earth's Climate in Transition**
Global warming as a result of the greenhouse effect may turn out to be the greatest environmental problem of modern times.

16 **Evolution in Combustion Turbines**
Increasingly efficient and reliable, combustion turbines have become an attractive option for utilities seeking small increments of new capacity.

22 **Remote Scanning of Low-Level Waste**
Two new methods improve the accuracy and lower the risk of waste assays by reading radiation levels and determining isotopic content from outside the waste container.

28 **Herbert Woodson: Encouraging Exploration in Research**
An electrical engineering professor for 32 years, Woodson keeps his hand in with utilities as a consultant, committee member, and member of EPRI's Advisory Council.

Departments

3 **Authors and Articles**
34 **At the Institute: Board Approves 1986 Budget Revision**
35 **Calendar**
36 **Technology Transfer News**
57 **New Contracts**
58 **New Technical Reports**
60 **New Computer Software**

R&D Status Reports

38 **Advanced Power Systems Division**
42 **Coal Combustion Systems Division**
46 **Electrical Systems Division**
50 **Energy Analysis and Environment Division**
54 **Nuclear Power Division**

The Scientific Unknowns of CO_2


Malès

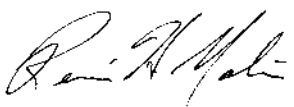
Coming to appropriate decisions on complex environmental issues is extremely difficult, a fact that is often ignored by advocates of one or another policy prescription. Usually, it is only with hindsight that an action appears to be undeniably the preferred policy option. Only 50 years ago the heavy particulate and gaseous loadings that make up urban smog were deemed a sign of industrial progress and a necessary concomitant cost of economic growth; in the United States, these levels of urban pollution are now perceived to be unacceptable. Although opinions may differ on the appropriate degree and method of restriction, few would argue that the emissions limitations imposed by state and federal laws and regulations are undesirable.

Unfortunately, the benefit of hindsight is not available for environmental issues we are studying today. The so-called greenhouse effect—the buildup of CO_2 in our atmosphere and the consequent possible effect on climate—is a classic example of the difficulty of dealing with complex scientific unknowns.

This issue involves tough basic questions: what happens to the CO_2 that is emitted from our industrial combustion processes? what are the other sources of CO_2? what are the sinks? Even when we become relatively knowledgeable about these questions, a whole series of others loom ominously: what will be the effect of various levels of CO_2 in the atmosphere? how do other greenhouse gases affect the climate? what are the possible feedback loops from initial warming effects? As with all scientific issues, research will never bring absolute certainty, but well-designed research can advance the understanding and reduce the degree of uncertainty for each of these phenomena.

The eventual decision on whether to limit emissions of CO_2 and the other greenhouse gases and how to effect such limits will be a political one—a decision that balances risks against costs, that takes into account public values. Yet such a decision will be easier to make and will be better designed if we know more about the science of the issue. EPRI has the role of developing such scientific and technical understanding for the electric utility industry.

Fortunately, DOE has a large ongoing research program addressing many of these scientific questions. EPRI can share in these results and build its much more modest research agenda as a complement to DOE's research. Similarly, other federal agencies are looking at issues related to CO_2. By coordinating with these agencies, EPRI can help utilities keep up to date on a field in which they may be called upon to take policy positions.



René H. Malès, Vice President
Energy Analysis and Environment Division

Authors and Articles



Hakkarinen Hansen Spencer Dolbec Dohner Gluckman Welty Robinson

The Greenhouse Effect: Earth's Climate in Transition (page 4) examines the myriad mechanisms by which carbon is exchanged between plants, oceans, and the atmosphere, and the potential outcomes. Written by Michael Shepard, *Journal* feature writer, who received principal technical guidance from three EPRI research managers.

Charles Hakkarinen is technical manager for environmental data analysis in the Energy Analysis and Environment Division. Formerly an assistant to the division director, he has been with EPRI since 1974, when he was still completing work on his PhD in environmental science and engineering at the University of California at Los Angeles.

Alan Hansen, also in the EAE Division, is a project manager in the Environmental Chemistry and Physics Program. He came to EPRI in March 1985 after eight years with Environmental Research & Technology, Inc., where he was manager of environmental chemistry. He was previously an environmental analyst and a research chemist with the Environmental Protection Agency, the University of California (Riverside) Air Pollution Research Center, and SRI International. Hansen earned a PhD in chemistry at the University of California (Irvine).

Dwain Spencer is an EPRI vice president and director of the Advanced Power Systems Division. Before he joined the Institute in 1974, he was with the Jet Propulsion Laboratory of the California Institute of Technology for 16 years, part of that time in studies of planetary atmospheres in which space vehicles would travel. Spencer has a BS in chemical engineering from the University of Notre Dame and an MS in engineering from Purdue University. ■

Evolution in Combustion Turbines (page 16) reviews the thinking and the R&D that are adapting an already-modular prime mover for intermediate and baseload use. Written by Michael Shepard, *Journal* feature writer, aided by members of EPRI's Advanced Power Systems Division.

Albert Dolbec has managed his division's research in power machinery since 1978. He came to EPRI a year earlier after nearly 26 years with General Electric Co., where he became manager of design engineering for gas turbine and combined-cycle plant controls. He is an electrical engineering graduate of Manhattan College.

Clark Dohner, a project manager in Dolbec's program, has been with EPRI since 1982, guiding R&D in gas turbines. He formerly was with General Electric for 20 years, the last 10 in the gas turbine division. Dohner has BS and MS degrees in mechanical engineering from Johns Hopkins University and the University of Pittsburgh, respectively.

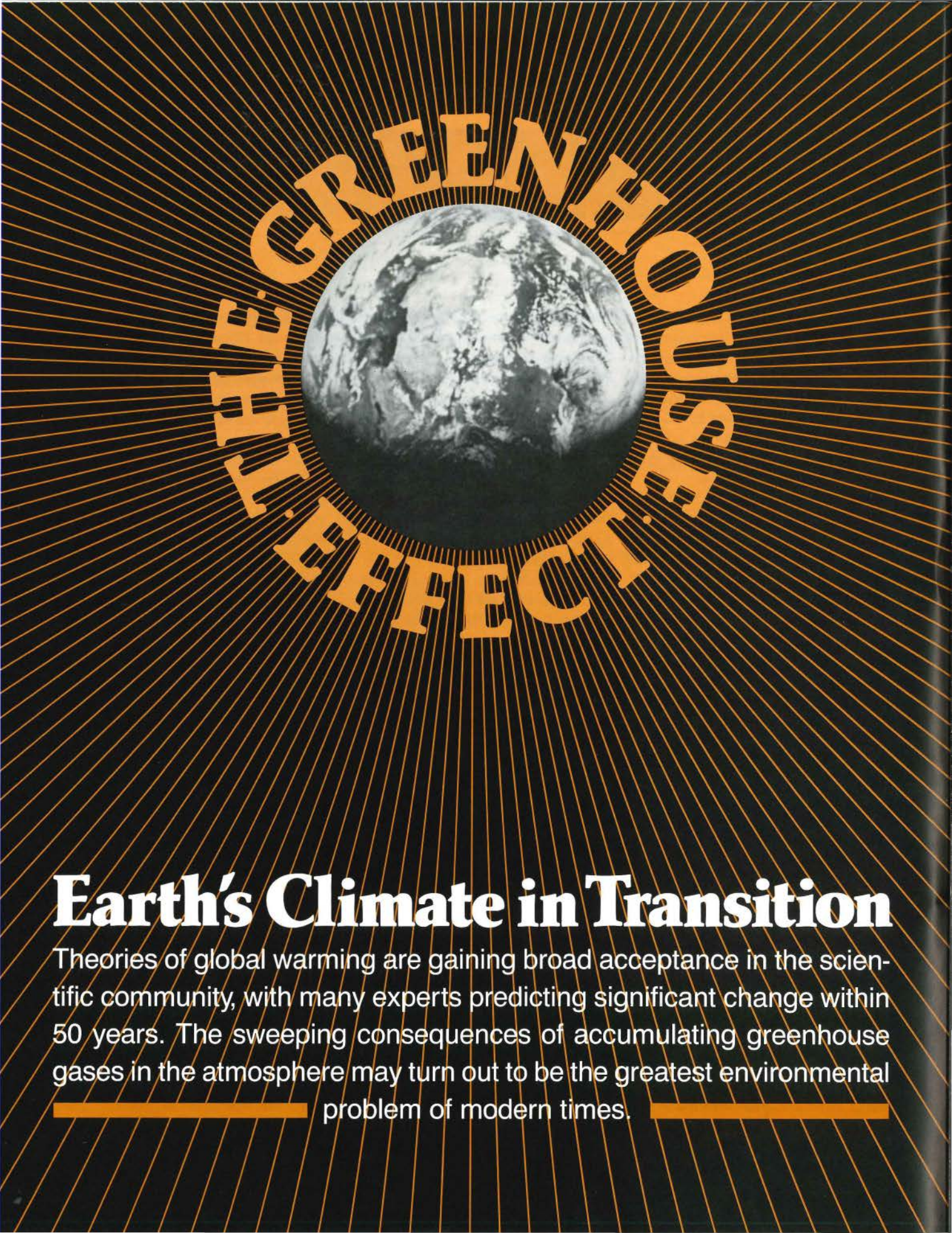
Michael Gluckman heads the Engineering and Economics Evaluation Program. He was named to the position in 1980 after five years as project manager in gasification system research. Between 1971 and 1975 he was an associate professor of chemical engineering at City College of the City University of New York, where he earned his PhD. ■

Remote Scanning of Low-Level Waste (page 22) presents two new, fast, safe, and thorough ways to measure certain radioisotopic contents of waste material. Written by Taylor Moore, the *Journal*'s senior feature writer, with the cooperation of two research managers in the Nuclear Power Division.

Charles Welty, a project manager in low-level waste and coolant technology research, has also managed EPRI research for the utility Steam Generator Owners Group. He came to EPRI in 1978 after three years as production manager and manager of the Dillingham Corp. shipyard in Honolulu. A graduate of the U.S. Naval Academy, Welty was an officer in the navy's nuclear submarine force for nine years.

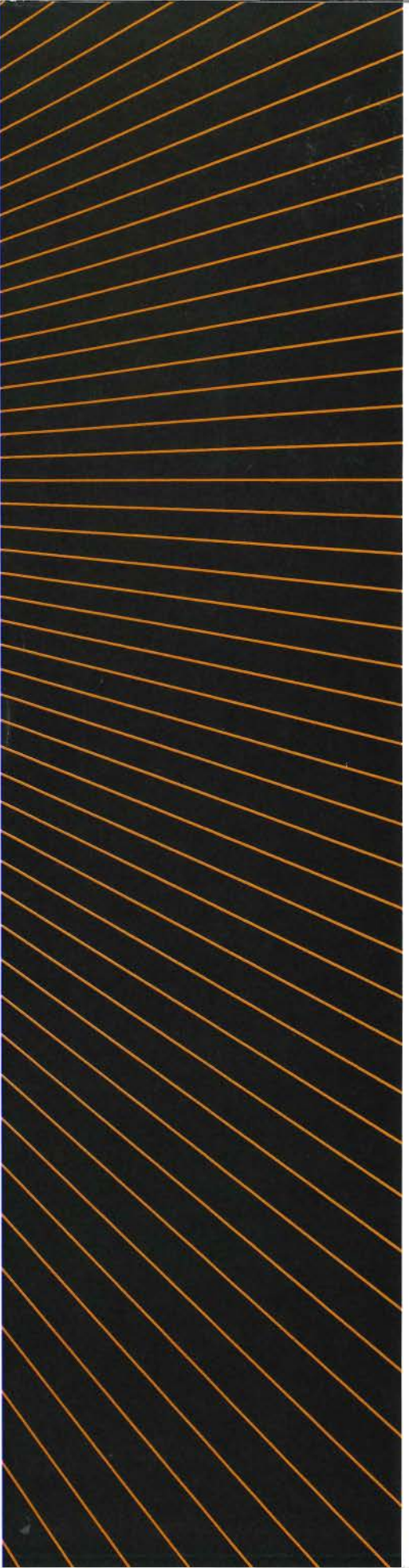
Patricia Robinson, also a project manager for low-level waste research, has been with EPRI since August 1985. She was formerly a research engineer at Battelle, Pacific Northwest Laboratories for two years. Between 1977 and 1983 Robinson worked for two companies providing reactor operation and waste transportation services at the federal government's Hanford site. She has a BS in chemical engineering from the University of Nevada (Reno). ■

Herbert Woodson: Encouraging Exploration in Research (page 28) introduces a Texas engineering professor and member of EPRI's Advisory Council who has a well-developed loyalty to R&D. Written by Ralph Whitaker, the *Journal*'s feature editor, from an interview with Woodson. ■



Earth's Climate in Transition

Theories of global warming are gaining broad acceptance in the scientific community, with many experts predicting significant change within 50 years. The sweeping consequences of accumulating greenhouse gases in the atmosphere may turn out to be the greatest environmental problem of modern times.



Climate, that amalgam of nature's moods, shapes the character of places and human activity as powerfully as any other force. It influences where we live and how we like it. Climate allows corn to flourish in Iowa and causes crops to fail in Africa. It makes Siberia harsh, Tahiti gentle, and lends distinct personalities to every other place on the globe.

Until recently, we took climate for granted and accepted that it would stay largely the same, at least in our lifetimes and those of our children. Evidence is mounting, however, that by burning fossil fuels, leveling tropical forests, and engaging in a number of other activities, humans are releasing gases to the atmosphere that could trap enough heat to raise the temperature of the earth's surface by a few degrees Celsius. No such increase has yet been detected. If and when it comes, however, even a few degrees' rise would change the climate of many regions. Some places may become sunnier, others wetter. Today's deserts may bloom and some farming regions may wither. The timing of frosts that bound growing seasons will change, as will the frequency of midsummer heat waves. Sea level could rise from several inches to a few feet, affecting coastal regions in numerous ways. Some areas will change very little. Others may change a lot.

The first signal of these potential changes came from measurements of the steady rise in atmospheric carbon dioxide (CO_2) made by Charles Keeling of the Scripps Institution of Oceanography. His readings from the observatory at Mauna Loa, Hawaii, show that CO_2 has climbed from a concentration of 315 parts per million (ppm) in 1958 to 345 ppm today. A National Academy of Sciences report released in 1983 projected that within 50 to 100 years the level of CO_2 is likely to rise to 600 ppm. Because CO_2 acts as a thermal blanket in the air, explains the NAS report, this doubling of gas concentration could raise average global temperature by 1.5–4.5°C (2.7–8.1°F). A 1.5°C warming within a century would produce the warmest climate seen on earth in 6000 years. A 4.5°C rise would place the world in a temperature regime last experienced in the Mesozoic era—the age of dinosaurs.

One of the key uncertainties in projecting temperature change centers on the question of how much of the CO_2 released to the atmosphere will remain there. We know from the measured increase in atmospheric CO_2 that 2.5 billion tons of carbon per year, an amount equal to half the annual emissions from fossil fuel combustion, accumulates in the air. The rest, scientists believe, must be going into terrestrial plants and into the oceans. Plants absorb CO_2 through photosynthesis and release it through respiration, storing some of the carbon that they metabolize in their leaves, stems, and roots. CO_2 enters the ocean by dissolving out of the air into the surface waters. Some of the carbon stays dissolved as CO_2 in the surface water, some is carried into the deep ocean by currents or precipitates into solid particles that fall to the bottom, and some bubbles back out to the atmosphere, much like gas escaping from a bottle of club soda.

Scientists do not yet agree on how the CO_2 that leaves the atmosphere is apportioned among the plants and oceans, nor do they know how much more CO_2 these reservoirs can absorb or how long they will hold it. Without a clear understanding of the pools and flows of carbon in the earth-water-air system, it is impossible to precisely estimate future atmospheric CO_2 levels. Knowing how much CO_2 will be in the atmosphere in the future only gets us to square one. From there we have to explore the gas's effects on temperature and ultimately on climate.

Temperature and climate: A question of balance

The earth's climate is driven in part by temperature, and temperature is a func-

tion of the balance between energy coming in from the sun and energy radiating back to space. This balance is influenced by the atmosphere, which is transparent to visible light (between 0.4 and 0.7 μm) but is opaque to certain wavelengths of infrared, or heat, radiation (longer than 0.7 μm).

Slightly more than half the light entering the atmosphere is absorbed by clouds and particles or reflected back to space. The remainder is absorbed at the surface, warming the oceans and land. The warmed surfaces then reradiate this energy in the form of heat. Naturally occurring water vapor and CO_2 in the atmosphere absorb certain wavelengths of this heat and radiate some of it back to earth. This phenomenon is referred to as the greenhouse effect, because it is analogous to the trapping of heat inside a glass enclosure. The air traps enough heat to keep the earth's surface about 30°C (54°F) warmer, on average, than it would be without an atmosphere.

Because naturally occurring gases in the atmosphere do not absorb all infrared wavelengths, some of the heat radiated by the land and sea escapes back to space. Most of this escaping heat is radiation with wavelengths between 7 and 12 μm, a band in which water vapor and CO_2 absorb weakly. Thus the atmosphere (even with high CO_2 levels) is largely transparent to infrared radiation in this range. This atmospheric window is critical to climate. Without the window, more heat would be trapped in the lower atmosphere, the earth would be warmer, and the patterns of atmospheric circulation that shape climate would be altered.

Factoring in trace gases

Ralph Cicerone of the National Center for Atmospheric Research (NCAR) and three colleagues recently published the results of an extensive study on the rate at which greenhouse gases other than CO_2 are accumulating in the atmosphere and the effects these gases may have on climate. The gases of concern are present in minute but rising amounts, they remain in the atmosphere for many years, and they are powerful absorbers of infrared radiation between 7 and 12 μm.

The ringleaders of this group are methane, ozone, nitrous oxide, and several chlorofluorocarbons (Freons). The chlorofluorocarbons arise exclusively from human activity. Although banned in the United States as aerosol propellants, these compounds are still used throughout the world as refrigerants and solvents and in numerous industrial processes.

The sources of other greenhouse gases are not as clearly understood. Methane, for instance, has been rising at 1%/yr over the past three decades. Cicerone believes that much of the increase in this gas can be traced to mineral exploration and mining, rapidly growing populations of cattle and termites, which excrete methane, and decomposition of organic matter in rice paddies that for the first time are bearing two and three crops annually with the expansion of modern irrigation systems. He traces the rise in nitrous oxide in part to the use of nitrogen fertilizer in agriculture.

Cicerone and his coworkers calculate that the combined effect of these gases is already 60% as great as the effect from current CO_2 levels and within 50 years will equal or exceed CO_2's influence. This additional effect could cause global temperature to rise faster than most models now predict.

Not all scientists agree with the magnitude of the prevailing warming predictions, however, and much of this disagreement hinges on estimates of the size and direction of various feedbacks that may occur in response to the initial perturbation of the climate. Some responses, called negative feedback, will have a cooling effect that will dampen the warming trend. Positive feedback, on the other hand, will reinforce the initial warming.

Understanding feedbacks

One of the key feedback uncertainties concerns clouds. "If the atmosphere warms," says Richard Somerville, a theoretical meteorologist and head of the climate research group at Scripps, "more water will evaporate into the air, changing the area, height, water content, and reflectivity of clouds." Plugging plausible numbers for changes in cloud reflectivity into a climate model, Somerville found that the range of projections for global warming could be either doubled or halved. He hastens to add that these results do not prove the models wrong. "Rather, they point to questions of potential importance that we have to understand better before we can rely with confidence on our model results."

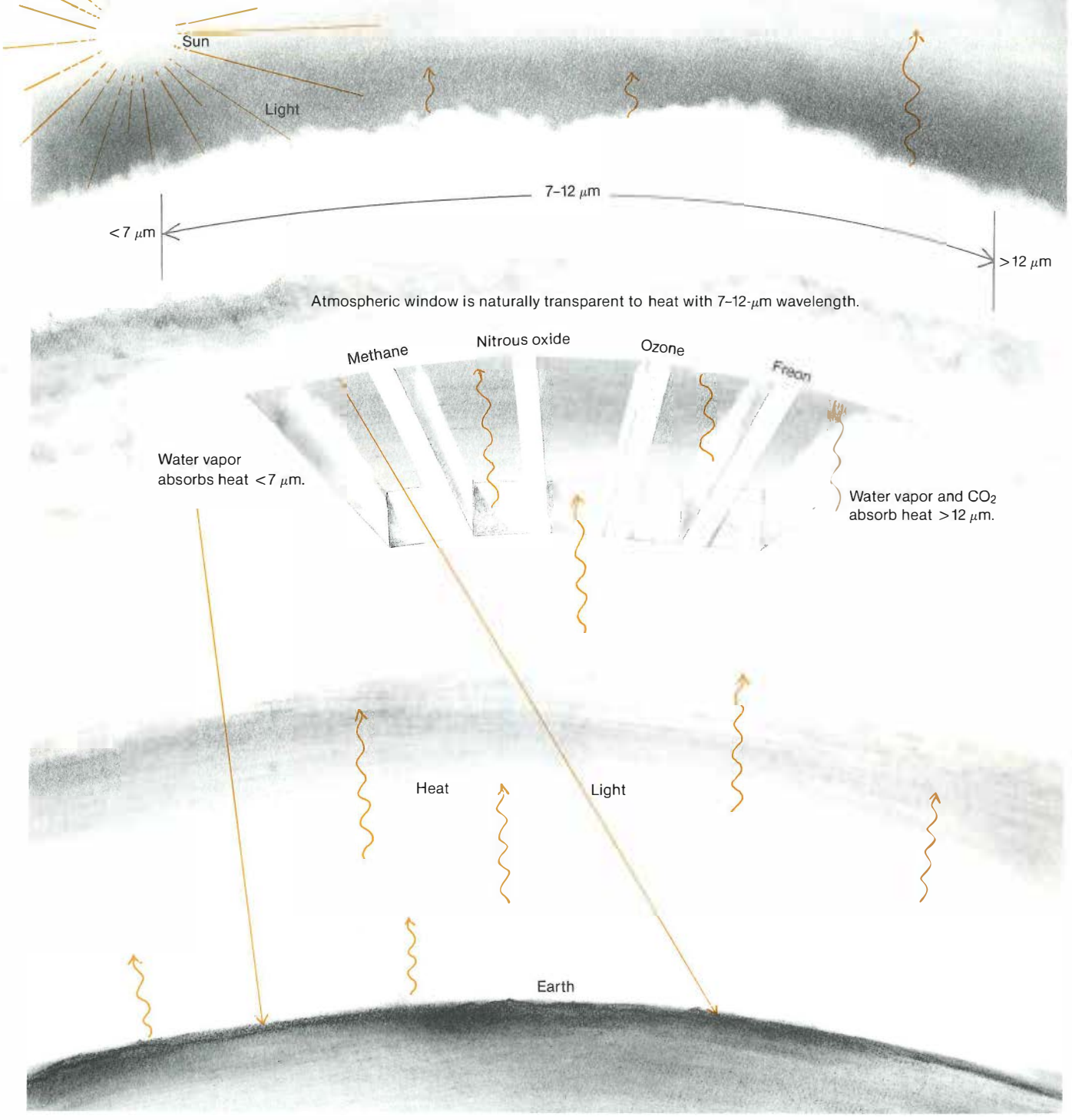
Another feedback uncertainty involves the response of plants to rising CO_2 levels. The Carbon Dioxide Research Office of the U.S. Department of Energy (DOE), the government's lead agency in the study of CO_2 and climate, devotes a considerable portion of its $13 million annual budget to investigating the effects of rising CO_2 on vegetation. In a series of controlled studies, agricultural crops grew 30–90% faster in a high-CO_2 environment, pulling more carbon out of the atmosphere and storing it in plant tissues. Moreover, water-use efficiency rose significantly in several of the crops. Some scientists point to such findings with hope that an atmosphere richer in CO_2 could lead to higher food yields in the future and that enhanced plant growth could slow the rise in CO_2 and global temperature.

Although crops may respond positively to higher CO_2 when other conditions are controlled, very little research has been conducted on the response of the unmanaged forests, grasslands, and tundra that cover much of the earth.

Walter Oechel, director of the Systems Ecology Research Group for the California State University at San Diego, conducted one of the few studies yet performed in a native ecosystem to

Blocking the Atmospheric Window

The so-called greenhouse effect is caused by atmospheric gases that absorb certain wavelengths of heat that would otherwise radiate out to space. Carbon dioxide is not the only greenhouse gas whose concentration is rising as a consequence of human activity. Methane, nitrous oxide, ozone, Freon, and several other gases are of particular concern because they remain in the air for many years and are potent absorbers of heat within the wavelength band (7–12 μm) through which much of the earth's heat escapes the atmosphere. By blocking parts of this atmospheric window, very small amounts of these gases can exert a warming effect as great as that caused by the much more abundant CO_2.



measure long-term plant responses to elevated CO_2. Oechel exposed several species of tundra plants to varying levels of CO_2 and temperature for three years. He found that the response in native species was less than that found for many agricultural crops. He also found significant variability in the responses of the native species examined. Some species exposed to elevated CO_2 and higher temperature grew faster and stored more carbon, but other species did not. "Overall," explains Oechel, "arctic tundra exposed to higher CO_2 and ambient temperatures stored more carbon than tundra under current CO_2 levels, but not as much as predicted."

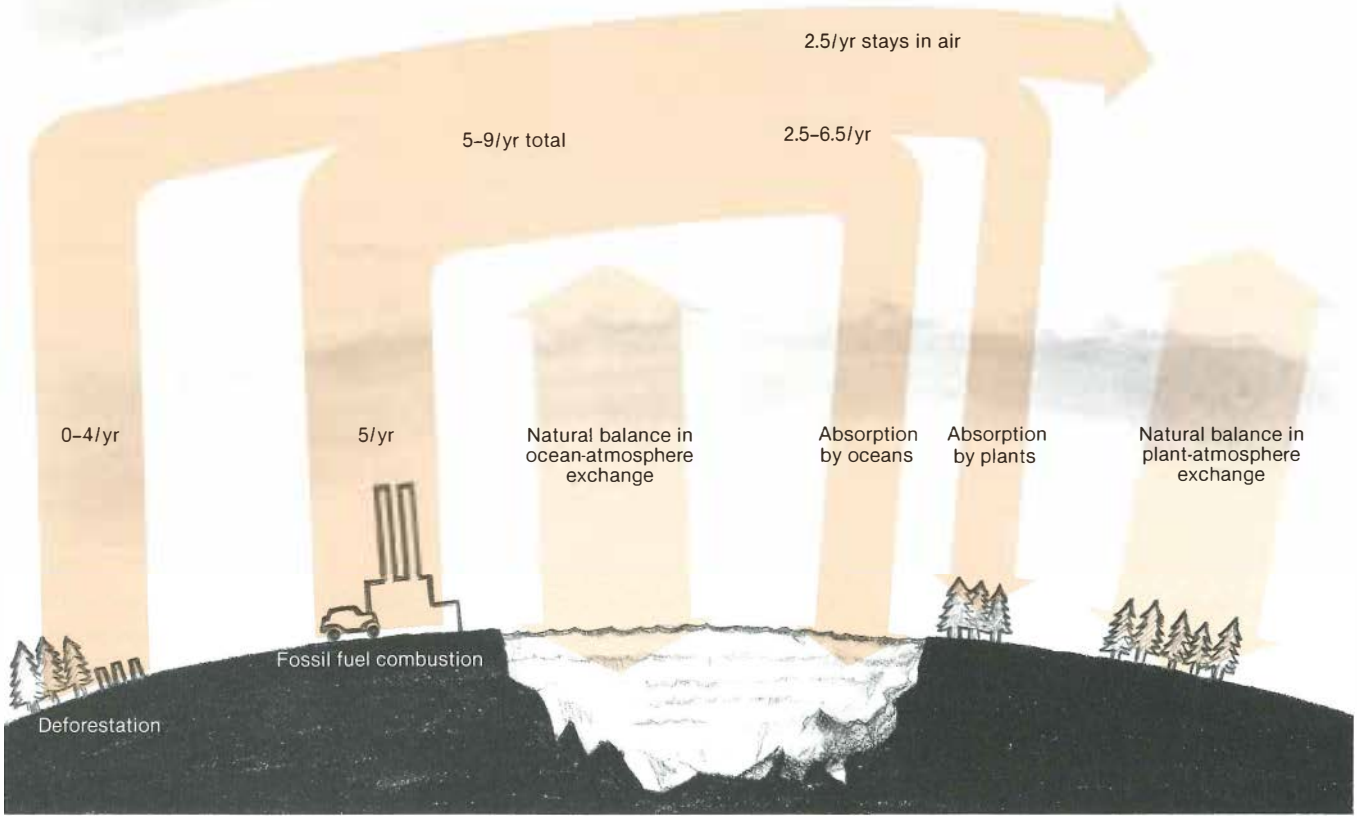
Oechel believes that more research is needed to determine the overall response of the tundra to rising CO_2. Moreover, he stresses that although much of what we learn in the arctic communities will carry over to the boreal forests and other ecosystems, additional research is necessary to understand the responses of those other communities.

George Woodwell, director of the Woods Hole Research Center, agrees that we need more research in the area of plant response. "There is no question that under experimental conditions when water and nutrients are not limiting, you can show that an increase in CO_2 can increase the rate of carbon fixation. But there is no evidence that this is occurring in nature. In fact, the higher rates of organic matter decay that would occur in the soils of the middle and high latitudes due to climate warming, in combination with the rapid deforestation now under way in the tropics, will release large amounts of CO_2 to the atmosphere. These effects will be counterbalanced to some degree by increased photosynthesis and longer growing seasons in some areas, but the net effect will be that plants will add more CO_2 to the atmosphere than they absorb."

The NAS report acknowledges the

Carbon Cycle Is Key to Temperature Change

Without man's influence, the flows of carbon (given in units of 10^9 t) between the air, plants, and ocean would be roughly balanced. Fossil fuel combustion adds about 5×10^9 t/yr of carbon to the atmosphere, about half of which remains in the atmosphere as rising CO_2 levels. The rest is absorbed by plants and oceans, but scientists disagree on how much goes to each reservoir (stocks in units of 10^9 t). Some believe that plants are growing faster in the CO_2-enriched atmosphere and are absorbing up to half the carbon that does not remain in the air. Others believe deforestation is outstripping any enhanced growth that might be occurring, causing plants to be a net source, rather than a sink for CO_2. Scientists must resolve this debate before they can confidently predict how CO_2 levels will rise in the future.



importance of this question, explaining that if deforestation has caused terrestrial ecosystems to be a net source of CO_2 in recent years, the oceans must be taking up far more CO_2 than current models suggest. If oceans are better at absorbing CO_2 than scientists currently believe them to be, the study concludes, "the CO_2 increase will probably occur more slowly than it otherwise would."

Perhaps of greater significance than the feedback involving terrestrial plants and soils are the immense and very complex ocean-atmosphere interactions. The oceans contain 55 times as much carbon as does the atmosphere and 20 times as much as do land plants. Thus, small changes in the oceans' capacity to store carbon can dramatically alter the atmospheric concentration.

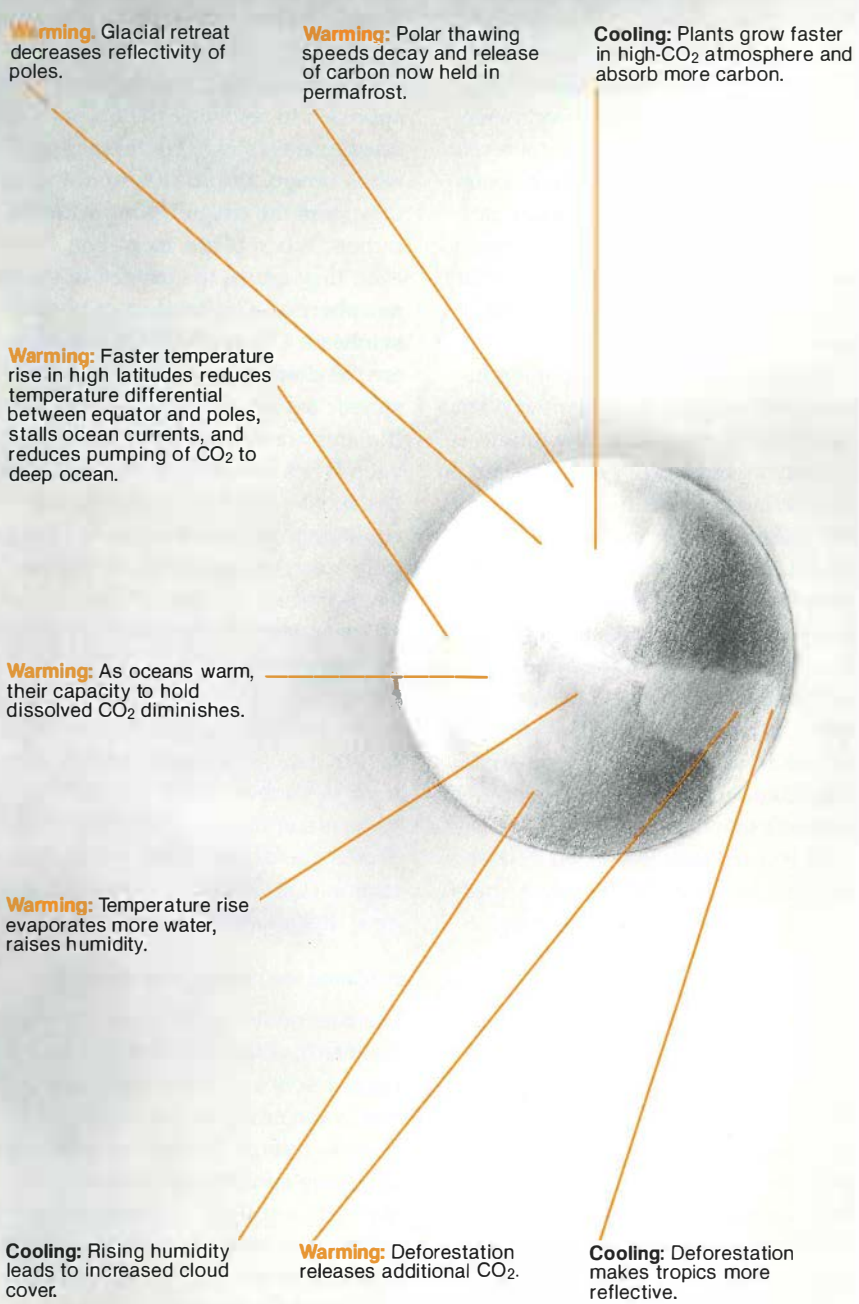
In most areas, atmospheric CO_2 mixes only with the top 100 m or so of sea water and is prevented from cycling downward by thermal gradients that separate the surface layer from deeper waters. However, researchers say that the only long-term way for the oceans to buffer the rise in atmospheric CO_2 is to pump the carbon into the deep ocean, either as dissolved gas or as solid carbonate particles that settle in the sediments at the ocean bottom. Scientists believe that CO_2 is drawn into the deep ocean through currents in a few key locations like the North Atlantic, where cold surface waters are known to sink to the bottom. Some researchers speculate that a global warming could cause the oceans' currents to become more sluggish, reducing their absorption and storage of carbon and exacerbating the greenhouse effect.

A needle in the haystack

Making the measurements needed to determine key parameters like uptake, storage, and release of CO_2 by oceans and plants is akin to burrowing through a haystack in search of one slender needle. Terrestrial ecosystems and oceans are huge, diverse reser-

Potential Feedbacks to Warming

Feedback related to an initial greenhouse warming will have important effects on long-term temperature change. Some responses (positive feedback) are expected to exacerbate the warming. Others (negative feedback) will probably have a cooling effect. The net result remains uncertain, although current estimates are for a 1.5–4.5°C temperature rise within a century.



voirs, and scientists are trying to measure minute changes in their composition. Compounding the difficulty, these reservoirs are not at all uniform. Trees absorb and store carbon very differently than do grasslands and tundra, and oceans vary widely in temperature, depth, water chemistry, and circulation. This heterogeneity means that measurements from a few locations only hint at what is happening worldwide. One researcher commented at a recent conference that it would take 10 years and hundreds of people in boats gathering water samples from all around the world to yield even a fuzzy picture of oceanic absorption, storage, and release of carbon.

Figuring out what is happening in plant communities is similarly challenging. Oechel's research in the tundra is the only in situ study yet conducted on ecosystem response to elevated CO_2, and even this work involves controlled conditions. For the most part, however, researchers are trying to deduce what is happening in the plants and oceans by measuring changes in the atmosphere more accurately. Because the atmosphere is better mixed and more uniform than the oceans and terrestrial plant communities, it is an easier reservoir to monitor.

"If you are only interested in average, long-term, global trends in atmospheric concentrations, one or two monitoring sites are sufficient," explains Pieter Tans, who directs the CO_2 monitoring program for the National Oceanic and Atmospheric Administration (NOAA). "But if you want to determine where the main sources and sinks are, you have to measure local gradients and see how they change with the seasons. This requires many measurements, over time, from lots of sites."

NOAA operates a network of 26 remote monitoring stations from Point Barrow, Alaska, to the South Pole. "Precision in gathering and analyzing samples is critical," says Tans. Technicians are instructed to take samples only on windy days when breezes are blowing from the sea so as to avoid local effects from land plants. Roughly 6000 samples a year are sent to NOAA in pressurized steel containers lined on the inside with gold or other inert substances that will not react with the sample gas.

Tans is pursuing an ingenious new approach to resolving the question of ocean-plant uptake. He reasons that when oceans absorb CO_2 from the air, they store the oxygen along with the carbon. When plants fix carbon, however, they return the oxygen to the atmosphere as a by-product of photosynthesis. Consequently, if the oceans are the dominant sink for CO_2, atmospheric oxygen levels should be falling. If plants are a major sink, however, oxygen levels should stay the same. Tans has spent several years developing equipment to measure minute changes in the oxygen content of air. He believes that his equipment, which uses an argon laser, fiber optics, and spectral analysis of gas samples, will soon be ready to be put into service.

The whole point behind these exhaustive monitoring efforts is to determine the rate at which greenhouse gases accumulate in the atmosphere. This is one of the critical pieces of information climate modelers need to study how climate may change.

Modeling the climate response

Climate models are nothing more than hundreds of linked mathematical equations describing how various phenomena in the environment cause conditions to change throughout the system. Incoming sunlight, for instance, heats the earth's surface, particularly near the equator, causing warmed air in the low latitudes to rise and circulate toward the poles. The earth's rotation interacts with these currents to cause the trade winds. Water evaporating off the oceans circulates in the atmosphere and falls to the surface as precipitation. The tilt of the earth's axis causes different amounts of energy to flow into the northern and southern hemispheres and leads to the annual cycles we call seasons. These and related processes that determine climate are reduced to numbers and symbols in sophisticated computer programs known as general circulation models. These are the tools climatologists use to study the climate and to predict how it will change in the future.

Climatologists check the accuracy of their models by running them forward and backward. Years can be reconstructed in a few days of computer time. If the models can reconstruct known present or past conditions, modelers feel confident in using them to project future climates.

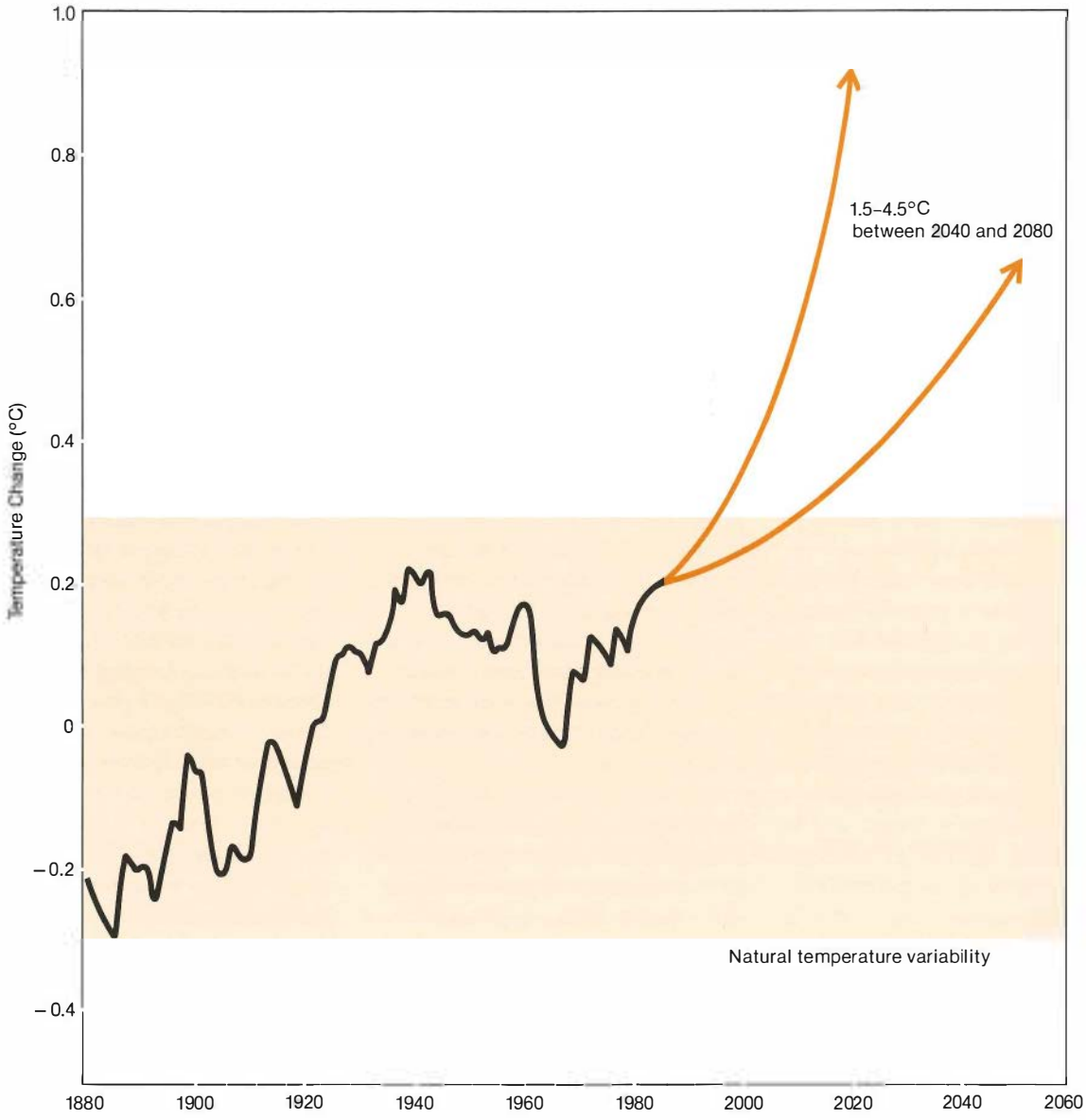
To determine if their models successfully recreate the past, climatologists have long been seeking reliable estimates of the CO_2 levels that existed in the atmosphere before the industrial revolution, when fossil fuels were first burned on a large scale. Several methods, including analysis of air trapped centuries ago in polar ice caps and carbon fixed in tree rings and slow-growing ocean sponges, have been used to unravel this mystery. The emerging consensus is that the CO_2 concentration stood at roughly 280 ppm in the eighteenth century, a level 65 ppm below today's concentration.

Most of the modeling studies of CO_2-induced climate change have been run on a few general circulation models (GCMs) in the United States. The Geophysical Fluid Dynamics Laboratory model at Princeton University predicts a global warming of 2°C for a doubling of CO_2, although the Goddard Institute for Space Studies (GISS) and NCAR models yield about a 4°C (7.2°F) increase.

Climatologists are anxiously poring over temperature measurements year by year to see if a greenhouse signal is emerging from the noise of natural temperature fluctuations. Nearly all

Observed and Projected Temperature

The earth's average temperature rose about 0.5°C (0.9°F) over the past century, with a 0.2°C (0.36°F) cooling observed (black) between 1940 and 1965. Although the temperature rise is not inconsistent with predicted effects of CO_2 and other greenhouse gases, the fluctuations are still within the normal range of temperature variation. Many climatologists expect a CO_2 signal to rise above the background noise in the 1990s. Projections (color) for temperature increases caused by a doubling of CO_2 are 1.5–4.5°C (2.7–8.1°F) within 50 to 100 years. These projections do not consider the influence of other greenhouse gases, which could speed the warming.



EPRI STUDIES GREENHOUSE EFFECT

EPRI has sponsored a number of research efforts in the area of greenhouse gases and climate change. These projects generally focus on one of two areas: the scientific aspects of the problem and the analytic and decision-making techniques for evaluating and responding to CO_2–induced changes.

Radian Corp. completed a study for EPRI's Coal Combustion Systems Division in 1980, assessing the scientific uncertainties of the issue, projecting CO_2 emissions worldwide, and evaluating the prospects for CO_2 emissions control and the social and economic implications of a global warming. Noting that U.S. utilities produce less than 10% of the global CO_2 emissions from fossil fuel combustion, the report concludes that an international effort to reduce fossil fuel use would be required to curb CO_2 buildup.

Half a dozen chemical and physical processes have been proposed for capturing the CO_2 from fossil-fuel-fired power plant emissions. Radian concluded that although some are technologically feasible, none are economically practical. They would add several hundred dollars per kilowatt to plant capital costs, would add an undetermined amount in operating expenses, and would consume half or more of the plant's energy output. Consequently, no cost-effective means has yet been found for storing the captured carbon over long periods to keep it from returning to the atmosphere.

EPRI's Energy Analysis and Environment (EAE) division has sponsored about half a dozen studies in the CO_2 area since 1978. René Malès, vice president and EAE division director, explains, "This issue is a classic environmental risk management problem. There are large uncertainties in possible outcomes, significant environmental consequences under certain conditions, and high costs for changing these conditions. The role we play is to get clearer scientific insights in order to be able to more accurately evaluate the risks involved."

Beginning in 1983, EAE sponsored a study with Scripps to resolve uncertainties concerning global sources and sinks of CO_2. Although the research team refined its atmospheric and oceanic models in this effort, many details of the carbon cycle remain elusive. Consequently, a proposal to continue this work, incorporating satellite imagery and enhanced three-dimensional modeling of ocean circulation, is now under review.

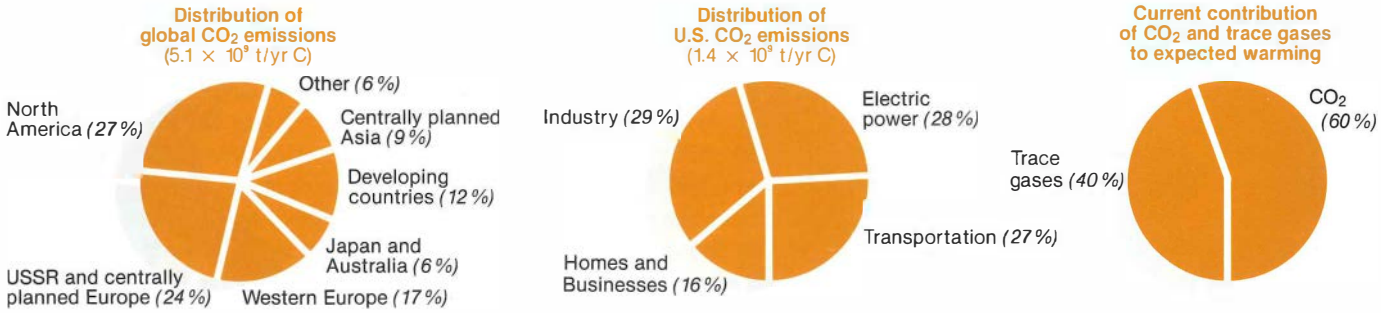
Another study, conducted for EPRI by the Oak Ridge National Laboratory, assessed how the rates of CO_2 accumulation would change under different electricity generation scenarios and then explored the potential effects on climate, agriculture, the economy, and ecosystems.

One recently completed study produced a preliminary greenhouse effect decision framework to help EPRI, utilities, and government research managers plan research on CO_2 and trace gases in a manner that focuses on the most important questions and yields the highest payoff. In another decision-related contract (cosponsored by EPRI, EPA, EEI, and NYSERDA), ICF, Inc., is exploring the potential effects of climate change on electric utilities. Using Florida Power & Light Co. as a case study, ICF is gathering information on the utility's demand and generation plans for the next 30 years. ICF will then analyze how a number of major factors may change with variations in temperature and rainfall, including the demand patterns of major customers, the utility's operating characteristics, new capacity requirements, demand management, and various financial issues. Once the FP&L analysis is complete, the methodology will be evaluated, changed as necessary, and then applied in two additional utility case studies. The project is scheduled for completion in early 1987.

EPRI's Advanced Power Systems Division has also supported a modest effort in the CO_2 area. In May 1985 APS sponsored a five-day conference at Lake Arrowhead, California, at which 40 leading scientists discussed their investigations of CO_2 transfer between the atmosphere, ocean, and terrestrial plants. The conference was organized by Scripps as part of a contract with the APS division to improve its models of ocean-atmosphere exchanges of CO_2. Topics ranged from the latest techniques for estimating preindustrial CO_2 levels, through ecosystem responses to elevated CO_2, to new developments in oceanic and atmospheric modeling. As Dwain Spencer, EPRI vice president and APS division director, explains, "We believe that the increases of carbon dioxide in the earth's atmosphere must be considered in planning a long-term research strategy for the power industry. At this time we are attempting to understand the key sources and sinks for CO_2 and the important feedback mechanisms that may either ameliorate or exacerbate the problem in the twenty-first century." □

A Global Issue

1980 figures on the distribution of CO_2 emissions from fossil fuels in the United States and from around the world demonstrate the international nature of the issue. The United States produces about one-quarter of global CO_2 emissions, and electric utilities produce about one-quarter of U.S. emissions, or less than 8% of the global total. Trace greenhouse gases are increasing rapidly and are expected to match CO_2's contribution to global warming within 50 years. These trace gases are also produced throughout the world, adding to the international complexity of the greenhouse issue.



agree that no definite signal has yet appeared, but many expect to see it within a decade.

One of the principal limitations in climate models is their ability to predict regional changes accurately—how will conditions change where people live, work, and farm? Will Iowa still be a good place to raise corn? Will the Gulf Stream stall and make Britain much colder? Will the drought-stricken areas of Africa get more rain? Some of the most sophisticated models are beginning to produce regional predictions, but the jury is still out on their accuracy. For now, most researchers shy away from regional prognoses, but they do feel confident about their projections of global average change.

So what's a few degrees?

Although an average warming of a few degrees does not sound like much, it could create dramatic changes in climatic extremes. The frequency of midsummer heat waves in certain locations, for example, could rise significantly. This could have important effects on, among other things, agriculture, energy consumption, and human comfort. NCAR climate specialist Steven Schneider and two colleagues found that the frequency of periods of five days or more exceeding 35°C (95°F) in the Corn Belt would grow threefold in the event of an average global warming of 1.7°C (3°F). Such conditions at critical stages in the growing season are known to harm corn and lead to reduced yields. A similar study conducted by James Hansen, director of GISS, and his student Paul Ashcraft concluded that the number of days warmer than 32°C (90°F) and 38°C (100°F) and nights above 27°C (80°F) would rise dramatically in eight major American cities as a result of doubled CO_2. The effect on utility cooling loads could be substantial.

Changes in the timing and amount of precipitation will almost certainly occur if the climate warms, affecting agriculture and hydroelectric resources, among other things. Soil moisture, which is critical during planting and early growth periods, will change. Rising CO_2 levels may enhance growth rates and water-use efficiency in some crops in certain areas. Some regions will probably become more productive, while other places may become less suited to agriculture. The North American grain belt, according to at least one climate model, will shift northward into Canada as the warming produces drier, hotter conditions in the American Midwest.

Of all the effects of a global warming, none has captured more attention than the prospect of rising sea levels from the melting of land-based glaciers and volume expansion of ocean water as it warms. Estimates of the rise range from several inches to a dozen or more feet by the year 2100, although the prevailing weight of opinion calls for an increase of about a foot and a half. The most dramatic scenario is that the West Antarctic ice sheet, which rests on land that is below sea level, could slide into the sea if the buttress of floating ice separating it from the ocean were to melt. This would raise the average sea level 15–20 ft (4.6–6.1 m).

Even a 1 ft (0.3-m) rise would have major effects on the erosion of coastlines, salt water intrusion into the water supply of coastal communities, flooding of marshes, and the inland extent of surges from large storms.

What can be done?

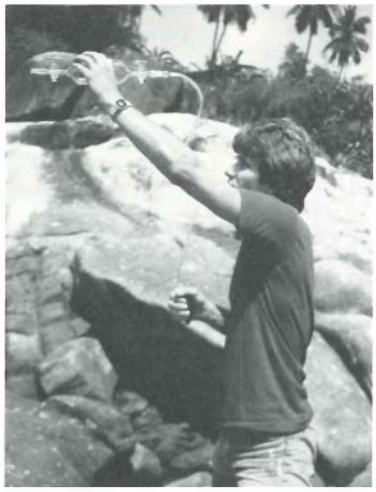
Many observers are beginning to discuss responses to potential climate change. Three basic views characterize the debate: we do not know enough yet about the fundamental processes to respond effectively; we should apply what we do know now to mitigate the changes; we should accept that climate change is inevitable and start immediately to adapt.

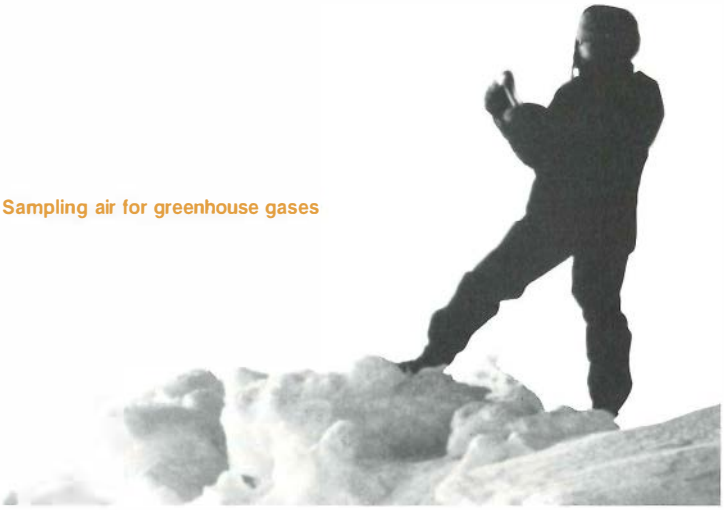
Frederick Koomanoff, who directs DOE's CO_2 research, holds firmly to the view that we have to conduct a lot more scientific research before we do

Measuring the Changes Through Laboratory and Field Studies

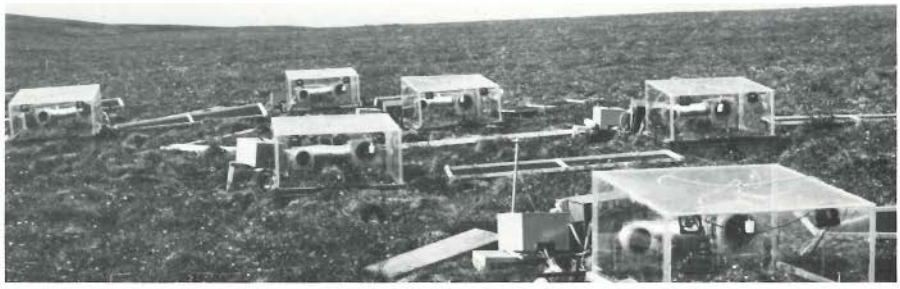
The global dimensions of the greenhouse effect require a correspondingly global research effort. Air sampling at remote sites from the tropics to Alaska and Antarctica is helping to identify the sources and sinks of CO_2 and other heat-absorbing gases. Field and laboratory studies on carbon uptake by plants exposed to various CO_2 levels are building understanding of the factors influencing the buildup of atmospheric CO_2.



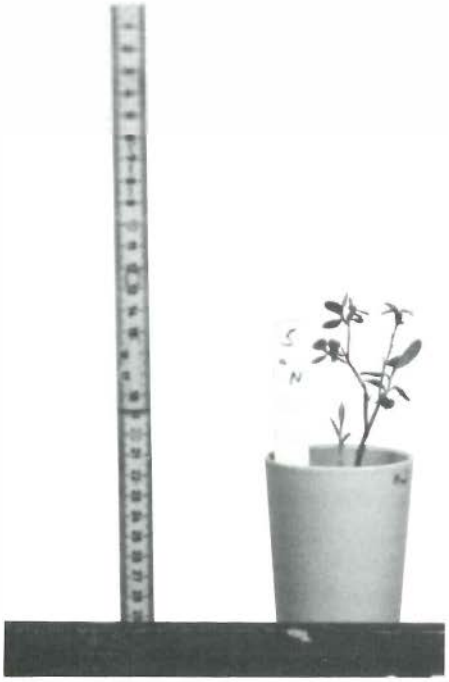




Sampling air for greenhouse gases



Measuring plant response to CO_2







anything else. "We simply do not know enough yet to respond intelligently," he asserts. "There are vast uncertainties in the carbon cycle, in the response of vegetation, in the coupling of oceanic and atmospheric processes, and in the way these factors will interact to change our environment. There are also gaps in our data on regional and seasonal climate change and in our understanding of the consequences of that change. We need another 10 years of concerted interdisciplinary research to resolve these uncertainties. By then we will have a clear enough understanding of the processes involved to give policymakers and the public the information necessary to make sound decisions."

Many scientists believe that although our understanding is incomplete, we do know enough to mitigate the greenhouse effect. "If uncertainty is a ground for no action," says Schneider, "then we would have no insurance companies and no armies." Energy policy is often identified as one area in which much could be done to reduce CO_2 emissions. Greater emphasis on end-use efficiency, certain renewable energy resources, and nuclear power are all pointed to as ways of providing energy without releasing CO_2. An examination of the sources of man-made CO_2 emissions, however, reveals that any effective effort to curb CO_2 releases would require extensive international cooperation.

Moreover, the fact that trace gases are fast approaching CO_2 in their greenhouse potency means that they too would have to be considered in an international effort to mitigate the warming. Controlling trace gases will not be easy. "If methane and nitrous oxide are rising as a consequence of a human activity as essential as food production," comments Cicerone, "it's going to be very difficult to limit their increase by agreed-upon social and political changes."

Dennis Tirpak directs a program looking at the effects of climate change for the Office of Policy Analysis in the U.S. Environmental Protection Agency (EPA). Tirpak and his colleagues maintain that society should begin exploring ways to adapt to the expected changes. "Ninety-nine percent of the government's efforts in this area are directed toward research on the mechanisms that may lead to climate change," reports Tirpak. "Very little emphasis is being placed on assessment and analysis of what this could mean for society and for the environment." Tirpak cites the recommendations of an international conference on the greenhouse effect held last October in Villach, Austria, calling for more assessment work in parallel with scientific research.

"Many important economic decisions are being made today," read a statement issued by the conferees, "on major irrigation, hydropower, and other projects; on drought and agricultural land use; on structural designs and coastal engineering projects; and on energy planning—all based on assumptions about climate a number of decades into the future."

Tirpak explains that EPA is supporting some "what if" studies that make assumptions about future climate and then explore potential adaptive strategies. One study now under way looks at the effects of a greenhouse warming on utilities. EPRI is a cosponsor of this research, along with EPA, Edison Electric Institute (EEI), and New York State Energy Research and Development Authority (NYSERDA).

Much to learn

Regardless of their views on whether we should be focusing exclusively on unraveling the scientific uncertainties or developing responses to the greenhouse effect, scientists agree that we still have much to learn about the ways in which human activities are influencing climate.

Keeling reflects, "The main problem with climate impact of CO_2 and other gases is that we don't like to see change. We don't want to face rising sea level, for example, because it means we'll have to move a lot of people around. The earth has seen it all before, though. The cycle was never in balance. CO_2 has been far higher and far lower in the geologic past. Climate has been warmer and colder, too. We don't know how fast the changes now under way will come or how far they will take us, but we do know that the decisions we make today will have implications far into the future. The memory of the fossil fuel era will be with the earth for tens of thousands of years." ■

Further reading

Gina Maranto. "Are We Close to the Road's End?" *Discover*, January 1986, p. 28.

U.S. Department of Energy, state-of-the-art series. December 1985. (Available from the National Technical Information Service, U.S. Dept. of Commerce, Springfield, Virginia 22161.)

Detecting the Climatic Effects of Increasing Carbon Dioxide, DOE/ER-0235.

Projecting the Climatic Effects of Increasing Carbon Dioxide, DOE/ER-0237.

Direct Effects of Increasing Carbon Dioxide in Vegetation, DOE/ER-0238.

Atmospheric Carbon Dioxide and the Global Carbon Cycle, DOE/ER-0239.

Glaciers, Ice Sheets, and Sea Level: Effect of a CO_2–Induced Climate Change. Prepared by the National Research Council for the U.S. Department of Energy. September 1985. DOE/ER/60235-1.

V. Ramanathan, R. J. Cicerone, H. B. Singh, and J. T. Kiehl. "Trace Gas Trends and Their Potential Role in Climate Change." *Journal of Geophysical Research*, Vol. 90, No. D3 (June 20, 1985), pp. 5547–5566.

Linda O. Mearns, Richard W. Katz, and Stephen H. Schneider. "Extreme High-Temperature Events: Changes in Their Probabilities With Changes in Mean Temperature." *Journal of Climate and Applied Meteorology*, Vol. 23, No. 12 (December 1984), pp. 1601–1613.

Richard C. J. Somerville and Lorraine A. Remer. "Cloud Optical Thickness Feedbacks in the CO_2 Problem." *Journal of Geophysical Research*, Vol. 89, No. D6 (October 20, 1984), pp. 9668–9672.

Changing Climate: Report of the Carbon Dioxide Assessment Committee. National Academy of Sciences. Washington, D.C.: National Academy Press. 1983.

An Assessment of the Implications of Increased CO_2 Emissions and Their Control for the U.S. Electrical Utility Industry Report prepared for TPS 77-751 by Radian Corp. January 1980.

This article was written by Michael Shepard. Technical background information was provided by Charles Hakkarinen and Alan Hansen, Energy Analysis and Environment Division, and Dwain Spencer, Advanced Power Systems Division. Additional support was provided by Mary Ann Allan, Seymour Alpert, Glenn Hilst, Ralph Perhac, and Thomas Wilson.

Annex 35

P. H. Gleick, “The Implications of Global Climatic Changes for International Security”, *Climatic Change,* 1989, pp. 309-325

THE IMPLICATIONS OF GLOBAL CLIMATIC CHANGES FOR INTERNATIONAL SECURITY

PETER H. GLEICK
Pacific Institute for Studies in Development, Environment, and Security, 1681 Shattuck Avenue, Suite H, Berkeley CA 94709, U.S.A.

Abstract. Global climatic changes caused by growing concentrations of atmospheric trace gases have the potential to alter international relationships, economics, behavior, and security. While there is debate about the extent to which environmental problems alone can lead to conflict, it is widely acknowledged that resource constraints can act as roots leading to economic pressures and tensions, or as triggers to conflict when other pressures and tensions exist between states. Recent widespread attention to the issue of global environmental problems, particularly climatic change, is leading to a re-examination and expansion of the traditional narrow definition of "international security". This paper discusses likely paths to international frictions and tensions and the responses that might be most appropriate to minimize the adverse consequences of climatic change for international security.

Introduction

Over the last few decades, there has been growing concern over the international implications of large-scale environmental problems. Recently, this attention has focused on the possibility of major climatic changes caused by growing atmospheric concentrations of carbon dioxide and other trace gases. Given the extent and severity of the possible climatic changes, we must begin to ask how such changes will affect international relationships, economics, behavior, and security.** There is debate about the extent to which resource constraints or environmental problems *alone* can lead to conflict, but it is widely acknowledged that resources can act as roots leading to economic pressures and tensions or as triggers to conflict when other pressures and tensions exist between states. This paper discusses the most likely paths for such effects and what responses might be appropriate to minimize the adverse consequences for international stability and tensions.

* This work was supported by a fellowship in International Peace and Security Studies from the Social Science Research Council/MacArthur Foundation Fellows Program. The author is presently the director of the Environment Program at the Pacific Institute for Studies in Development, Environment, and Security in Berkeley, California.

** Threats to security can be defined to include actions that (1) threaten to drastically and quickly degrade the quality of life for the inhabitants of a state, or (2) threaten to significantly narrow the range of policy choices available to governments or non-governmental entities (Ullman, 1983). Climatic changes that lead to the deterioration of environmental quality or limit access to resources fall into both categories.

Climatic Change **15**: 309–325, 1989.
© 1989 *Kluwer Academic Publishers. Printed in the Netherlands.*

Precise information on the regional impacts of climatic changes is unlikely to be available soon. Rather than waiting for such information, a more valuable approach would be to identify the greatest susceptibilities to existing climatic variability on the assumption that those vulnerabilities are likely candidates for further analysis. Three areas are likely to affect national and international relationships, behavior, and policy: agricultural productivity, the availability and quality of freshwater resources, and access to strategic minerals (Budyko, 1977; Roberts and Lansford, 1979; Gustafson, 1981; Wilson, 1983; Tickell, 1986). Agricultural productivity fluctuates with the weather, and the level of international trade is large. Water resources are sensitive to both floods and droughts and are limited in many regions due to natural variability or high societal demand. Certain mineral resources, including oil and gas, are found in significant amounts in regions constrained by climatic conditions and the importance of these resources to particular nations and alliances warrants attention. By looking at past climatic experience we can begin to understand the extent of future vulnerabilities.

Any analogies linking past climatic variability with international political effects are necessarily imperfect. One problem is that the links between political behavior and climatic conditions are often tenuous, given the many other relevant factors that affect such behavior. A further complication is that the magnitude and severity of future climatic changes is likely to be considerably greater than past climatic variability.

An alternative approach is to wait for more research and more detailed regional information on the environmental and economic impacts of climatic changes before taking preventative actions. This approach has two serious flaws. First, the complexity of modeling climatic behavior means that the necessary research will be slow and difficult. Unless actions begin soon to reduce the emissions of carbon dioxide and other gases, the earth will be irreversibly committed to substantial warming. Second, any international agreement to prevent major climatic changes may be complicated by a desire of certain actors (alliances, nations, sub-national groups, corporations) to capitalize on perceived regional advantages. Those actors who believe – rightly or wrongly – that they will benefit from a warmer earth will have no direct incentive to cooperate in any international agreement to prevent climatic change.

These problems are discussed below in the context of three issues that play a role in international affairs: (1) agricultural productivity and the lopsided nature of present international grain production and trade; (2) water availability and the importance of shared international freshwater resources; and (3) access to strategic northern energy minerals such as oil and gas, and the increasing difficulty of developing the remaining remote resources.

Agricultural Productivity and Trade

Threats to the basic food supplies of a country are cause for frictions and tensions

between nations (Wallensteen 1986). Possible mechanisms for such threats include trade embargoes or other forms of political manipulation of access to food, environmental degradation such as loss of soil fertility, or competition among conflicting land uses. Because regional scarcity is a fundamental condition for a good to become a political tool, the disparity in food needs and food resources between the developing and the developed world has long hinted at the possibility of future conflict over access to food resources.

Food availability depends on a complex array of factors, including patterns of production, purchasing ability, and the operation of food distribution systems. The vulnerability of political behavior to the availability and quality of agricultural resources has been highlighted in recent years by internal conflicts and riots over food shortages throughout the Sahel in the 1970s, in Sudan in 1981 and 1985, in Poland in 1980, in Tunisia in 1983 and 1984, and in Morocco in 1984. These internal events often serve to increase external tensions as well (Schneider, 1983; Wallensteen, 1986).

Even today, some countries are acutely vulnerable to natural climatic variability that may cripple their own food production or substantially reduce the supply and raise the price of foodstuffs on the world market. Under conditions of changing climate and growing population, this situation may grow more precarious.

The situation for large grain producers is equally uncertain. As temperatures increase, agricultural production could expand into northern regions of the United States, the Soviet Union, China, and Canada if soil conditions, water availability, and other factors permit. But output in regions that are now productive, such as the Central Plains of the United States, the Ukraine, and Kazakhstan, could be reduced by higher temperatures and changes in water availability.

Analysis of the net effect (both regionally and globally) of climatic changes on food production is complicated by the difficulties of estimating the effect of changes in yields on world agricultural markets. Short-term reductions in yields alone are not necessarily bad for overall long-term productivity and food availability. Confounding factors include the size of stocks, subsequent investments in other regions, planting patterns, international prices, and the character of trading agreements. Thus changes in the comparative advantage of the different actors can play a greater role than absolute changes in agricultural productivity.

A Case Study: Agricultural Productivity and International Grain Trade

International tensions and conflict may be provoked by changes in the productivity of major grain importers, by the demand for grain on the international market, and by the ability of present grain suppliers to continue to generate surpluses. For example, periodic crop failures can turn into a distinct political danger. In the Soviet Union, climatic constraints play an important role in limiting agricultural productivity, where one of the problems is water availability. Uncertain rainfall is the greatest single climatic hindrance to Soviet agriculture and sixty percent of the

Soviet grain-growing area suffers some loss from inadequate moisture on the average in three or four years out of ten (Gustafson, 1981).

The direct effect of Soviet grain productivity problems is to force them to purchase grain in international markets to make up deficiencies. Figure 1 shows Soviet imports of cereals as a percentage of total world cereal trade. In recent years the Soviets have been the largest single cereal importer, accounting for 20 percent of total grain purchases. According to Gustafson (1981),

> The need to turn to international markets for grain became a regular humiliation and a drain of scarce foreign currency. In the eyes of Soviet leaders, problems with agricultural productivity threatened domestic stability, national security, and economic growth.

One of the political risks of international trade in grain is the threat of a grain embargo. In 1980, the United States imposed such an embargo on the Soviet Union in response to the Soviet intervention in Afghanistan. Because of this experience with U.S. unreliability as a grain supplier, the Soviets have made efforts to reduce their dependence on U.S. grain by spreading their purchases among the other main grain suppliers.

The principal effect of the grain embargo was to give the Soviet leadership a sharp reminder of the risks of depending on world markets for such a critical commodity. The willingness of the Soviets to continue to purchase foreign grain results from their ability as a major grain purchaser to find favorable terms from a mix of suppliers, from their ability to continue to generate foreign currency through the

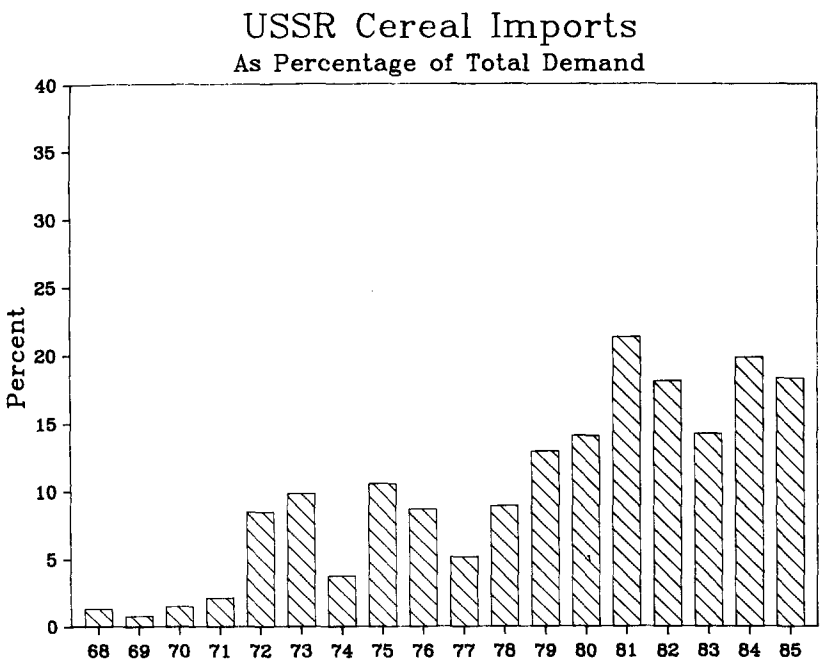


Fig. 1. Imports of cereal crops by the Soviet Union as a percentage of total world trade in cereal (1968 to 1985). The Soviet Union is the single largest importer of cereal grains (FAO, 1985).

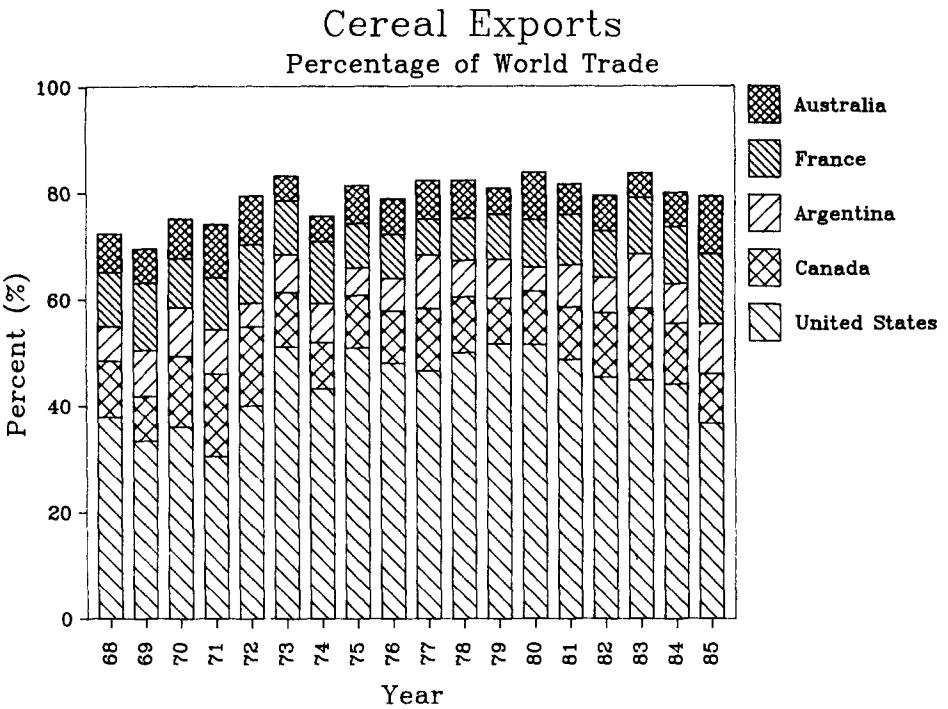


Fig. 2. Exports of cereal crops by the principal exporters as a percentage of world cereal trade (1968 to 1985). Together, the United States, Australia, France, Argentina, and Canada export around 80% of all cereal crops (FAO, 1985).

sale of other natural resources (notably fossil fuels, gold, and certain minerals), and from their belief that as their agricultural industry becomes more efficient, their reliance on foreign grain sources will decrease. In fact, the vulnerabilities arising from international trade in grain cut both ways. In recent years, drought in Russia and Kazakhstan has been one of the major uncertainties for Western grain markets, and sudden and massive purchases by the Soviet Union have played havoc with world prices.

Given this type of climatic vulnerability and the importance of a limited number of countries in the international grain markets (see Figure 2), further attention to increasing the reliability of agricultural production and reducing climatic constraints is warranted. Some specific recommendations include developing a more robust food-distribution system, particularly in food-importing regions, developing strains of grain that are climatically resistant to temperature extremes and moisture shortages, planting crops with different physiological characteristics in a single region to minimize the risk of a localized adverse event, or the parallel idea of dispersing a single crop type over several areas to decrease impacts from the same adverse event, and larger available food reserves to buffer climatically-induced changes in production.

Water and Security

International political frictions and tensions have arisen over the control of, access to, or the quality of freshwater resources (Naff and Matson, 1984; Falkenmark, 1986; Gleick, 1988). Even in the absence of climatic changes, pressures on existing water resources are growing due to increases in population, industrial water demand, and development in semi-arid and arid regions. Where water resources are shared, as in international river basins or bodies of water bordering more than one country, the possibility of friction and conflicting demands exists. The nature of such frictions varies from region to region – from disputes over water quality in humid regions to competition for scarce resources in arid and semi-arid regions.

Nearly 50 countries on four continents (shown in Table I) have more than three-quarters of their total land area falling within international river basins, while globally 47% of all land area falls within international river basins. Over 200 river basins are multinational, including 57 in Africa and 48 in Europe (see Table II). The extent of this interdependence can be seen in Table III, which lists thirteen different major rivers with five or more nations forming part of the watershed. Examples from the different continents include the Danube, whose basin lies within 12 different nations; the Nile, which runs through nine; the Amazon, which runs through seven; the Mekong, which runs through six; and the Ganges-Brahmaputra, which runs through five (United Nations, 1978).

TABLE I: Number of countries with >75% of total area falling within international river basins

Africa	23
North and Central America	0
South America	6
Asia	8
Europe	13

Source: United Nations (1978).

TABLE II: International river basins

	International river basins	% of area in international basin
Africa	57	60
North and Central America	34	40
South America	36	60
Asia	40	65
Europe	48	50
Total	215	47

Source: United Nations (1978).

TABLE III: Rivers with five or more nations forming part of the basin

	#	Area (km^2)
Danube	12	817,000
Niger	10	2,200,000
Nile	9	3,030,700
Zaire	9	3,720,000
Rhine	8	168,757
Zambezi	8	1,419,960
Amazon	7	5,870,000
Mekong	6	786,000
Lake Chad	6	1,910,000
Volta	6	379,000
Ganges-Brahmaputra	5	1,600,400
Elbe	5	144,500
La Plata	5	3,200,000

Source: United Nations (1978).

Regions with a history of international tensions or competition over water resources include the Jordan and Euphrates Rivers in the Middle East, the Nile, Zambezi, and Niger Rivers in Africa, the Ganges in Asia, and the Colorado and Rio Grande Rivers in North America. As water demands increase, the probability of conflict over remaining water resources will also increase. Problems may be indicated by low per-capita water availability, which suggests high population, few overall water resources, and a sensitivity to water quality. Table IV provides a partial list of those countries that are both dominated by international river basins and that have limited per-capita water availability. If better data can be made available, such indicators can be used to identify regions that may be susceptible to future water conflicts (Gleick, 1989).

Future climatic changes can reduce or exacerbate these water-related tensions. Among the critical concerns are changes in (1) water availability from altered precipitation patterns or evaporative losses due to higher temperatures, (2) the seasonality of precipitation and runoff, (3) flooding or drought frequencies, and (4) the demand for and the supply of irrigation water for agriculture.

Two Case Studies: The Colorado River and the Nile River

Details about water allocation and use in the Colorado River and the Nile River – both international rivers – can provide insights into how water conflicts arise and what appropriate mechanisms for resolving such frictions might look like.

The Colorado River flows through some of the most arid regions of the United States and Mexico and it is vital for agriculture in both countries. As a result, the Colorado is extensively used – so extensively that Mexico would receive almost no flow were it not for an international treaty signed in 1944 that guarantees a fixed

TABLE IV: Selected countries dominated by international river basins with low per-capita water availability[1,2]

Country	Area in international river basin (%)	Per-capita water availability 10^3 m^3 yr^{-1}
Ethiopia	80	2.39
Gambia	91	4.48
Ghana	75	3.65
Sudan	81	1.31
Togo	77	3.66
Peru	78	1.93
Afghanistan	91	2.76
Iraq	83	2.00
Belgium	96	0.85
Bulgaria	79	1.97
Czechoslovakia	100	1.79
Germany (D.D.R.)	93	1.01
Hungary	100	0.56
Poland	95	1.31
Romania	98	1.59

[1] This list is incomplete because of limited data on water availability by country. As better data become available, this indicator will become more reliable as a measure of water stress in a region.

[2] Examples of countries with high per-capita water availability and few international river basins include: Cameroon (27.4×10^3 m^3 yr^{-1}), Canada (134.2×10^3 m^3 yr^{-1}), Colombia (68.9×10^3 m^3 yr^{-1}), Norway (98.8×10^3 m^3 yr^{-1}), and New Zealand (140.8×10^3 m^3 yr^{-1}).

Sources: World Resources Institute (1987), United Nations (1978).

volume of water to Mexico annually. This treaty was negotiated after nearly 50 years of contention and disagreement over the sharing of the Colorado River.

Unfortunately, the treaty provisions for allocating shortages during a drought are ambiguous and have never been tested. Also, no provisions in the treaty cover the possibility of a climatic change that could alter the long-term availability of water in the river. These ambiguities and omissions could result in a revival of U.S. – Mexican frictions if the runoff available in the Colorado were to be reduced by climatic changes (Gleick, 1988). In fact, there are some suggestions that carbon dioxide-induced climatic changes could lead to a reduction in streamflow in this region (Revelle and Waggoner, 1983; Flaschka *et al.*, 1987). A solution worth pursuing is for the two nations to resolve the ambiguities over the allocation of shortages and to reach a specific agreement about how climatic changes are to be identified and handled before such changes appear.

A similar agreement for the Nile River is complicated by the fact that the Nile's catchment and riparian drainage area is in the territory of nine nations: Egypt, Sudan, Ethiopia, Kenya, Tanzania, Zaire, Uganda, Rwanda, and Burundi. Although the principal water users are Egypt and the Sudan, the runoff is mostly generated by precipitation in Ethiopia and the other countries. Competition for the

waters of the Nile first arose in the early 1900s over growing Egyptian needs. The question of allocation of the Nile flow was submitted to international mediation in 1920, and in 1929, a Nile Waters Agreement was adopted that reflected Egypt's dominant interest. Conflict over allocations resurfaced in the 1950s, a period of growing water use in Sudan and internal unrest in both countries. In 1959, after minor military skirmishing between Egypt and the Sudan, the Sudanese abrogated the 1929 Nile Agreement by unilaterally raising the height of the Sennar Dam in the Sudan. By late 1959, due to a change in the political climate, negotiations were reopened and a new "Agreement for the Full Utilization of the Nile Waters" was signed.

The agreement reached in 1959 between Egypt and the Sudan, while settling the Egypt-Sudan conflicts, ignores all other riparian users. In the future, these users are likely to play a larger role in the use of the Nile (Uganda and Zaire with Lake Mobutu, Uganda, Kenya, and Tanzania with Lake Victoria, and Lake Tana in Ethiopia) because of growing population and irrigation demands. Any climatically-induced change in water availability will further complicate the future use of the Nile, contributing to political jousting and friction.

These examples suggest that attention could usefully be focused on those regions where existing pressures over water resources are already a problem. In these cases, mechanisms for allocating shortages must be designed and agreed upon before climatic changes begin to alter the hydrologic regime. International water law, though immature in its development and application, must play a role. By codifying these allocation schemes, mechanisms can be put into place to resolve conflicts before they become acute.

Northern Mineral Resources

Access to certain strategic minerals is already constrained in some regions by climatic conditions. In particular, the ability to extract oil and natural gas in Arctic continental and offshore regions depends on expensive and vulnerable methods and materials. Yet significant resources underlie these regions and they are a vital element in national economies and world trade markets. Any change in climate that affects the ease of extracting these resources will play a role in the response of international actors to initiatives to control climatic change.

The oil and gas potential of the northern Arctic regions is very large. Despite only limited exploration, Arctic proven reserves already comprise a substantial fraction of the proved reserves of the countries of the region, as shown in Table V, and the volume of 'potentially recoverable' oil is several times larger. These figures should be compared with estimated global 'proved' oil reserves of 95 billion tonnes (700 billion barrels) of oil, and gas reserves of 100 trillion cubic meters (3600 trillion cubic feet).

The technical and environmental challenges, monetary costs, and ecological and economic risks of finding and extracting Arctic energy resources are immense.

TABLE V: Arctic oil resources

	Arctic potentially recoverable[a] (10^9 bbl)	Arctic proved reserves (10^9 bbl)	Total proved reserves[c] (10^9 bbl)	Arctic proved reserves as a percent of total proved reserves
United States	17–55	7	33	21
Soviet Union	50–80	22	59	37
Canada	15	1–2	8	12–24
Norway	10–15	[b]	11	[b]

Sources: Garrett 1984, Bergesen *et al.* 1987, British Petroleum 1987.

[a] Undiscovered potential. Most U.S. estimates fall in the range of 17 to 24 billion barrels. High-side estimates for the United States are 39 to 55 billion barrels (Garrett, 1984). Gas resources could be as great as 60 trillion cubic meters (2000 trillion cubic feet). Gas estimates are highly uncertain.

[b] Accurate Norwegian Arctic oil reserves data are unavailable, but estimates range between 100 and 300 million tonnes (or 0.7 to 2 billion barrels).

[c] Estimates of world 1986 proven oil reserves total 700 billion barrels, of which 480 billion are in the Middle East.

Development of much of the new oil and gas potential in the Arctic will be substantially more expensive than the production of the already costly Prudhoe Bay and Western Siberian fields. The average cost of production in the Soviet oil industry is about $7 per barrel, while estimates of the production costs for the most expensive new fields in Western Siberia are nearly $50 per barrel (Bergesen *et al.*, 1987). The difference in capital costs of production between Saudia Arabia and the Arctic Chukchi Sea (between the U.S. and the Soviet Union) is a factor of 60.

The major environmental constraints to economic and resource development in the onshore Arctic are cold, wind conditions, snow duration and depth, permafrost, storm intensities and durations, and ice formation. Climatic problems in the offshore oil regions of the Arctic include extreme low temperatures, ice on the platforms, sea-ice extent and movement during the winter, and typhoon-like storms produced by polar low-pressure regions. In an average year in Siberia, 33% of the total loss of work time is attributed to low temperatures (Mote, 1983). For example, in the continental United States, a 3000-m oil well is drilled in a maximum of 34 days. Under Siberian conditions, such a well cannot be drilled in under 90 days, even though the Soviet Union has considerable expertise in working with permafrost and Arctic conditions. While part of the difference may be explained by differences in equipment, the greatest constraint is the climate. Even supposedly ice-resistant oil-drilling platforms are now often constrained during winters by severe ice (Bergesen *et al.*, 1987). Table VI lists the additional costs of development imposed by environmental constraints in Siberia over average mid-latitude development costs.

Higher temperatures from climatic changes could reduce some of the difficulties of extracting mineral resources in the far north, but as Table VI shows, other cli-

TABLE VI: Major environmental constraints to Siberian energy development

Condition	Additional costs of development over mid-latitude costs (%)
Cold, wind, humidity	30–115
Snow duration, blizzards, and depth	10–12
Permafrost	15–30
Icings, other[a]	15–40

Source: adapted from Mote (1983).
[a] 'Other' includes seismicity, avalanches, swampiness, water availability, and polar light levels.

matic factors also contribute to these difficulties. For example, as temperatures rise, partial melting of the permafrost layer may occur, affecting construction practices and existing physical developments. Similarly, a reduction in sea-ice extent may lead to higher precipitation in the region due to greater evaporation from a warmer, open ocean. This in turn may lead to higher snowfall and more difficult operating conditions. The possibility of a gradual buildup of northern glaciers and ice caps has even been raised (Antonov, 1978).

Given the importance of northern mineral resources, climatic constraints are unlikely to prevent future development. Even today, despite the difficulties in exploiting northern minerals, the Western Siberian oil fields produce about half of all Soviet oil (Mote, 1983), and more than 50% of all Soviet hard currency income during the 1980s has been derived from oil. The question is whether or not future climate changes will significantly increase or decrease the difficulty – and hence the expense – of that production. Current analyses of Soviet economic conditions suggest that the maintenance or increase of oil exports is a key to sustaining import levels (including grain) essential for the Soviet Union's economic plans and political priorities (Bergesen *et al.*, 1987). Similarly, the goal of reducing U.S. dependence on Middle Eastern oil (and thus theoretically increasing national security) is often claimed to hinge upon the development of Alaskan/Arctic oil reserves. The uncertainties posed by future climatic changes will complicate these problems.

Winners and Losers: The Complication of Perceptions

Avoiding political polarization on the issue of climatic change depends greatly on the perception of the participants. If some international actors believe that they will benefit from climatic changes while others suffer, such perceptions – correct or not – will drive policy actions and decisions. The views of those with the financial and technological means at their disposal to affect the outcome or mitigate the impacts of climatic changes are especially important. Arguments for international action are complicated by individual actors taking positions dependent not on the global

good, but on the perceived advantage or disadvantage to them of the likely change and impact.

There is only one thing to suggest *a priori* that climatic changes away from present climatic conditions will be disadvantageous: that is the argument that world agricultural and industrial systems have evolved under climatic conditions that have been relatively constant and that society has maximized its ability to produce food, energy, and resources under these conditions.

This argument has some merit. The distribution of crop production, the design and operation of water-supply systems, and other important physical and institutional structures were designed and developed with existing climatic conditions in mind. Any deviation from those conditions will necessarily entail expensive modifications, adaptations, and reorganizations. But despite efforts to reduce our vulnerability to climatic conditions, our climatic independence is incomplete. The growing evidence that anthropogenic climatic changes will produce climatic conditions considerably more extreme than those experienced in recent history raises even greater concerns.

There are hints that certain regions of the world will benefit, at least initially, from increases in average temperatures. China and Japan could benefit from increased rice yields and multiple cropping seasons; the U.S.S.R., the northern U.S., and southern Canada could benefit from increases in the length of their growing seasons; and so on. If these predictions are accepted, *whether or not they are true*, then other incentives for international cooperation for managing CO_2 emissions must be developed.

But there are two serious problems with setting policy today using forecasts of future benefits. First, the net societal impact depends on not just regions that benefit but on those that suffer as well. Second, the uncertainties about actual regional effects are so great that policies made on the basis of early and incomplete predictions would be both highly unreliable and difficult to justify. For example, poor conditions in one area are sometimes compensated for by more favorable conditions in another. Similarly, short-term improvements may be followed by long-term productivity losses as the climatic changes become more severe. Figure 3 shows this type of impact. Pitovranov *et al.* (1987) show that transient changes in climate derived from climate model data may lead to different agricultural impacts in the short-term and the long-term in the Leningrad area. In their study, yields of winter rye are projected to increase in the short-term because of higher temperatures and unchanged summer precipitation but then drop after 2010 because of large increases in summer precipitation and decreases in soil fertility. Yield reductions may be further exacerbated by increases in surface water pollution from nitrate leaching.

The importance of perceptions depends directly upon the ability of the 'perceiver' to affect the outcome. Table VII lists those countries that are the greatest sources of carbon dioxide and other trace gases as of the late 1980s. These coun-

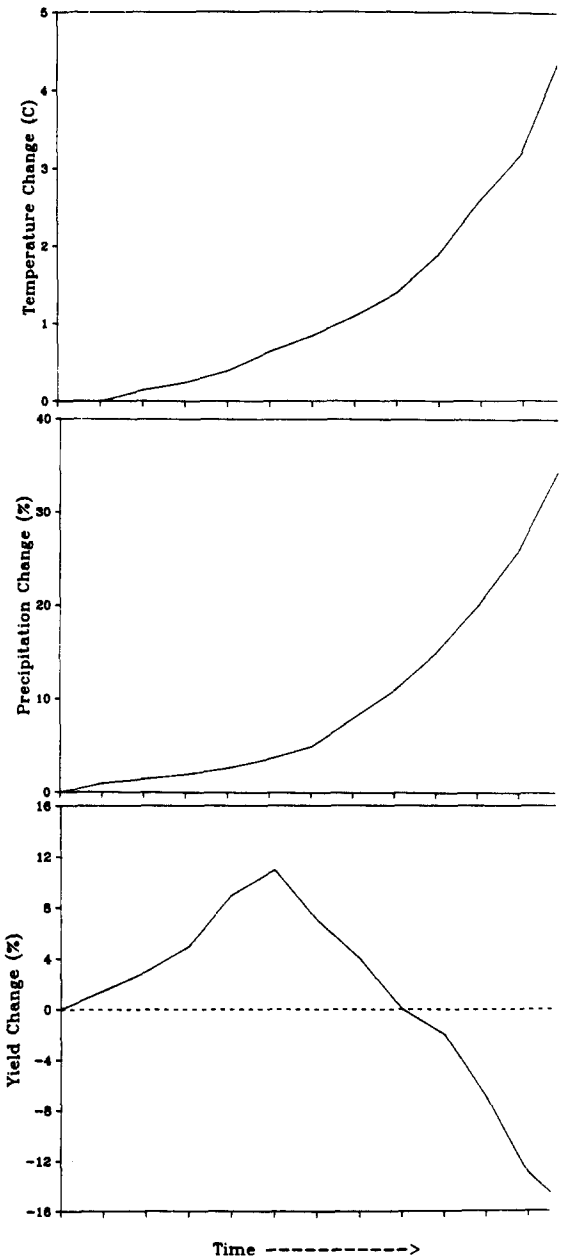


Fig. 3. Possible transient changes in agricultural yield with time. The bottom graph shows yields initially increasing as mean temperatures (top graph) and mean precipitation (middle graph) increase. Further increases in yields, however, are prevented by additional increases in temperature and precipitation, which may cause crop damage when they reach certain levels. This type of effect will complicate the analysis of climatic impacts over a long period of time.

TABLE VII: Percent of world production of CO_2 and chlorofluorocarbons

	CO_2[a]	CFC-11[b]	CFC-12
United States	24	23	30
Western Europe and Canada	16	49	33
Japan, Australia, and New Zealand	6	20	15
Soviet Union and other CPEs[c]	26	6	19
All others	28	2	3

[a] These figures include carbon dioxide from fossil fuel combustion and industrial fuel use, but do not include the contribution from biomass burning (Rotty, 1987a).
[b] Chlorofluorocarbon data are from Mintzer (1987).
[c] CPE: Centrally-planned economies.

tries are disproportionately able to affect the outcome given their populations and physical size.

Most previous international environmental disputes have been among developed countries – the Western European community, the United States, and Canada over acid rain; the industrialized nations over chlorofluorocarbon emissions; the United States, Canada, and the Soviet Union over Arctic haze, and so on. In part, this has been because these countries have been either the principal polluters (as Table VII suggests) or the principal victims of the pollution.

Large-scale climatic impacts alter this picture, because of the global extent of the impacts. Among the principal victims of climatic change will be those nations least able to either adapt to or mitigate the changes – developing countries dependent on international agricultural trade, with access to few mineral resources, and with little international economic clout. At the same time, the principal carbon dioxide polluters may be shifting from the major industrialized powers to developing countries with growing populations and a growing need for energy. By the mid-1980s, developing countries produced as much carbon dioxide from fossil fuel combustion as did Western Europe, and their share is growing (Rotty, 1987b).

Discussion and Need for Future Work

Future climatic changes caused by industrial activities will have widespread societal impacts. Among these impacts will be changes in the quality of, quantity of, or ease of access to freshwater and mineral and energy resources, and changes in the productivity of agriculture. These impacts, in turn, will alter human well-being, the quality of life, and the range of options and policy choices available to governments. In order to prevent these climatic impacts from causing international tensions and conflicts, they must be more thoroughly explored and strategies developed to either mitigate or prevent the worst effects.

A wide range of options is available. For world markets, such as the international trade of agriculture, many tools are already used to reduce the severity of climatic variability. These include food-storage programs, distribution systems, and

famine identification and assistance plans. Each of these existing mechanisms must be strengthened. Other options can also play a role under conditions of long-term climatic change. Among the more promising are the development of climatically-resilient strains of crops, better long-term forecasting abilities, and strategies for reducing the vulnerability of mono-cropping to specific climatic events.

Where existing tensions may be exacerbated by climatic change, such as in disputes over water resources, advances are needed in both conflict resolution among states and in the development of international resource law. Such advances would be useful not only for resolving international resource controversies, but for addressing the very issue of future climatic change.

There are a variety of international "rules" used to allocate resources and arbitrate disputes among the nations of the world. But for problems concerning the atmospheric environment – a true global commons – there are very few precedents. In this case, individual nations both pollute the resource and are, in turn, affected by the environmental impacts. When the affected resources are common to more than one state – such as where rivers or lakes lie within more than one country – rules involving problems of international pollution apply. Principle 21 of the UN Declaration on the Environment, adopted in 1976, says:

> States have, in accordance with the Charter of the United Nations and the principles of international law, the sovereign right to exploit their own resources pursuant to their own environmental policies, and the responsibility to ensure that activities within their jurisdiction or control do not cause damage to the environment of other States or of areas beyond the limits of national jurisdiction.

Similarly, an agreement drafted by UNEP in 1977 says:

> States have a duty to cooperate in the field of the environment concerning the conservation and harmonious utilization of natural resources shared by two or more States. Accordingly, consistent with the concept of equitable utilization of shared natural resources, States should cooperate with a view to controlling, preventing, reducing and eliminating adverse environmental effects which may result from the utilization of such resources. Such cooperation shall take place on an equal footing and due account shall be taken of the sovereignty and interests of the States concerned.

International laws and agreements provide tools for cooperative efforts on international resource problems. Such tools provide the structures and mechanisms through which nation-states manage their interactions. International law is only one factor among many – including political, economic, social, scientific, and technological factors – that influence national policymaking and decisions, but it is a necessary element in natural resource issues. Unfortunately, international law presently lacks the kind of highly-developed legal institutions of national legal systems. One major problem is that international environmental law does not have an effective system of sanctions.

Emerging principles of international environmental law suggest some constraints on the ability of a nation to pursue any resource policy it chooses if those policies degrade the environment of other nations (Bilder, 1980). Nations may not in principle (although they do in practice) pollute an international river or discharge wastes into the atmosphere or oceans, if these threaten severe environ-

mental damage to neighbors or the global community. Thus even in internal resource decisions, states should take into account the impact of these decisions on other nations' interests.

Finally, differing perceptions about the severity of global climatic changes must not be allowed to stop comprehensive international negotiations. Although there are likely to be disagreements about specific regional impacts, no region or country can expect to benefit from rapid climatic changes that would overwhelm the capacity of even wealthy countries to adapt. Many actions that would prevent or delay climatic change are appropriate in their own right, such as energy conservation, a reduction of dependence on fossil fuels, and a ban on the use of certain trace gases with long-term atmospheric effects. These cooperative strategies can reduce the rate of climatic change and give us time to both improve our understanding of climatic impacts and to reflect on appropriate international responses.

References

Antonov. V. S.: 1978, 'The Possible Impact on the Arctic Ocean from the Proposed Transfer of Water from the Northern Rivers of the U.S.S.R. to the South', *Polar Geology* **2**, 223–231.

Bergesen, H. O., Moe, A., and Ostreng, W.: 1987, *Soviet Oil and Security Interests in the Barents Sea*, Frances Pinter, Publishers, London, England, 144 pp.

Bilder, R. B.: 1980, 'International Law and Natural Resource Policies', in Dorner, P. and M. A. El-Shafie (eds.), *Resources and Development*, The University of Wisconsin Press, Croom Helm, London, pp. 385–421.

British Petroleum (BP): 1987, *BP Statistical Review of World Energy*, British Petroleum Company, Britannic House, Moor Lane, London, 36 pp.

Budyko, M. I.: 1977, *Climatic Changes*, American Geophysical Union Translation, Waverly Press, Inc., Baltimore, Maryland, 261 pp.

Falkenmark, M.: 1986, 'Fresh Waters as a Factor in Strategic Policy and Action', in A. H. Westing (ed.), *Global Resources and International Conflict: Environmental Factors in Strategic Policy and Action*, Oxford University Press, New York, pp. 85–113.

Flaschka, I., Stockton, C. W., and Boggess, W. R.: 1987, 'Climatic Variation and Surface Water Resources in the Great Basin', *Water Resources Bulletin* **23**. No. 1. pp. 47–57.

Garrett, J. N.: 1984, 'Conventional Hydrocarbons in the United States Arctic: An Industry Appraisal', in Westernmeyer, W. E. and K. M. Shusterich (eds.), *United States Arctic Interests: The 1980s and 1990s*, Springer-Verlag, Inc. New York, pp. 39–58.

Gleick, P. H.: 1988, 'The Effects of Future Climatic Changes on International Water Resources: The Colorado River, The United States, and Mexico', *Policy Sciences* **21**, 23–39.

Gleick, P. H.: 1989, 'Vulnerability of Water-Supply Systems', in P. Waggoner and R. R. Revelle (eds.), *Climate and Water: Climate Variability, Climate Change, and the Planning and Management of U.S. Water Resources*, American Association for the Advancement of Sciences, John Wiley & Sons. New York (in press.)

Gustafson, T.: 1981, *Reform in Soviet Politics: Lessons of Recent Policies on Land and Water*, Cambridge University Press, Cambridge, England, 218 pp.

Mintzer, I. M.: 1987, *A Matter of Degrees: The Potential for Controlling the Greenhouse Effect*, World Resources Institute, Washington, D.C., 60 pp.

Mote, V. L.: 1983, 'Environmental Constraints to the Economic Development of Siberia', in Jensen, R. G., Shabad, T. and A. W. Wright (eds.), *Soviet Natural Resources in the World Economy*, The University of Chicago Press, Chicago, pp. 15–71.

Naff, T. and Matson, R. C. (eds.): 1984, *Water in the Middle East: Conflict or Cooperation*, Westview Press, Boulder, Colorado, 236 pp.

Pitovranov, S., Iakimets, V., Kiselev, V., and Sirotenko, O.: 1987, 'The Effects of Climatic Variations on Agriculture in the SubArctic Zone of the USSR, in M.L. Parry, T. R. Carter, and N. T. Konijn (eds.), *The Impact of Climatic Variations on Agriculture. Volume 1. Assessments in Cool Temperate and Cold Regions*, Kluwer Acad. Publ., Dordrecht, The Netherlands, pp. 617–722.

Revelle, R. R. and Waggoner, P. E.: 1983, 'Effects of a Carbon Dioxide-Induced Climatic Change on Water Supplies in the Western United States', in *Changing Climate*, National Academy of Sciences National Academy Press, Washington, D.C., pp. 419–432.

Roberts, W. O. and Lansford, H.: 1979, *The Climate Mandate*, W. H. Freeman and Company, San Francisco, California, 197 pp.

Rotty, R. M.: 1987a, 'Estimates of Seasonal Variation in Fossil Fuel CO_2 Emissions', *Tellus* **39B**, 184–202.

Rotty, R. M.: 1987b, 'A Look at 1983 CO_2 Emissions from Fossil Fuel (with Preliminary Data for 1984)', *Tellus* **39B**, 203–208.

Schneider, S. H.: 1983, 'Food and Climate: Basic Issues and Some Policy Implications', in V. P. Nanda (ed.), *World Climate Change: The Role of International Law and Institutions*, Westview Press, Boulder, Colorado, pp. 46–63.

Tickell, C.: 1986, *Climatic Change and World Affairs*, Revised edition. Center for International Affairs, Harvard University, University Press of America, Lanham, Maryland, 76 pp.

Ullman, R. H.: 1983, 'Redefining Security', *International Security* **8**, 129–153.

United Nations: 1978, *Register of International Rivers*, Pergamon Press, Oxford, England, 58 pp.

Wallensteen, P.: 1986, 'Food Crops as a Factor in Strategic Policy and Action', in A. H. Westing (ed.), *Global Resources and International Conflict: Environmental Factors in Strategic Policy and Action*, Stockholm International Peace Research Institute, United Nations Environment Programme, Oxford University Press, Oxford, pp. 143–158.

Wilson, T. W. Jr.: 1983, 'Global Climate, World Politics and National Security', in Nanda, V. P. (ed.), *World Climate Change: The Role of International Law and Institutions*, Westview Press, Boulder, Colorado, pp. 71–78.

World Resources Institute: 1987, *World Resources 1986*, Basic Books, Inc., New York, 353 pp.

(Received 1 March, 1988; in revised form 27 January, 1989)

Annex 36

"Special Report – Methodological and Technological issues in Technological Transfer. Summary for Policy Makers", *Intergovernmental Panel on Climate Change,* 2000, pages 3-4

WMO

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

UNEP



IPCC SPECIAL REPORT

METHODOLOGICAL AND TECHNOLOGICAL ISSUES IN TECHNOLOGY TRANSFER

Summary for Policymakers

WMO

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

UNEP

Summary for Policymakers

Methodological and Technological Issues in Technology Transfer

A Special Report of IPCC Working Group III

Published for the Intergovernmental Panel on Climate Change

Contents

Foreword v

Preface vii

1. Introduction 3
- **Background** 3
- **The role of technology transfer in addressing climate change** 3
- **What do we mean by technology transfer?** 3
- **Trends of technology transfer** 4
- **Stakeholders, pathways, stages and barriers** 4

2. Increase the flow; improve the quality 4
- **Building capacity** 4
- **Enabling environment and extra effort to enhance technology transfer** 5
- **Mechanisms for technology transfer** 6

3. Sectorial actions 7
- **Buildings** 7
- **Transport** 7
- **Industry** 8
- **Energy supply** 8
- **Agriculture** 8
- **Forestry** 8
- **Waste management** 8
- **Human health** 8
- **Coastal adaptation** 8

SUMMARY FOR POLICYMAKERS

METHODOLOGICAL AND TECHNOLOGICAL ISSUES IN TECHNOLOGY TRANSFER

A Special Report of Working Group III
of the Intergovernmental Panel on Climate Change

Based on a draft prepared by:
Stephen O. Andersen (USA), William Chandler (USA), Renate Christ (Austria), Ogunlade Davidson (Sierra Leone), Sukumar Devotta (India), Michael Grubb (UK), Joyeeta Gupta (The Netherlands), Thomas C. Heller (USA), Maithili Iyer (India), Daniel M. Kammen (USA), Richard J.T. Klein (The Netherlands/Germany), Dina Kruger (USA), Ritu Kumar (India), Mark Levine (USA), Lin Erda (China), Patricia Iturregui (Peru), Merylyn McKenzie Hedger (UK), Anthony McMichael (UK), Mark Mansley (UK), Jan-Willem Martens (The Netherlands), Eric Martinot (USA), Ajay Mathur (India), Bert Metz (The Netherlands), John Millhone (USA), Jose Roberto Moreira (Brazil), Tongroj Onchan (Thailand), Mark Radka (USA), Kilaparti Ramakrishna (India), N.H. Ravindranath (India), Sascha van Rooijen (The Netherlands), Jayant Sathaye (USA), Youba Sokona (Mali), Sergio C. Trindade (Brazil), David Wallace (UK), Ernst Worrell (The Netherlands)

1. Introduction

Background

Article 4.5 of the United Nations Framework Convention on Climate Change (UNFCCC) states that developed country Parties and other developed Parties included in Annex II "shall take all practicable steps to promote, facilitate and finance, as appropriate, the transfer of, or access to, environmentally sound technologies and know-how to other Parties, particularly developing country Parties, to enable them to implement the provisions of the Convention." The Subsidiary Body for Scientific and Technological Advice (SBSTA) identified at its first session a list of areas in which it could draw upon the assistance of the IPCC. This Special Report was prepared in response to this request. It addresses the technology transfer problem in the context of all relevant UNFCCC provisions, including decisions of the Conference of Parties (COP), and Chapter 34 in Agenda 21. It attempts to respond to recent development in the UNFCCC debate on technology transfer, by providing available scientific and technical information to enable Parties to address issues and questions identified in Decision 4/CP.4 adopted by COP-4.

The role of technology transfer in addressing climate change

Achieving the ultimate objective of the UNFCCC, as formulated in Article 2[1], will require technological innovation and the rapid and widespread transfer and implementation of technologies, including know-how for mitigation of greenhouse gas (GHG) emissions. Transfer of technology for adaptation to climate change is also an important element of reducing vulnerability to climate change.

This technological innovation must occur fast enough and continue over a period of time to allow greenhouse gas concentrations to stabilize and reduce vulnerability to climate change. Technology for mitigating and adapting to climate change should be environmentally sound technology (EST) and should support sustainable development.

Sustainable development on a global scale will require radical technological and related changes in both developed and developing countries. Economic development is most rapid in developing countries, but it will not be sustainable if these countries follow the historic greenhouse gas emission trends of developed countries. Development with modern knowledge offers many opportunities to avoid past unsustainable practices and move more rapidly towards better technologies, techniques and associated institutions. The literature indicates that to achieve this developing countries require assistance with developing human capacity (knowledge, techniques and management skills), developing appropriate institutions and networks, and with acquiring and adapting specific hardware. Technology transfer, in particular from developed countries to developing countries, must therefore operate on a broad front covering these software and hardware challenges, and ideally within a framework of helping to find new sustainable paths for economies as a whole. There is, however, no simple definition of a "sustainable development agenda" for developing countries. Sustainable development is a context driven concept and each society may define it differently, based on Agenda 21. Technologies that may be suitable in each of such contexts may differ considerably. This makes it important to ensure that transferred technologies meet local needs and priorities, thus increasing the likelihood that they will be successful, and that there is an appropriate enabling environment for promoting environmentally sound technologies (ESTs).

The Report analyses the special challenges of transferring ESTs to address climate change in the context of sustainable development. The literature provides ample evidence of the many problems in current processes of technology transfer which makes it very unlikely to meet this challenge without additional actions for the transfer of mitigation and adaptation technologies.

What do we mean by technology transfer?

The Report defines the term "technology transfer" as a broad set of processes covering the flows of know-how, experience and equipment for mitigating and adapting to climate change amongst different stakeholders such as governments, private sector entities, financial institutions, non-governmental organizations (NGOs) and research/education institutions. Therefore, the treatment of technology transfer in this Report is much broader than that in the UNFCCC or of any particular Article of that Convention. The broad and inclusive term "transfer" encompasses diffusion of technologies and technology cooperation across and within countries. It covers technology transfer processes between developed countries, developing countries and countries with economies in transition, amongst developed countries, amongst developing countries and amongst countries with economies in transition. It comprises the process of learning to understand, utilize and replicate[2] the technology, including the capacity to choose it and adapt it to local conditions and integrate it with indigenous technologies.

The Report generally makes a distinction between developed and developing countries. Although economies in transition are included as developed countries under the UNFCCC, they may have characteristics in common with both developed and developing countries.

[1] "The ultimate objective of this Convention and any related legal instruments that the Conference of Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilisation of greenhouse gas concentrations in the atmosphere at such a level that would prevent dangerous interference with the climate system. Such a level should be achieved within a timeframe sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner."

[2] The final stage of the five basic stages of technology transfer (assessment, agreement, implementation, evaluation and adjustment, replication) as defined in the Report as a combination of actions that lead to the deployment of a given technology, once transferred, to meet a new demand elsewhere.

Trends of technology transfer

It is difficult to quantify how much climate-relevant hardware is successfully transferred annually. When software elements such as education, training and other capacity building activities are included, the task of quantification is further complicated. Financial flows, often used as proxies, allow only a limited comparison of technology transfer trends over time. The 1990s have seen broad changes in the types and magnitudes of the international financial flows that drive technology transfer.

Official Development Assistance (ODA) experienced a downward trend in the period from 1993 to 1997, both in absolute terms and as a percentage of funding for projects with significant impact on technology flows to developing countries. However, in 1998 there was an increase in ODA funding. ODA is still important for those parts of the world and sectors where private sector flows are comparatively low, like agriculture, forestry, human health and coastal zone management. Moreover, it can support the creation of enabling conditions, which may leverage larger flows of private finance into ESTs in the context of overall sustainable development goals in the recipient countries.

Levels of foreign direct investment (FDI), commercial lending, and equity investment all increased greatly in recent years. These are the dominant means by which the private sector makes technology-based investments in developing countries and economies in transition, often in the industry, energy supply and transportation sectors. However, private sector investment in the form of FDI in developing countries has favoured East and South East Asia, and Latin America.

These trends are altering the relative capacities and roles of different stakeholders. The importance of the private sector has increased substantially. However, there is a definite role for governments both in providing an enabling environment for the technology transfer process as well as participating directly in it. Many NGOs support technology transfer activities.

Stakeholders, pathways, stages and barriers

Technology transfer results from actions taken by various stakeholders. Key stakeholders include developers; owners; suppliers, buyers, recipients and users of technology (such as private firms, state enterprises, and individual consumers); financiers and donors; governments; international institutions; NGOs and community groups. Some technology is transferred directly between government agencies or wholly within vertically integrated firms, but increasingly technology flows depend also on the coordination of multiple organizations such as networks of information service providers, business consultants and financial firms. Although stakeholders play different roles, there is a need for partnerships among stakeholders to create successful transfers. Governments can facilitate such partnerships.

There is a large number of pathways through which stakeholders can interact to transfer technologies. They vary depending on sectors, country circumstances and type of technology. Pathways may be different for "close to market" technologies and for technology innovations still in the development phase. Common pathways include government assistance programmes, direct purchases, licensing, foreign direct investment, joint ventures, cooperative research arrangements and co-production agreements, education and training, and government direct investment.

While technology transfer processes can be complex and intertwined, certain stages can be identified. These may include the identification of needs, choice of technology, assessment of conditions of transfer, agreement and implementation. Evaluation and adjustment to local conditions, and replication[2] are other important stages.

Barriers to the transfer of ESTs may arise at each stage of the process. These vary according to the specific context, for example from sector to sector, and can manifest themselves differently in developed countries, developing countries and countries with economies in transition. These barriers range from lack of information; insufficient human capabilities; political and economic barriers such as lack of capital, high transaction costs, lack of full cost pricing, and trade and policy barriers; lack of understanding of local needs; business limitations, such as risk aversion in financial institutions; and institutional limitations such as insufficient legal protection, and inadequate environmental codes and standards.[3]

There is no pre-set answer to enhancing technology transfer. The identification, analysis and prioritization of barriers should be country based. It is important to tailor action to the specific barriers, interests and influences of different stakeholders in order to develop effective policy tools.

2. Increase the flow; improve the quality

Government actions can transform the conditions under which technology transfer takes place. The spread of proven ESTs that would diffuse through commercial transactions may be limited because of the barriers listed above.

The three major dimensions of making technology transfer more effective are capacity building, an enabling environment and mechanisms for technology transfer, all of which are discussed in more detail in the subsections below.

Building capacity

Capacity building is required at all stages in the process of technology transfer. Social structures and personal values evolve with a society's physical infrastructure, institutions, and the technologies embodied within them. New technological trajectories for an economy therefore imply new social challenges. This requires a capacity of people and organizations to continuously adapt to new circumstances and to acquire new skills. This applies both for mitigation and adaptation technologies.

[2] See previous page.
[3] See Technical Summary and Chapters 3, 4 and 5 of the main report.

Annex 37

"Historical Overview of Climate Change – Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change" Cambridge University Press, *Intergovernmental Panel on Climate Change,* 2007, pages 115-116

1

Historical Overview of Climate Change Science

Coordinating Lead Authors:
Hervé Le Treut (France), Richard Somerville (USA)

Lead Authors:
Ulrich Cubasch (Germany), Yihui Ding (China), Cecilie Mauritzen (Norway), Abdalah Mokssit (Morocco), Thomas Peterson (USA), Michael Prather (USA)

Contributing Authors:
M. Allen (UK), I. Auer (Austria), J. Biercamp (Germany), C. Covey (USA), J.R. Fleming (USA), R. García-Herrera (Spain), P. Gleckler (USA), J. Haigh (UK), G.C. Hegerl (USA, Germany), K. Isaksen (Norway), J. Jones (Germany, UK), J. Luterbacher (Switzerland), M. MacCracken (USA), J.E. Penner (USA), C. Pfister (Switzerland), E. Roeckner (Germany), B. Santer (USA), F. Schott (Germany), F. Sirocko (Germany), A. Staniforth (UK), T.F. Stocker (Switzerland), R.J. Stouffer (USA), K.E. Taylor (USA), K.E. Trenberth (USA), A. Weisheimer (ECMWF, Germany), M. Widmann (Germany, UK)

Review Editors:
Alphonsus Baede (Netherlands), David Griggs (UK)

This chapter should be cited as:
Le Treut, H., R. Somerville, U. Cubasch, Y. Ding, C. Mauritzen, A. Mokssit, T. Peterson and M. Prather, 2007: Historical Overview of Climate Change. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Table of Contents

Executive Summary 95

1.1 Overview of the Chapter 95

1.2 The Nature of Earth Science 95

1.3 Examples of Progress in Detecting and Attributing Recent Climate Change 100

1.3.1 The Human Fingerprint on Greenhouse Gases 100

1.3.2 Global Surface Temperature 100

1.3.3 Detection and Attribution 102

1.4 Examples of Progress in Understanding Climate Processes 103

1.4.1 The Earth's Greenhouse Effect 103

1.4.2 Past Climate Observations, Astronomical Theory and Abrupt Climate Changes 106

1.4.3 Solar Variability and the Total Solar Irradiance 107

1.4.4 Biogeochemistry and Radiative Forcing 108

1.4.5 Cryospheric Topics 110

1.4.6 Ocean and Coupled Ocean-Atmosphere Dynamics 111

1.5 Examples of Progress in Modelling the Climate 112

1.5.1 Model Evolution and Model Hierarchies 112

1.5.2 Model Clouds and Climate Sensitivity 114

1.5.3 Coupled Models: Evolution, Use, Assessment 117

1.6 The IPCC Assessments of Climate Change and Uncertainties 118

Box 1.1: Treatment of Uncertainties in the Working Group I Assessment 120

1.7 Summary 121

Frequently Asked Questions

FAQ 1.1: *What Factors Determine Earth's Climate?* 96

FAQ 1.2: *What is the Relationship between Climate Change and Weather?* 104

FAQ 1.3: *What is the Greenhouse Effect?* 115

References 122

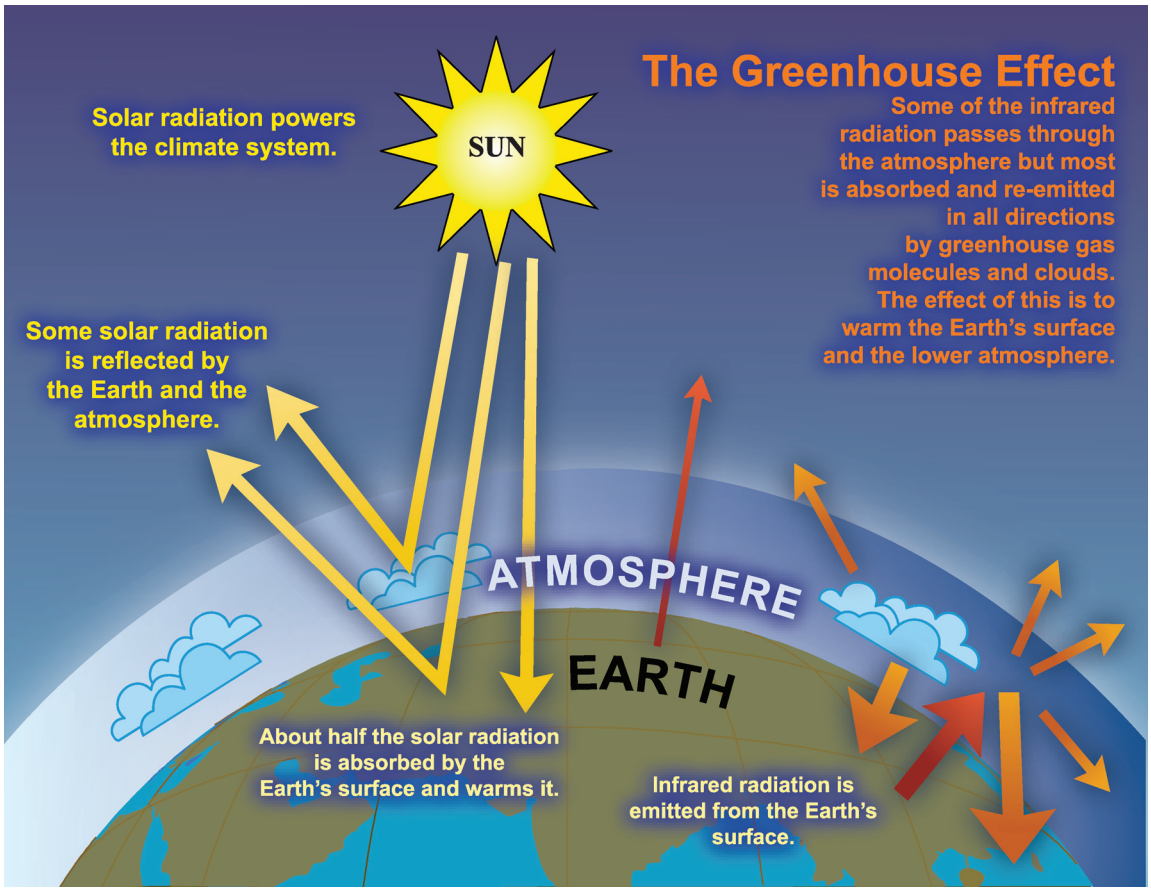
Frequently Asked Question 1.3

What is the Greenhouse Effect?

The Sun powers Earth's climate, radiating energy at very short wavelengths, predominately in the visible or near-visible (e.g., ultraviolet) part of the spectrum. Roughly one-third of the solar energy that reaches the top of Earth's atmosphere is reflected directly back to space. The remaining two-thirds is absorbed by the surface and, to a lesser extent, by the atmosphere. To balance the absorbed incoming energy, the Earth must, on average, radiate the same amount of energy back to space. Because the Earth is much colder than the Sun, it radiates at much longer wavelengths, primarily in the infrared part of the spectrum (see Figure 1). Much of this thermal radiation emitted by the land and ocean is absorbed by the atmosphere, including clouds, and reradiated back to Earth. This is called the greenhouse effect. The glass walls in a greenhouse reduce airflow and increase the temperature of the air inside. Analogously, but through a different physical process, the Earth's greenhouse effect warms the surface of the planet. Without the natural greenhouse effect, the average temperature at Earth's surface would be below the freezing point of water. Thus, Earth's natural greenhouse effect makes life as we know it possible. However, human activities, primarily the burning of fossil fuels and clearing of forests, have greatly intensified the natural greenhouse effect, causing global warming.

The two most abundant gases in the atmosphere, nitrogen (comprising 78% of the dry atmosphere) and oxygen (comprising 21%), exert almost no greenhouse effect. Instead, the greenhouse effect comes from molecules that are more complex and much less common. Water vapour is the most important greenhouse gas, and carbon dioxide (CO_2) is the second-most important one. Methane, nitrous oxide, ozone and several other gases present in the atmosphere in small amounts also contribute to the greenhouse effect. In the humid equatorial regions, where there is so much water vapour in the air that the greenhouse effect is very large, adding a small additional amount of CO_2 or water vapour has only a small direct impact on downward infrared radiation. However, in the cold, dry polar regions, the effect of a small increase in CO_2 or

(continued)



FAQ 1.3, Figure 1. *An idealised model of the natural greenhouse effect. See text for explanation.*

water vapour is much greater. The same is true for the cold, dry upper atmosphere where a small increase in water vapour has a greater influence on the greenhouse effect than the same change in water vapour would have near the surface.

Several components of the climate system, notably the oceans and living things, affect atmospheric concentrations of greenhouse gases. A prime example of this is plants taking CO_2 out of the atmosphere and converting it (and water) into carbohydrates via photosynthesis. In the industrial era, human activities have added greenhouse gases to the atmosphere, primarily through the burning of fossil fuels and clearing of forests.

Adding more of a greenhouse gas, such as CO_2, to the atmosphere intensifies the greenhouse effect, thus warming Earth's climate. The amount of warming depends on various feedback mechanisms. For example, as the atmosphere warms due to rising levels of greenhouse gases, its concentration of water vapour increases, further intensifying the greenhouse effect. This in turn causes more warming, which causes an additional increase in water vapour, in a self-reinforcing cycle. This water vapour feedback may be strong enough to approximately double the increase in the greenhouse effect due to the added CO_2 alone.

Additional important feedback mechanisms involve clouds. Clouds are effective at absorbing infrared radiation and therefore exert a large greenhouse effect, thus warming the Earth. Clouds are also effective at reflecting away incoming solar radiation, thus cooling the Earth. A change in almost any aspect of clouds, such as their type, location, water content, cloud altitude, particle size and shape, or lifetimes, affects the degree to which clouds warm or cool the Earth. Some changes amplify warming while others diminish it. Much research is in progress to better understand how clouds change in response to climate warming, and how these changes affect climate through various feedback mechanisms.

consistently obtained widely varying results by trying other techniques of incorporating cloud microphysical processes and their radiative interactions (e.g., Roeckner et al., 1987; Le Treut and Li, 1991), which differed from the approach of Senior and Mitchell (1993) through the treatment of partial cloudiness or mixed-phase properties. The model intercomparisons presented in the TAR showed no clear resolution of this unsatisfactory situation.

The scientific community realised long ago that using adequate data to constrain models was the only way to solve this problem. Using climate changes in the distant past to constrain the amplitude of cloud feedback has definite limitations (Ramstein et al., 1998). The study of cloud changes at decadal, interannual or seasonal time scales therefore remains a necessary path to constrain models. A long history of cloud observations now runs parallel to that of model development. Operational ground-based measurements, carried out for the purpose of weather prediction, constitute a valuable source of information that has been gathered and analysed by Warren et al. (1986, 1988). The International Satellite Cloud Climatology Project (ISCCP; Rossow and Schiffer, 1991) has developed an analysis of cloud cover and cloud properties using the measurements of operational meteorological satellites over a period of more than two decades. These data have been complemented by other satellite remote sensing data sets, such as those associated with the Nimbus-7 Temperature Humidity Infrared Radiometer (THIR) instrument (Stowe et al., 1988), with high-resolution spectrometers such as the High Resolution Infrared Radiation Sounder (HIRS) (Susskind et al., 1987), and with microwave absorption, as used by the Special Sensor Microwave/Imager (SSM/I). Chapter 8 provides an update of this ongoing observational effort.

A parallel effort has been carried out to develop a wider range of ground-based measurements, not only to provide an adequate reference for satellite observations, but also to make possible a detailed and empirically based analysis of the entire range of space and time scales involved in cloud processes. The longest-lasting and most comprehensive effort has been the Atmospheric Radiation Measurement (ARM) Program in the USA, which has established elaborately instrumented observational sites to monitor the full complexity of cloud systems on a long-term basis (Ackerman and Stokes, 2003). Shorter field campaigns dedicated to the observation of specific phenomena have also been established, such as the TOGA Coupled Ocean-Atmosphere Response Experiment (COARE) for convective systems (Webster and Lukas, 1992), or the Atlantic Stratocumulus Transition Experiment (ASTEX) for stratocumulus (Albrecht et al., 1995).

Observational data have clearly helped the development of models. The ISCCP data have greatly aided the development of cloud representations in climate models since the mid-1980s (e.g., Le Treut and Li, 1988; Del Genio et al., 1996). However, existing data have not yet brought about any reduction in the existing range of simulated cloud feedbacks. More recently, new theoretical tools have been developed to aid in validating parametrizations in a mode that emphasizes the role of cloud processes participating in climatic feedbacks. One such approach has been to focus on comprehensively observed episodes of cloudiness for which the large-scale forcing is observationally known, using single-column models (Randall et al., 1996; Somerville, 2000) and higher-resolution cloud-resolving models to evaluate GCM parametrizations. Another approach is to make use of the more global and continuous satellite data, on a statistical basis, through an investigation of the correlation between climate forcing and cloud parameters (Bony et al., 1997), in such a way as to provide a test of feedbacks between different climate variables. Chapter 8 assesses recent progress in this area.

Annex 38

Z. Yang, "An Analysis of Technology Transfer as a Response to Climate Change",
Copenhagen Consensus on Climate, 2009

An Analysis of Technology Transfers as a Response to Climate Change

Zili Yang



COPENHAGEN CONSENSUS CENTER

COPENHAGEN CONSENSUS ON CLIMATE

An Analysis of Technology Transfers as a Response to Climate Change

Zili Yang, Professor of Economics
State University of New York at Binghamton

This is an assessment report on technology transfer issues prepared for the Copenhagen Consensus on Climate Change. I thank Christian Bjornskov and David Popp for their insightful comments and suggestions on the earlier draft of this paper.

Copenhagen Consensus Center
Copenhagen Business School
Solbjerg Plads 3
DK-2000 Frederiksberg
Denmark

+45 3815 2255
info.ccc@cbs.dk
www.copenhagenconsensus.com

PREFACE

ABSTRACT

Climate change poses daunting challenges to the future of humanities. Technology transfer is an effective and comprehensive approach for dealing with climate change. International cooperation on greenhouse gas mitigation and adaptation of climate change all involve in transfers of mitigation technologies or dissemination of knowledge on climate change. Technology transfer is an inseparable component of any policy response of GHG mitigation and adaptation to climate change. In this paper, we briefly define the scope of technology transfer in climate change; concisely survey the literature regarding technology transfer issues.

The central theme of this assessment paper is to provide a tentative estimation of benefit and cost ratio (B/C ratio) of technology transfers in climate change. Technology transfer is an encompassing notion in climate change policies because mitigation and adaptation all requires technologies. Quantifying B/C ratio of technology transfer is extremely difficult due to diversity of technologies and different institutional setting of transfers. In this paper, we adopt an indirect approach to estimate B/C ratio of technology transfer. Namely, we capture the financial transfer flows - the dual part of technology transfer flows. Using the RICE model, the optimal financial transfers that facilitate technology transfers are calculated under two representative policy scenarios and two different discount rates. The B/C ratios are estimated from the model solutions.

Major findings include: magnitudes of technology transfers are policy-related and vary significantly in different policy scenario; enabling technology transfers always have net gains thus are desirable; assessing the benefits and costs of technology transfers have to be in connection with the underlining policies; promoting tangible and intangible technology transfers is crucial for dealing with climate change.

COPENHAGEN CONSENSUS ON CLIMATE

The Copenhagen Consensus Center has commissioned 21 papers to examine the costs and benefits of different solutions to global warming. The project's goal is to answer the question:

"If the global community wants to spend up to, say $250 billion per year over the next 10 years to diminish the adverse effects of climate changes, and to do most good for the world, which solutions would yield the greatest net benefits?"

The series of papers is divided into Assessment Papers and Perspective Papers. Each Assessment Paper outlines the costs and benefits of one way to respond to global warming. Each Perspective Paper reviews the assumptions and analyses made within an Assessment Paper.

It is hoped that, as a body of work, this research will provide a foundation for an informed debate about the best way to respond to this threat.

COPENHAGEN CONSENSUS CENTER

CONTENTS

Introduction 5

Describing Technology Transfers 5
- 2.1. The Definition of Technology Transfers 6
- 2.2. Transfer Issues in the Literature 7
- 2.3. Technology Transfers in Practice 7

Cost Benefit Analysis of TT under Different Assumptions and Policy Backgrounds 8
- 3.1 Backgrounds and assumptions 8
- 3.2. Methodologies 9
- 3.3. Calculation results of cost benefit analysis 12

Conclusions 16

References 17

INTRODUCTION

Climate change is a persevering challenge faced by entire humanities in the 21st century and beyond. Economic activities since the industrial revolution, mainly fossil fuel combustions and agriculture, have emitted huge amounts of greenhouse gases (GHGs) into the atmosphere. The anthropogenic GHG emission is the main source for measureable atmospheric temperature increases over the past decades (IPCC, 2007). Economists predict that global GHG emissions will keep increasing in the future, which will lead to further temperature increase. The climate that human beings have been used to for centuries will change drastically (IPCC, 2007).

The detrimental impacts of climate change have long-lasting, sometimes irreversible, consequences. To alleviate these impacts, international cooperation on GHG emission reduction is urgently called for. The United Nations framework Convention on Climate Change (UNFCCC), established in 1992, has been the grand institutional setting for potential international cooperation on climate change. Technology transfers as the means of international cooperation and concrete approach of GHG mitigation have been at the center of policy debates and on the negotiation table.

International community has recognized the vital importance of technology transfer in coping with climate change. Without technology transfers, "it may be difficult to achieve emission reduction at a significant scale." (IPCC, 2007) Technology transfer should be a key component of any effective GHG mitigation strategies. Therefore, comprehensive studies of technology transfer issues are crucial to GHG mitigation policy designs and implementations.

In this assessment paper, I survey the scope of issues surrounding technology transfers in the context of climate change and conduct some rudimental cost benefit analysis on a few options of technology transfers. The remaining parts of the paper are organized as follows: Section 2 contains general discussions and surveys on technology transfers; Section 3 is the cost benefit analysis of transfer issues under different assumptions and policy backgrounds; Section 4 contains some concluding thoughts.

DESCRIBING TECHNOLOGY TRANSFERS

Technology transfer (TT) is an encompassing theme in policy discussions of climate change. In the text of UNFCCC, "transfer of technologies" is identified as the means for mitigating GHG emissions and adapting the impacts of climate change (UNFCCC, Articles 4, 9, and 11). In subsequent 14 sessions of Conference of Parties (COP), decisions made on "development and technology transfer" appeared 12 times (all but COP – 6 and COP – 9). The Clean Development Mechanism (CDM), an important channel for potential transfers of GHG mitigation technologies, is the treaty contents of the Kyoto Protocol (Article 14). Since the inception of IPCC in 1988, technology transfer has been a perpetual theme on its agenda. All 4 assessment reports of IPCC (IPCC, 1992, 1996, 2001, 2007) contain detailed analysis of TT issues. In 2000, IPCC published a special report on technology transfer, titled ***Methodological and Technological Issues in Technology*** Transfer (IPCC, 2000a). This volume of over 400 pages, collaborated by over 200 contributors, is the most comprehensive study on TT in the context of climate change.

Transfer of environmentally sound technologies (EST) from developed countries to developing countries plays a key role in mitigation and adaptation in climate change; technology diffusions among developed countries also enhance the effectiveness of GHG mitigation efforts. COP documents and IPCC reports demonstrate the vital importance of technology transfers in dealing with climate change.

2.1. The Definition of Technology Transfers

The concept of technology transfer can be very broad. Here we quote the definition of technology transfer from IPCC (2000a): "[technology transfer is] a broad set of processes covering the flows of know-how, experience and equipment for mitigating and adapting to climate change amongst different stakeholders such as governments, private sector entities, financial institutions, NGOs and research/education institutions". Nevertheless, TT may convey varied connotations by scholars or decision makers under different contexts. The above definition is a balanced one.

The description of TT concept contains several components. In TT processes, there are providers/donors and recipients. Providers/donors are generally from developed countries; recipients are in developing countries. A TT process takes place across borders. The entities (stakeholders) in a TT process can be governments, NGOs, international agencies, or private sectors. In this assessment paper, we use developed countries (North) and developing countries (South) as "proxies" for entities in TT processes.

TT processes involve primary flows and dual flows. The primary flow is tangible technologies or intangible "know-how" from developed countries to developing countries; the dual flow is the money that finances the TT. While the sources and destinations of the primary flows are transparent (from North to South), the directions of the dual flows can be complicated. If developed countries fund the TT process, money flows from North to South; if the TT process is a part of international trade transaction, money flows from South to North.

The institutional setting and market structure of TT processes are diverse. Both governments and international organizations sponsor and channel TT. Some exemplary projects of TT have governmental backings on both sides. For example, many EST projects have been launched under the auspice of OECD/IEA (Philibert, 2004); sizeable TT projects are under way under the framework of CDM (de Connick etc., 2007). In these circumstances, North is properly called "donor." Nevertheless, many TT activities are mixed in commercial trades or are parts of foreign direct investments (FDI) (Less and McMillan, 2005). In such setting, technology is sold to developing countries by developed countries. Thus North is a "provider" (of technology) not a "donor."

The implementation of TT includes a litany of possible projects and measures in many sectors in developing countries. The tangible TTs take place in energy supply, transportation, agriculture, and many other industries; the intangible TTs are spreads of knowledge on more effective energy usage, protecting the global environment, etc. The intangible TTs permeate from North to South through education and exchange of ideas.

2.2. Transfer Issues in the Literature

Over the past decade, studies of transfer issues in the context of climate change have been extensive. Hundreds, if not thousands, of scholarly papers, reports, and documents have been devoted to TT in climate change. The literature on transfers can be categorized in four strands:

i. The publications by IPCC. Discussions of TT in ARs (IPCC, 1996, 2001, 2007) and Special Report on TT (IPCC, 2000a) represent collective understanding of TT in climate change by international communities. They also offer policy guidelines for implementing TT projects. Particularly, IPCC (2000a) is a rich source of TT literature. Its bibliographies in chapters include hundreds of articles and documents on all aspects of TT issues.

ii. Independent studies of TT issues in the context of climate change. Many peer-reviewed articles as well as reports assess TT issues outlined in UNFCCC and the Kyoto Protocol. For example, Ellis et al. (2004) reviewed the progress and outlook of CDM; Brewer (2008) examined the institutional and legal aspects of TT issues; Saggi (2004) surveyed the relationship between trade, FDI, and TT; Martinot et al. (1997) engaged in country studies of TT in climate change. The literature on broad issues related to technologies is a huge reservoir. Comprehensive survey requires extensive volumes.

iii. Transfer issues in international environmental agreement (IEA) studies. Climate change stimulates the studies of IEA by game theorists and environmental economists. Transfers in IEA studies, an abstract monetary transfer that is broader than TT as defined in UPCC (2000a), are widely adopted to ensure the formation of IEA. In numerical simulations of IEA models, the transfer amounts are quantified. In this line of the literature, timing and intensity of transfers are not in consideration. The amounts and directions of transfers sometimes are questionable from policy perspective.[1]

iv. Transfer issues in integrated assessment modeling (IAM) of climate change.[2] In most IAMs, various financial transfer mechanisms are introduced to calculate "efficient" GHG mitigation policies. Economic theories state that a global GHG mitigation policy is efficient when marginal costs (MC) of GHG mitigation are equalized across regions. Such MC equalization requires financial transfers. The interpretation of material flow counterpart of such transfers is TT. The transfer amounts and directions in IA models are much more reasonable than those in (iii). Nevertheless, the speed of TT or "absorptive capacity" of recipients is not considered in these models. Such restrictions always exist in real economies (Borensztein et al., 1998).

2.3. Technology Transfers in Practice

The history of TT is as long as that of international trade. TTs targeted at coping with climate change have grown in the past decade. Many TTs project between developed and developing countries are in negotiation processes. IPCC (2000a) includes 30 case studies of TT in GHG mitigation and adaptation of climate change. The diversity of these projects shows promising potentials of TT in

1 The literature in this field is abundant. Because they are not connected to the issues in this assessment paper, we do not survey them here.

2 For comprehensive descriptions of major IAMs, see Energy Modeling Forum 22 at http://emf.stanford.edu

the future international cooperation on climate change. Nevertheless, the scopes and magnitudes of TT projects thus far fall short of demanding tasks of global GHG mitigation.

COST BENEFIT ANALYSIS OF TT UNDER DIFFERENT ASSUMPTIONS AND POLICY BACKGROUNDS

3.1 Backgrounds and assumptions

TT is an important and all-inclusive option for GHG mitigation and adaptation of climate change. All perceivable international cooperation on climate change is necessarily implemented through TT directly or indirectly. Cost-effective GHG mitigation policies require that mitigation costs are equal at margin for all regions. When developed countries helping developing countries in their GHG mitigation efforts with money, TTs are behind such financial transfers. Regardless of institutional setting, such as CDM, JI, or FDI at private sectors, TTs are material counterparts of financial transfers from North to South.

Due to the "all-inclusive" characteristics of TT issues, TT as a "solution" option for climate change always encompasses with other "solutions" in this assessment paper series. If GHG mitigation and adaption measures takes place domestically (traditional or alternative), the TT does not occur; if GHG mitigation in developing countries is supported with technologies from developed countries, TT is in play. In latter case, TT offers incremental benefits to solving climate change. In figurative terms, we try to quantify the cost and benefit of the second T in TT while treating the first T as a pre-condition. However, it is difficult to credit a share of potential gains of trans-boundary mitigation activities to TT or to mitigation itself. Conventional cost-benefit analysis approach is not valid here.

It is widely recognized that the scope and costs of TTs are very difficult to quantify, as concluded in IPCC SR (2000a) that "little is known about how much climate-relevant hardware is successfully 'transferred' annually." Cost estimates on individual TT projects are hard to aggregate into regional or global levels. Intangible TTs, such as capacity building and education, are not quantifiable monetarily, especially for their potential benefits in long-run. In addition, the future of technological progresses often turns out to be unpredictable. Therefore, cost benefit analysis of TT as a "solution" for climate change cannot base on a plethora of project evaluations. In other words, direct engineering approach is not feasible for such assessment. We must adopt an indirect economic approach.

The tentative analysis provided in this assessment paper is established on the "dual" side of material flows of TT. Namely, we follow the financial transfers associated with TT. In the literature, financial flows are accepted as "proxies" for TT with qualifications (IPCC, 2000a). In IPCC (2000a), "financial resource flows" are used to track historical trends and patterns of TT in climate change. In fact, any financial flows in the context of climate change necessarily have material flow counterparts. Such material flows are TTs defined in the previous section. However, there are caveats in this approach. To make the analysis more credible and to avoid misunderstanding, the assumptions for the analysis framework need to be elaborated.

i. Intangible TTs are not included in the analysis. From cost benefit analysis point of view, the costs of spreading "know-how" are very low but the "intangible" benefits are huge. For the reasons stated previously, such benefits are difficult to quantify. Furthermore, the impacts of intangible TTs do not transpire directly or immediately into GHG mitigation measures. Having said so, the potential contribution of intangible TT to GHG mitigation and adaptation to climate change can be tremendous in the long run, as the impacts of technology spillovers on other dimensions of societies (Keller, 2004).

ii. Financial transfers are efficient. The assumption implies that a unit of financial transfer is backed by TT at competitive market price. In addition, TTs are applied to the most cost-effective sectors for GHG mitigation or adaptation of climate change in developing countries. Thus, the financial transfers represent the efficient allocations of mitigation technologies worldwide. Admittedly, such "low-hanging fruits" principle may not be the case in real life. For example, EU and China are negotiating on transferring advanced carbon sequestration technologies now despite large portion of Chinese energy supplies continue using out-of-date inefficient technologies.

iii. Broad interpretation of financial transfers follows category (iv), not category (iii), in the literature reviews. In IEA studies, transfers are used as tools to facilitate the formation of coalition. Institutional reality and practicality of transfers are not considered in these types of models. In the numerical simulations of coalition models, the transfer values at billion even trillion dollars can flow into any regions on annual basis. On the other hand, IA models are more attentive to data calibration and are policy oriented. Forecasting scenarios and policy solutions in IAMs are based on the best knowledge of the modelers and consensus among the peers. In these IA models, transfer channels are set up in such way that sole purpose of its presence is to ensure cost-effective GHG mitigation globally. The magnitude and directions of transfers are much more realistic in IAMs. Consequently, transfers in IAMs are the best reflection of TTs. Nevertheless, the "absorptive capacity" is not considered in most models.

iv. Optimal TTs are policy dependent or policy-driven. Different GHG mitigation policy scenarios require different transfer regimes. Particularly, when regions fulfill their international GHG mitigation obligations, such as set by the Kyoto Protocol, they may offer transfers (developed countries) or receive transfers (developing countries) to achieve their mitigation targets collectively. Transfer amounts and directions are determined by policy targets. Assessing GHG mitigation policies, TT is a part of larger picture and seldom a whole picture. For example, many pilot projects under CDM framework of the Kyoto Protocol are parts of donors' and recipients' cooperation on GHG mitigation. One cannot say that CDM projects represent the entirety of donors or recipients GHG mitigation policy.

3.2. Methodologies

As mentioned above, the cost benefit analysis here targets at "transfer", not "technology." There are at least three measurements of B/C ratios of TT. The first is defined as follows: the costs are measured at total mitigation cost under the TT scheme; the benefits are measured

as total mitigation cost reduction without the transfers. Here B is avoided high mitigation costs and C is actually incurred mitigation costs.

Optimal TTs always have net gains, otherwise they do not happen. Based on these observations, the second measurement of B/C ratios of TT is follows: the cost is measured at total financial transfer amount T; the benefit is the net gains in mitigation cost reductions from the TT scheme. Namely, B/C ratio is defined as: $(B_1-C_1)/T$. Here B_1 and C_1 are benefit and cost calculated in the first measurement. In this assessment paper, we present both measurements.

The third measurement is broader, but probably vague. We use reduced climate damage (compared with business as usual (BaU) scenario) in policy scenario with TT as the benefit of TT; transfer amounts incurred in the policy as the cost. Here B/C ratio is defined as $\Delta D/T$.

Because TT is associated with GHG mitigation activities and particular policies, separating cost and benefit of TT from mitigation itself can be tricky. TT should not take credit for the total benefit of whole mitigation efforts. The contribution of TT may be large, may be small. For example, in two mitigation policy scenarios involving TT, the inferior one with lower overall B/C ratio might have higher B/C ratio from TT. In a simple arithmetic expression: when $B_{t,1} > B_{t,2}$, it does not imply that $B_1/C_1 > B_2/C_2$ (here $B_{t,1}$ and $B_{t,2}$ are benefits from TT in policy #1 and #2; B_1, C_1 and B_2, C_2 are total benefits and costs of policy #1 and #2 respectively).

We use the following hypothetical example to illustrate first two B/C measurements. Suppose achieving certain mitigation target incurs 10 million dollars of cost globally without TT. A TT scheme with 1 million dollars transfers combining with domestic mitigation efforts reduces the global mitigation cost to 8 million dollars. The benefit (avoided high costs) B = 10 million dollars; the cost (actually incurred) C = 8 million dollars; B/C ratio is: B/C = 10/8 = 1.25 in the first measurement. The net gains from TT here are (10-8) = 2 million dollars. The second measurement of B/C ratio is $(B_1-C_1) / T = (10-8)/1 = 2$.

There are different approaches to assess a project or policy in cost benefit analysis (Layard, 1994). It is difficult to claim that one B/C ratio measurement is always superior to another, at least in the case here. The three B/C ratio measurements cover different aspects of TT. The complementary nature renders them both useful.

Using the above mentioned three measurements of B/C ratios, this paper conducts cost benefit analysis of TT in the RICE model developed by Nordhaus and Yang (1996). Estimation methodologies are heavily relied on Yang (1999), Yang and Nordhaus (2006), and Yang (2008). The RICE model is a multi-region extension of aggregate DICE model (Nordhaus, 1994, 2008). Regional breakdown of RICE is essential for modeling TT issues because transfers flow across borders.

To set up the model for dealing with TT issues, financial transfers are introduced in the RICE in such ways that the transfer costs of donors (developed countries) are deducted from their GDP, the transfers go into the GHG mitigation functions of recipients (developing countries). The purpose of transfer is to mitigate GHG emissions more cheaply in recipient countries. The donors benefit from the transfer through reduced climate change impacts. Such model

structure rules out the effects of pure welfare transfers that monies go directly into developing countries' treasury and nothing happen to GHG mitigation.[3] The modeling methodology is proper for connecting financial transfer to TT. Finally, the transfer amounts are endogenous. The model solution reflects the optimal transfers under a given policy scenario.

For this assessment paper, two policy scenarios (solution categories) are proposed for cost benefit analysis of TT. The first is the Kyoto Protocol like scenario that lasts for the entire modeling horizon. In this case, developing countries do not obligate to reduce their baseline GHG emissions. They will mitigate GHG emissions, if developed countries pay them to do so through CDM, JI, or FDI. On the technology part, all mitigation efforts in South use the technologies provided by North. North takes credits for the outcome. The final outcome of such TT scheme is equalization of marginal costs of GHG mitigation across all regions. Using the "fruit" metaphor, all "fruits", low hanging or high hanging, in Southern orchard, are picked with North technologies and financed with Northern money. The harvesting activities in Southern orchard will go on until all untouched fruits hang at the same height as the remaining fruits in Northern orchard.

In the second scenario, developing countries shoulder certain GHG mitigation obligations that are compatible with their own incentives (considering climate change impacts on them).[4] After developing countries fulfill their mitigation obligations, developed countries will help developing countries on further GHG mitigation, through TT, to achieve a globally cost-effective GHG mitigation outcome. A scenario of international cooperation on GHG mitigation like this has been a target sought by some developed countries in post-Kyoto negotiations. Particularly, GHG mitigation commitment by major developing countries, such as China, India, and Brazil, is probably the focal agenda in the coming Copenhagen COP-15. In this scenario, developing countries with their indigenous technologies will exploit the "low hanging fruits" mitigation opportunities. For example, it is not necessary to use advanced technology from Europe to replace all old coal burning technologies in China. Equipments with mature technologies and manufactured in China can improve the fuel efficiency sufficiently.

In calculation of TTs in the above two scenarios, how much the global community wants to spend on TT is based on the optimal solution of the model under the given policy scenario, not prescribed. We cannot phrase the TT issue by treating the amount of TT as exogenous, such as "what is the cost and benefit of spending 1 billion dollars on TT in a year." Our calculations of B/C ratios are ex-post or side calculations after policy driven TTs, along with other control and state variables, are solved endogenously.

Many other TT scenarios in parallels can be proposed. The above two probably locate on the polar ends of potential roles of TT. Due to volume limitation of this paper, technical aspects of modeling are not fully explained here. Readers can find the detailed modeling methodologies in RICE that are related to the scenarios here in the papers and the book cited above.

3 In most IAMs, the distributional (wealth) effects of transfers are not separated from GHG mitigation cost reduction effects. Therefore, financial transfers in these models probably are over-estimate optimal TT volumes.

4 More specifically, the policy scheme is close to the Lindahl equilibrium outcome in Yang (2008). Each region's initial mitigation obligation is based on respective 'willingness to pay" principle.

3.3. Calculation results of cost benefit analysis

The time frame of the calculation follows the guideline set for assessment papers. The costs and benefits are expressed as the present values of flows of costs and benefits for 100 years (2005- 2105) at given discount rate (r = 3% and r =5%). In addition, the current values of these flows are also calculated. TTs, costs and benefits associated with them are flows over time. Policy scenarios may affect the timing and volume of TT. Therefore, current value (CV) is a useful piece of information.

We summarize the simulation scenarios as follows:

i. Scenario 1: Kyoto Protocol like case at r = 3% and 5%. In this case, global GHG mitigation outcome is stringent. Much of initial GHG mitigation burdens are on developed countries.

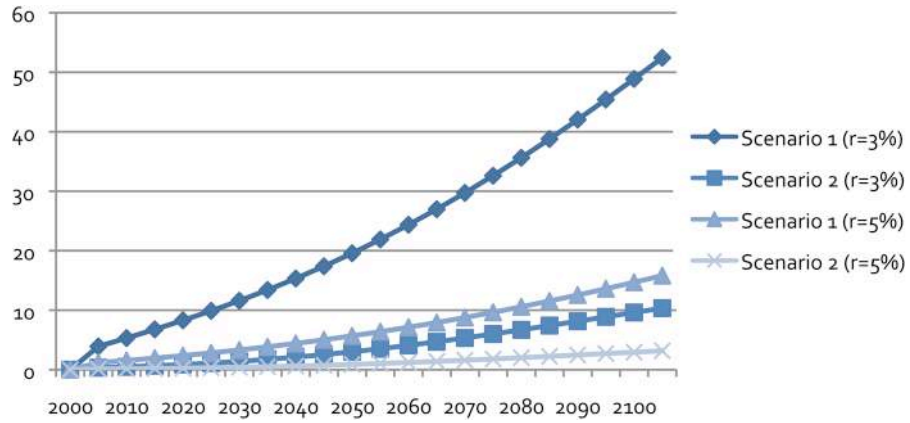
ii. Scenario 2: A full-cooperation case based on willingness to pay principle at r = 3% and 5%. In this case, global GHG mitigation outcome is less stringent, compared with scenario 1. All regions obligate to GHG mitigation based on their mitigation costs and climate damage situations.

The numerical calculations are based on a six-region version RICE model used in Yang (2008). In this version, three regions (USA, European Union, and other high-income countries (OHI)) are donors/providers in TT schemes; the remaining three regions (China (CHI), Former Soviet Union and Eastern European countries (EEC), and the rest of the world (ROW)) are recipients. The model's baseline GHG emission prediction is in the mid-range of IPCC SRES (IPCC, 2000b). The optimal solutions in Yang (2008) are moderate, comparing with other IAMs.

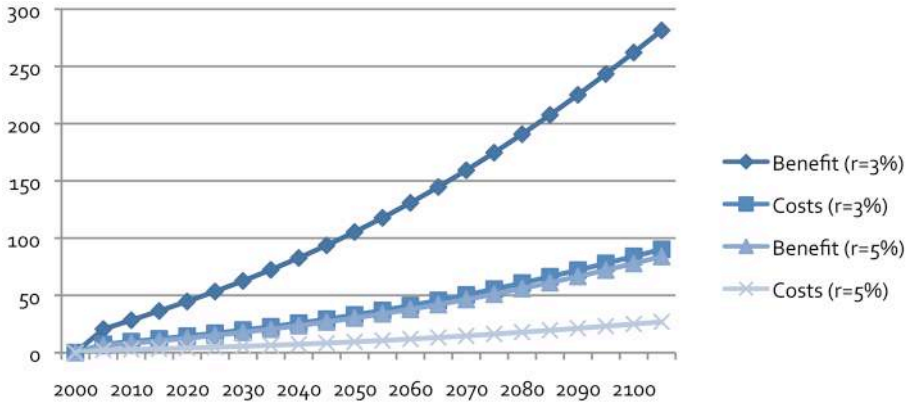
The results of cost benefit analysis of TT are presented in the following three overview tables. The calculations procedure is outlined as follows: first, the optimal solutions without transfers in different scenarios are obtained. This step is as if each region is picking the "low hanging fruits" in GHG mitigation opportunities within the borders, according to their obligations specified by the policy. In the solutions, North always reaches higher "fruits." It implies that North incurs higher mitigation costs than South. Second, the necessary (minimum) amounts of transfers that enable the equalization of marginal mitigation costs are obtained through a set of side-calculations. The outcome reflects that North explores "low hanging fruits" opportunities in South through TT, "returns" some "high hanging fruits" in North, and the total numbers of harvested "fruits" remains the same globally before and after TT. Third, addition calculations are conducted to obtain cost and benefit values according to the definitions discussed in section 3.2.

Other relevant results are presented in the following graphs: Graph 1 contains the optimal transfer flows over time in different scenarios; graph 2 depicts benefit and costs flows, as defined in the first measurement, in Scenario 1; graph3 is the same flows as in graph 2 for Scenario 2. Graphs 2 and 3 capture the shift of mitigation flows caused by TT.

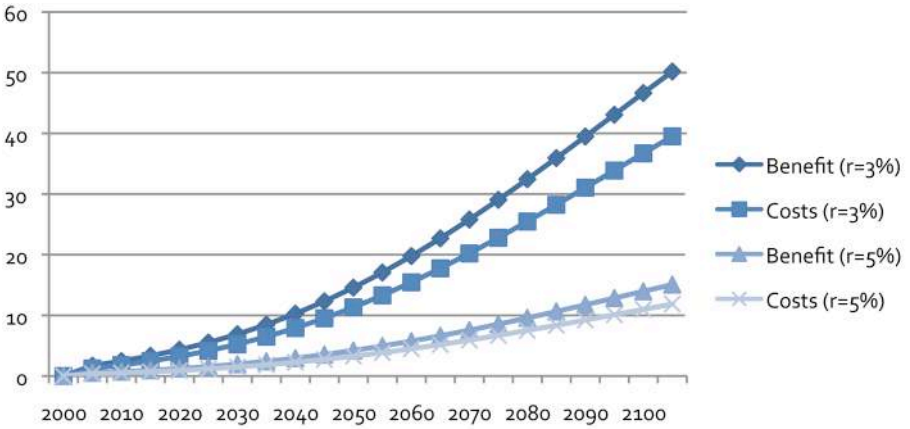
Graph 1. Optimal Transfer Amounts (Billion 2000US$)



Graph 2 Flows of Benefit and Costs (Scenario 1)



Graph 3 Flows of Benefit and Costs (Scenario 2)



Overview Table 1 Present Value of Total Global Benefits and Costs of TT in 100 Years (the First Measurement) (unit: billion 2000 US$)

Scenario 1								
Benefit and Costs	r = 3% Benefit	Costs	CV Benefit	Cost	r = 5% Benefit	Costs	CV Benefit	Cost
	2523	805	13688	4355	347	112	4000	1272
B/C Ratios	3.134		3.143		3.098		3.144	
Scenario 2								
Benefit and Costs	r = 3% Benefit	Costs	CV Benefit	Cost	r = 5% Benefit	Costs	CV Benefit	Cost
	339	262	2160	1688	42	32	637	498
B/C Ratios	1.294		1.280		1.312		1.279	

Overview Table 2 Present Value of Total Global Benefits and Costs of TT in 100 Years (the Second Measurement) (unit: billion 2000 US$)

Scenario 1								
Benefit and Costs	r = 3% Benefit	Costs	CV Benefit	Cost	r = 5% Benefit	Costs	CV Benefit	Cost
	1718	470	9333	2551	236	66	2728	754
B/C Ratios	3.655		3.659		3.576		3.618	
Scenario 2								
Benefit and Costs	r = 3% Benefit	Costs	CV Benefit	Cost	r = 5% Benefit	Costs	CV Benefit	Cost
	77	70	472	445	10	8.5	139	134
B/C Ratios	1.10		1.061		1.17		1.037	

Overview Table 3 Present Value of Total Global Benefits and Costs of TT in 100 Years (the Third Measurement) (unit: billion 2000 US$)

Scenario 1				
Benefit and Costs	r = 3% Benefit	Costs	r = 5% Benefit	Costs
	1221	470	190	66
B/C Ratios	2.60		2.88	
Scenario 2				
Benefit and Costs	r = 3% Benefit	Costs	r = 5% Benefit	Costs
	746	70	112	8.5
B/C Ratios	10.66		13.18	

The above tables and graphs outline the general overviews of TT as reflected by the RICE model. In scenario 1, both the magnitude of and potential gains from TT are huge. Valued with both cost/benefit measurements, B/C ratios are greater than 3 in Scenario 1. In this case, developed countries have to rely on TT to reduce the costs of their GHG mitigation burdens. Here, TT plays the most important role in reducing global GHG mitigation costs. Most GHG mitigation activities in developing countries are financed by developed countries and use imported technologies. Given the burden sharing rule like this, one would wonder why developed countries agree to such arrangement in the first place. TT reduces mitigation costs of developed countries; TT attracts developing countries joining in the global cooperation in GHG mitigation. However, the initial policy setting is not the most desirable one for some regions.

Scenario 2 represents the case in which all "low hanging fruits" of GHG mitigation options in developing countries are exploited domestically with indigenous technologies. Such voluntary actions are based on common concerns about climate change by all regions. Maximum participation by developing countries has been pushed very hard by some developed countries, such as the United States, in post-Kyoto negotiations. On top of domestic efforts with indigenous technologies in developing countries, advanced TTs take place to equalize MC of mitigation costs across all regions after all cheap options are exhausted domestically. In Scenario 2, both the magnitude of and the gains from TT are much lower than they are in Scenario 1. B/C ratios under two measurements are slightly higher than 1. Such result shows that marginal gains from "picking high hanging fruits" are small. The result in this scenario does not imply that technology has little to do with GHG mitigation. It indicates a scenario in which transfer amounts could be moderate. Domestic GHG mitigations need technologies.

The three measurements are basically consistent with one another. They all show that implementing TT create a win-win outcome for both donors/providers and recipients when compared with no TT results. Here we should also indicate that climate damages are predicted to be more severe beyond the 100 year time span for this assessment work. Mitigation efforts in this century, in part, are aimed at reducing climate damage beyond 100 years. Cost benefit measurement truncated in time may under-estimate true benefits, compared with longer time horizon calculation. This caution is applicable for the third measurement.

The two scenarios reflect two extreme situations involving TT. The calculated transfer amounts are the minimal/optimal transfers that equalize the marginal mitigation costs globally. Net of values of intangible TT, the estimated total costs and benefits of TT and transfer amounts in Scenario 1 should be on the upper bound of the potential scope of TT in the next century; those in Scenario 2 should be on the very low bottom of the potential scope of TT in the next century. The actual outcomes of TT are probably somewhere in the middle of the two scenarios. If the values of intangible TT could be included in the estimation, the net benefits of TT in the long run would be much higher.

Finally, all TTs are motivated by specific mitigation policies or international negotiation outcomes. We cannot draw any conclusions on the policies or infer B/C ratios of those policies based on cost benefit analysis of TT alone. In this assessment paper, we do not claim that policies behind Scenario 1 are superior to those in Scenario 2 because the gains from TT are larger. As we emphasized repeatedly, the evaluation of TT has to be in connection with other parts of mitigation and/or adaptation processes. For any GHG mitigation policy,

incorporating TT can reduce the aggregate costs further. Therefore, TT is ubiquitous in optimal GHG mitigation policies.

CONCLUSIONS

TT, in conjunction with other "solution categories" in this series, is an effective option of GHG mitigation and adaptation of climate change. Despite that it is never a stand- alone solution, TT is a part of all meaningful GHG mitigation policies from global perspective. Technology progress is the key for the challenges human beings will be facing in the future. Climate change is one of such challenges. Since climate change is a global phenomenon, international cooperation that involves all nations is necessary for cost-effective GHG mitigations. TT is combination of technology and international cooperation. Therefore, it is an inseparable component of any climate change policies.

In this assessment paper, we conduct the cost benefit analysis of TT in the context of climate change. Cost and benefit analysis of TT at global level and in the long run, is very difficult. Unlike the project evaluation of individual CDM undertaking where costs and benefit (to lesser degree) are measurable, aggregate effects of TT are not simple additions of individual projects. We hope that the indirect methods used here can shed some lights on evaluation of effectiveness of TT in dealing with climate change.

REFERENCES

Borensztein, E., J. De Gregorio, and J-W. Lee, 1998: How does Foreign Direct Investment Affect Economic Growth?, ***Journal of International Economics***, **45**, 115-135

Brewer, T., 2008: Climate Change Technology Transfer: a New Paradigm and Policy Agenda, ***Climate Policy***, **8**(5), 516-526

deConnick, H., F. Haake, N. van der Linden, 2007: Technology Transfer in the Clean Development Mechanism, ***Climate Policy,*** **7**: 444-456

Ellis, J. etc., 2004: CDM: Taking stock and looking forward, ***Energy Policy,*** **32**(1), 15-28.

IPCC, 1996: ***Climate Change 1995, the Second Assessment Report***, Cambridge University Press, Cambridge, UK.

IPCC, 2000a: ***Methodological and Technological Issues in Technology Transfer***, Cambridge University Press, Cambridge, UK

IPCC, 2000b: ***Emission Scenarios***, Cambridge University Press, Cambridge, UK

IPCC, 2001: ***Climate Change 2000, the Third Assessment Report***, Cambridge University Press, Cambridge, UK.

IPCC, 2007: ***Climate Change 2007, the Fourth Assessment Report***, Cambridge University Press, Cambridge, UK.

Keller, W., 2004: International Technology Diffusion, ***Journal of Economic Literature***, **42**(3), 752-782.

Layard, R., 1994: ***Cost-Benefit Analysis***, Cambridge University Press, Cambridge, UK.

Less, C. and S. McMillan, 2005: Achieving the Successful Transfer of Environmentally

Sound Technologies: Trade-Related Aspects, ***OECD Trade and Environment Working Paper,*** 2005-02.

Martinot, E., J. Sinton, and B. Haddad, 1997: International Technology Transfer for Climate Change and the Cases of Russia and China, ***Annual Reviews of Energy and Environment*** **22**, 357-401.

Nordhaus, W. D., 1994: ***Managing the Global Commons***, the MIT Press, Cambridge, MA

Nordhaus, W. D., 2008: ***A Question of Balance***, Yale University Press, New Haven, CT.

Nordhaus, W. D. and Z. Yang, 1996: A Regional Dynamic General-Equilibrium Model of Alternative Climate-Change Strategies, ***American Economic Review***, **86**(4), 741-765.

Philibert, C. 2004: International Energy Collaboration and Climate Change Mitigation, COM/ENV/EPOC/IEA/SLT (2004) 1

Saggi, K, 2002: Trade, Foreign Direct Investment, and International Technology Transfer: a Survey, ***The World Bank Research Observer***, **17**(2), 191-235

Yang, Z., 1999: Should North Make Unilateral Technology Transfers to South? --- North-South Cooperation and Conflicts in Responses to Global Climate Change, ***Resource and Energy Economics***, **21**(1), 67 – 87

Yang, Z. and W. Nordhaus, 2006: magnitude and Direction of Technological Transfers for Mitigating GHG Emissions, ***Energy Economics,*** **28**, 730-741.

Yang, Z., 2008: ***Strategic Bargaining and Cooperation in Greenhouse Gas Mitigations: An Integrated Assessment Modeling Approach***, the MIT Press, Cambridge, MA.

COPENHAGEN CONSENSUS CENTER

COPENHAGEN CONSENSUS ON CLIMATE

The science is clear. Human-caused global warming is a problem that we must confront.

But which response to global warming will be best for the planet? The Copenhagen Consensus Center believes that it is vital to hold a global discussion on this topic.

The world turned to scientists to tell us about the problem of global warming. Now, we need to ensure that we have a solid scientific foundation when we choose global warming's solution. That is why the Copenhagen Consensus Center has commissioned research papers from specialist climate economists, outlining the costs and benefits of each way to respond to global warming.

It is the Copenhagen Consensus Center's view that the best solution to global warming will be the one that achieves the most 'good' for the lowest cost. To identify this solution and to further advance debate, the Copenhagen Consensus Center has assembled an Expert Panel of five world-class economists – including three recipients of the Nobel Prize –to deliberate on which solution to climate change would be most effective.

It is the Copenhagen Consensus Center's hope that this research will help provide a foundation for an informed debate about the best way to respond to this threat.

COPENHAGEN CONSENSUS CENTER

The Copenhagen Consensus Center is a global think-tank based in Denmark that publicizes the best ways for governments and philanthropists to spend aid and development money.

The Center commissions and conducts new research and analysis into competing spending priorities. In particular it focuses on the international community's efforts to solve the world's biggest challenges.

www.copenhagenconsensus.com

Annex 38 bis

J. D. Campbell et al., “Future climate of the Caribbean from a regional climate model”, *International Journal of Climatology*, 2010, pp. 1866-1878

INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. (2010)
Published online in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/joc.2200

RMetS
Royal Meteorological Society

Future climate of the Caribbean from a regional climate model

Jayaka D. Campbell, Michael A. Taylor,* Tannecia S. Stephenson, Rhodene A. Watson and Felicia S. Whyte

The Climate Studies Group Mona, The University of the West Indies, Mona, Kingston 7, Jamaica, West Indies

ABSTRACT: Scenarios of rainfall and temperature changes for the period 2071–2100 under the A2 and B2 Special Report on Emissions scenarios are examined using the Hadley Centre Providing Regional Climates for Impacts Studies regional climate model. The model simulates 'present-day' (1979–1990) rainfall and temperature climatologies reasonably well, capturing the characteristic bimodality of Caribbean rainfall and the boreal summer maximum and winter minimum temperatures. Seasonal spatial patterns are also reproduced, but rainfall amounts are underestimated over the northern Caribbean island masses, including Cuba, Jamaica, Hispaniola and Puerto Rico. Temperatures over the region are also overestimated by 1–3 °C. For the period 2071–2100, temperatures are projected to increase across the region by 1–4 °C for all months irrespective of the scenario. The rainfall response varies with season with one of the more robust changes being an intensification of a gradient pattern in November–January, in which the northern Caribbean (i.e. north of 22°N) gets wetter and the southern Caribbean gets drier. There is also a robust June–October drying signal. The results point to changes in the regional circulation patterns due to the human-induced climate change and warrants further investigation. Copyright © 2010 Royal Meteorological Society

KEY WORDS climate change; Caribbean; scenarios; rainfall; temperature

Received 23 February 2009; Revised 12 June 2010; Accepted 16 June 2010

1. Introduction

In recent times, due to both anthropogenic and natural effects, the earth's climate has been changing. Globally, mean surface temperatures have increased by approximately 0.74 ± 0.18 °C since the turn of the 19th century [Inter Governmental Panel on Climate Change (IPCC) Fourth Assessment Report] (Solomon *et al*., 2007), with further increases projected through the end of the century. This will result in shifts in regional rainfall and temperature regimes and climate extremes (Solomon *et al*., 2007).

Station observations in the Caribbean (Figure 1) show a statistically significant warming trend over the latter half of the 20th century (Peterson *et al*., 2002). Future shifts in climate regimes will have implications for the developing states within the Caribbean given the climate sensitivity of their economies (Jury, 2009). Caribbean states largely rely on sectors such as tourism or agriculture for economic sustainability and growth. The generation of climate change projections and scenarios for the Caribbean at appropriate scales is therefore an important exercise particularly for long-term planning.

Global climate models (GCMs) are the most common tools for investigating climate change and making projections for the future. GCMs are mathematical representations of physical processes in the atmosphere, ocean, cryosphere and land surface. They represent the climate using a three-dimensional grid over the globe, typically with a horizontal resolution between 125 and 600 km, 10–20 vertical layers in the atmosphere and as many as 30 ocean layers. In recent decades, the evolution of GCMs has allowed for a much better scientific understanding of anthropogenic global climate change, much of which has been reported in the IPCC's Assessment Reports (Solomon *et al*., 2007). In the Caribbean, GCM realizations have been used to project a 1–2 °C temperature rise by the mid-2050s and increases in sea-surface temperatures and vertical windshear (Singh, 1997a, 1997b; Angeles *et al*., 2006) under a 'business as usual' scenario. Other GCM-based rainfall projections for the region suggest (1) a slight decline in annual rainfall ($-6.8 \pm 15.8\%$) (Nurse and Sem, 2001); (2) a slight increase in December–February rainfall (Nurse and Sem, 2001); (3) a decrease in June–August rainfall (Nurse and Sem, 2001); (4) an increase in early and late season rainfall (Angeles *et al*., 2006); (5) a decrease in annual rainy days (Nurse and Sem, 2001; Solomon *et al*., 2007) and (6) an increase in the daily intensity of rainfall (Nurse and Sem, 2001; Solomon *et al*., 2007). Gamble and Curtis

* Correspondence to: Michael A. Taylor, The Climate Studies Group Mona, The University of the West Indies, Mona, Kingston 7, Jamaica, West Indies. E-mail: michael.taylor@uwimona.edu.jm

Copyright © 2010 Royal Meteorological Society

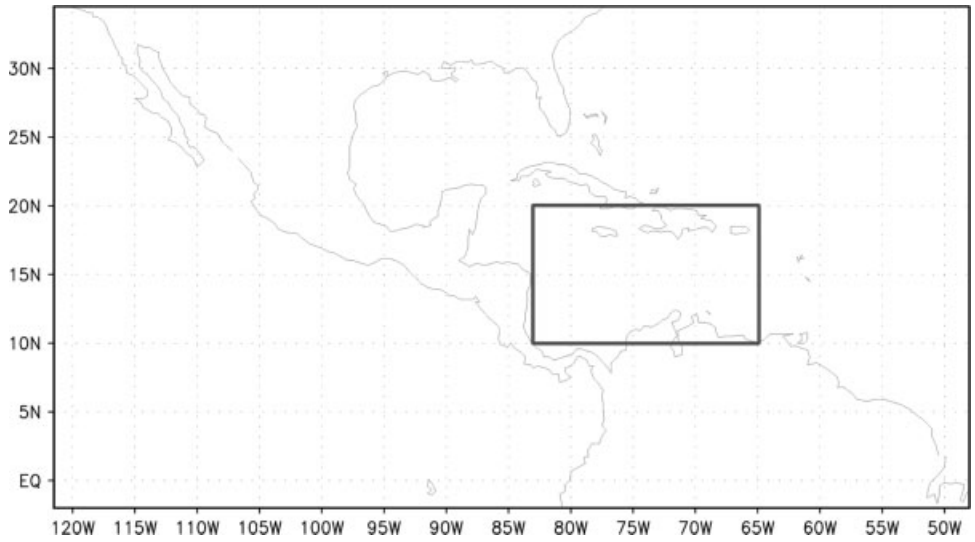


Figure 1. Map showing PRECIS domain over the Caribbean and adjacent Caribbean region. The box shows the Caribbean rainfall index domain as defined by Chen and Taylor (2002).

(2008) present a review of Caribbean rainfall projections from GCMs.

The resolution of global models is, however, too coarse to provide information at the local and regional scales needed for vulnerability assessments and the development of local adaptation strategies (Aldrian *et al*., 2004; Xianfu, 2006). This is particularly true for the Caribbean as most of the small islands are not represented in the GCMs. Regionalization or downscaling techniques are therefore necessary for extracting finer scale information from GCM output, which may prove useful for the impacts and adaptation communities. Downscaling techniques can be classified into three categories: (1) high resolution and variable resolution 'time-slice' Atmosphere GCM experiments; (2) nested limited area (or regional) climate models (RCMs) and (3) empirical/statistical and statistical/dynamical methods (Mearns *et al*., 2003). Each category has its suitability depending on varying criteria including the scale of climate information that is required (see discussions by Wilby and Wigley, 1997; Mearns *et al*., 2003; Dobler and Ahrens, 2008).

This paper has its foundation in type (2) downscaling, and is an examination of climate change projections for the Caribbean region from the Hadley Centre HadRM3P model (Jones *et al*., 2004), which is the RCM within the Providing Regional Climates for Impacts Studies (PRECIS) model. For this study, the RCM is driven with boundary conditions from the HadAM3P GCM. Very few downscaling studies for the Caribbean are to be found in peer review literature (e.g. the sensitivity studies of Castro *et al*., 2006, using the International Centre for Theoretical Physics (ICTP) RegCM3 for the simulation of summer precipitation, temperature and local wind field). The authors are unaware of any studies detailing climate change scenarios for the Caribbean from RCMs. This study not only complements previous modelling work for the Caribbean, but, importantly, also documents for the first time RCM-derived future climates for the region.

The PRECIS regional model has been widely used to develop regional climate change scenarios worldwide and to study extremes (Moberg and Jones, 2004; Tadross *et al*., 2005; Kumar *et al*., 2006; Zhang *et al*., 2006; Bloom *et al*., 2008; Kotroni *et al*., 2008; Islam *et al*., 2009; Marengo *et al*., 2009). Its choice for use in the Caribbean results from a deliberate collaborative effort to develop regional scenarios, which was initiated in 2003. The collaboration included institutions in four Caribbean countries (Belize, Jamaica, Cuba and Barbados) and was driven by the Caribbean Community Climate Change Centre. Details of the PRECIS-Caribbean project are given in Taylor *et al*. (2007). The overall aim is to use multiple RCMs and driving models to generate climate scenarios for the region, as is done in other parts of the world. The use of PRECIS represents an attempt not only to generate initial downscaled projections of climate change for the region, but also to build modelling capacity. The effort also allows for an evaluation of the PRECIS model's ability to simulate the climate of the Caribbean region. This is also reported in this study.

The remainder of the paper is sectioned as follows. Section 2 describes the PRECIS RCM and the subset of model experiments performed. The section also details the datasets used for the validation of the model. Section 3 presents an evaluation of the model skill in simulating present-day Caribbean climate using selected fields. Section 4 examines the model projections and Section 5 presents the summary and discussion of the results.

2. Data and methodology

2.1. Model description

The study uses version 1.3 of the Hadley Centre's regional climate modelling system – PRECIS. The PRECIS RCM is a dynamical downscaling atmospheric and

Copyright © 2010 Royal Meteorological Society

land surface model, which generates regional-scale climate scenarios at a minimum and maximum horizontal resolution of 25 and 50 km, respectively. The model, which is locatable over any part of the globe and is computationally inexpensive, can be used to diagnose a full range of meteorological variables at up to 19 levels of the atmosphere and surface variables on varying timescales. A description of the model's physics is found in Jones *et al*. (2003, 2004).

In this study, lateral boundary conditions for the PRECIS RCM are from the global atmospheric GCM, HadAM3P, which has a horizontal resolution of 1.25° latitude × 1.875° longitude. The model formulation of the HadAM3P is the same as for the PRECIS RCM, thereby promoting consistency between high resolution and global model climate change projections. The PRECIS results reported in this paper derive from (1) a model simulated baseline spanning 1961–1990, which is considered representative of pre-industrialised climate, (2) a full range of different but equally plausible future climate scenarios for the 2071–2100 as gleaned from one realization consistent with each of the Special Report on Emissions (SRES) A2 and B2 emission scenarios, and (3) an actualised climate generated from the model driven by a reanalysis of the European Centre for Medium-Range Weather Forecast (ECMWF) dataset (ERA-15 hereafter) from 1979 to 1993.

The SRES scenarios are plausible representations of future emissions of greenhouse gases based on a coherent and internally consistent set of assumptions about driving forces such as demographics, socio–economic development and technological changes (Nakicenovic *et al*., 2000). The reanalysis simulation is used in the validation of the model. For all the simulations, the sea-surface boundary conditions are derived from recent past observations and from future SSTs formed from the addition of mean changes and trends calculated from the global coupled ocean–atmosphere GCM HadCM3 (Jones *et al*., 2004; Rowell, 2005).

2.2. Domain, data and methodology

Because of the region's location, large-scale influences, which modulate the underlying climatology, come from both the tropical Atlantic and Pacific oceans. These include the north Atlantic subtropical High, the northeast trade wind regime, sea-surface temperatures and their gradients over the tropical Pacific and Atlantic, the Caribbean low-level jet, vertical shear and divergence within the basin, and the effects of transient tropical and extra-tropical systems (detailed reviews of Caribbean climate dynamics are found in the study of Jury, 2009; Gamble and Curtis 2008; Ashby *et al*., 2005). The model's domain was chosen such that it represents an area large enough to allow the development of regional-scale circulations due to the above influences but not large enough to facilitate the RCM deviating from the GCM in the centre of the domain (Kumar *et al*., 2006). The PRECIS experiments were run at the 50 km resolution over 0°–36°N and 55°–120°W (Figure 1). The domain includes the Caribbean, Central America, Florida and the northern territories of South America.

In assessing the model's ability to simulate regional seasonal variability, the baseline and ERA-15 driven model results are first compared with precipitation maps for the Caribbean extracted from the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) datasets (Xie and Arkin, 1997) and surface temperature maps obtained from the National Centers for Environmental Prediction–National Centers for Atmospheric Research (NCEP-NCAR) reanalysis-1 dataset (Kalnay *et al*., 1996). The CMAP dataset is based on gauge observations, satellite estimates and model output constructed on a 2.5° longitude–latitude grid from 1979 to the present. The horizontal resolution for the reanalysis dataset is 2.5° × 2.5°. Because the Caribbean basin is largely ocean, the climatologies of individual islands are to a large extent determined by their location in the background spatial patterns. Consequently, these initial comparisons evaluate the model's ability to capture seasonal variability in the large-scale patterns over the Caribbean basin (a must for any model used over the region), even though it is recognized that the resolutions of the validating datasets are too coarse to enable comparison of the finer details produced by the PRECIS model (Castro *et al*., 2006).

Validation at the scale of the model is however important as further sub-regional climatological variations across the islands are induced by (among other things) the impact of orography and the orientation of the islands (see Hastenrath, 1976; Chen *et al*., 1997; Giannini *et al*., 2000; Chen and Taylor, 2002; Taylor *et al*., 2002 for more on Caribbean climatology). Ideally validation at the RCM scale is done by comparison to station observations, but Caribbean station data are notoriously sparse. Consequently, evaluation of the model biases for seasonal precipitation and temperature fields were done using difference maps between a 0.5° × 0.5° observational dataset from the Climatic Research Unit (CRU) (New *et al*., 2001) and both the ERA-15 and baseline simulations.

Simulated and observed monthly, seasonal and annual time series were also computed for present-day and future periods by averaging over the whole domain (temperature) or over 10°–20°N and 65°–83°W (rainfall). The latter domain coincides with the Caribbean rainfall index of Taylor *et al*. (2002) (Figure 1). The seasons used were February–April (FMA), May–July (MJJ), August–October (ASO) and November–January (NDJ) to be consistent with the seasonality of the region as identified by Chen and Taylor (2002).

In determining climate change scenarios for the region, the absolute change in temperature and percentage change in precipitation for the period 2071–2100 relative to the simulated baseline under the A2 and B2 SRES scenarios were also computed. The changes are depicted using plots of monthly, seasonal and annual change values for the

Copyright © 2010 Royal Meteorological Society

Table I. List of extreme indices and their associated meanings.

Variable name	Definition
Consecutive dry days (CDD)	Maximum number of consecutive days with RR <1 mm
Number of heavy precipitation days (R10)	Annual count of days when PRCP > = 10 mm
Maximum 5-day precipitation amount (Rx5 day)	Monthly maximum consecutive 5-day precipitation
Very wet days (R95p)	Annual total PRCP when RR >95th percentile
Cool nights (TN10p)	Percentage of days when TN <10thpercentile
Cool days (TX10p)	Percentage of days when TX <10th percentile
Warm nights (TN90p)	Percentage of days when TN >90th percentile
Warm days (TX90p)	Percentage of days when TX >90th percentile

Table II. Metadata for eight Caribbean stations.

Station	Country	Metadata	Data	
			Length (years)	Missing (%)
Le Raizet	Guadeloupe	16.27N 61.60W	25	38.7
Freeport	Bahamas	26.55N 78.70W	23	25.7
Worthy Park	Jamaica	18.50N 77.92W	40	30.4
Catie	Costa Rica	9.90N 63.75W	43	15.7
Casa Blanca	Cuba	23.17N 82.35W	43	0
Santa Rosa de Copan	Honduras	14.78N 88.78W	43	3.5
Picaro Iap	Trinidad & Tobago	10.37N 61.21W	43	7.2
Hewanorra	St. Lucia	13.75N 60.95W	35	7.1

Caribbean rainfall and temperature indices defined above and using seasonal and annual spatial maps.

Finally, an attempt was made to assess the model's ability to (1) simulate current trends in climate extremes and (2) project changes in the extremes. The validation was hampered by the sparse station data distribution in the region and in the end eight indices representative of short term climate events were calculated for eight stations, which had daily time series of reasonable lengths (20 or more years). The indices are listed in Table I and the stations are given in Table II. Future changes in the indices for the same stations were also calculated for the A2 and B2 scenarios. Because of the limited sample, caution is taken in interpreting the results.

3. Model validation

3.1. Precipitation

The PRECIS model demonstrates reasonable skill in reproducing the global-scale climatological patterns of precipitation across the Caribbean basin. The main feature of precipitation over the Caribbean is a well-defined annual cycle, which exhibits maximum precipitation from May through November and a dry period peaking in February–March. The wet season is also bimodal (Chen *et al.*, 1997) with peaks in May–June (early season) and August–October (late season). The latter peak coincides with peak hurricane activity.

Figure 2 shows the seasonal rainfall patterns from CMAP (row 1), PRECIS model simulated baseline (row 2) and for CRU minus model simulated baseline (row 3). All maps are for the period 1979–1990, which is the common period of overlap for all the three datasets. The precipitation analyses are also restricted to a 5°–28°N and 57°–90 °W domain because of our primary interest in the Caribbean. The large-scale seasonal variability in the Caribbean basin is well simulated by the model. There is a clear shift towards greater rainfall amounts with the onset of the rainfall season in MJJ (row 2) and the basin is driest in FMA.

The spatial patterns of each season are also equally well simulated. The zonal band of dryness which spans the Caribbean basin and the Caribbean coastline of Central America in FMA (between 10°N and 25°N) is evident in the model. In the wet seasons (MJJ and ASO), the precipitation centre off the Caribbean coastline of Panama associated with the Caribbean low-level jet (Whyte *et al.*, 2008) is captured, as well as heavy rainfall in the equatorial Pacific (lower left corner of the domain). The dry belt over the southern Caribbean Netherland Antilles islands is also simulated for all seasons except NDJ, which is in keeping with the climatology of those islands (Martis *et al.*, 2002). The model however extends the area of wetness associated with the southwestern Caribbean basin in NDJ further eastward, and places a larger rainfall maximum than seen in the CMAP dataset just east of Trinidad and Tobago. The benefit of the greater resolution in differentiating finer scale features, particularly over Caribbean landmasses, is also to be noted.

The difference maps depicting CRU observations minus model baseline (row 3) suggest that over most of

Copyright © 2010 Royal Meteorological Society

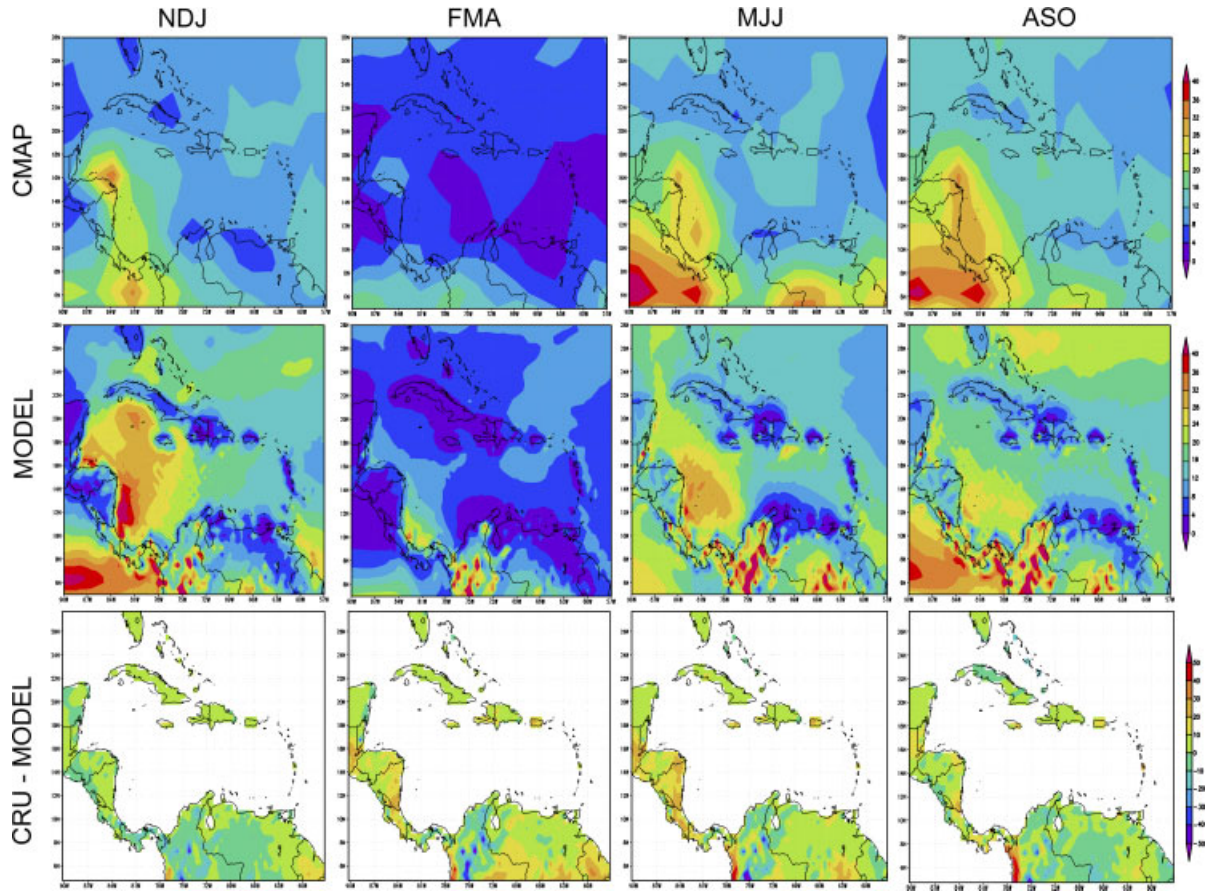


Figure 2. Diagram showing the spatial distribution of seasonal NDJ, FMA, MJJ and ASO precipitations, respectively, for CMAP (top row), PRECIS model simulated baseline (middle row) and CRU minus PRECIS model simulated baseline (bottom). All averages are for the period 1979–1990. Units are in cm. This figure is available in colour online at www.interscience.wiley.com/ijoc

the domain shown, regardless of season, the model underestimates precipitation. The only place where the model overestimates precipitation is over portions of northern South America, i.e. over northern Columbia for all seasons and over north western Venezuela in NDJ and ASO. The patterns over northern South America are similar to those shown by Alves and Marengo (2009) in winter and summer validation maps for the continent using the PRECIS model. The model also produces more rainfall than observed over Panama and the Pacific coast of Guatemala in NDJ.

Over the Caribbean region, the model's dry bias is evident in all seasons over all island masses. PRECIS is consistent in simulating 1–2 mm/day less rainfall over Cuba, Hispaniola, Jamaica and Puerto Rico for all seasons. Alves and Marengo (2009) note that rainfall underestimations in PRECIS are likely related to poor representation of some components of the hydrological cycle (soil moisture, surface fluxes and vegetation types) or the convective parameterization. It is also noted that the maps in row 3 were essentially the same whether the differences were with respect to the simulated baseline or the model simulations using ERA reanalysis. For this reason the latter differences are not shown.

Finally, quantitative estimates of the model's precipitation biases and a more detailed analysis of its mean annual cycle are obtained from Figure 3. Figure 3(a) shows the simulated, observed (CRU) and CMAP reanalysis rainfall climatologies averaged over the Caribbean index region defined earlier (Figure 1). In the case of CRU only the land points in the domain are averaged. Key characteristics of the rainfall climatology, which are reproduced by the RCM include (1) lowest rainfall amounts at the start of the year; (2) distinct early (MJJ) and late wet seasons (ASO) and (3) a mid-summer rainfall minimum in July (Chen *et al*., 1997; Chen and Taylor, 2002). However, also evident is an overestimation of rainfall amounts in the late rainfall season months of October and November. The overestimation, though seemingly incongruous with the dry bias for the Caribbean noted earlier, is as a result of the rainfall maximum simulated over the waters south of Jamaica in NDJ (Figure 2), which falls within the Caribbean index domain. If only land points are averaged for the RCM, then the simulated late season values become comparable with the observed.

3.2. Temperature

The seasonal variability and general patterns associated with temperature are also well captured by the model. Figure 4 shows seasonal temperature patterns from NCEP (row 1) and PRECIS model simulated baseline (row 2).

Copyright © 2010 Royal Meteorological Society

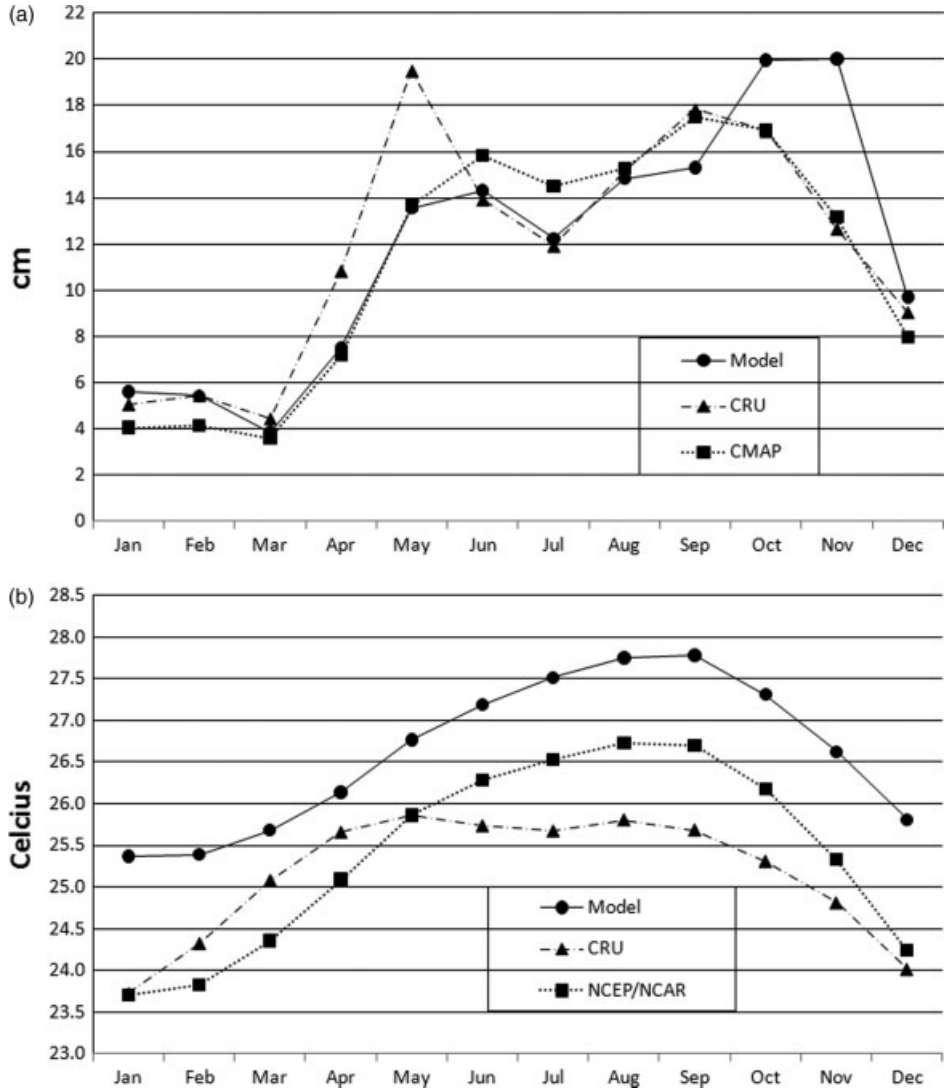


Figure 3. (a) Caribbean rainfall climatological time series, averaged over the area 10 °N–20 °N and 65 °W–83 °W, obtained from CMAP (dashed line with squares), CRU observations (dashed line with triangles) and PRECIS simulation (solid line with circles) for the period 1979–1990. Units are in cm. (b) Caribbean temperature climatological time series, averaged over the entire domain, obtained from NCEP–NCAR reanalysis (dashed line with squares), CRU observations (dashed line with triangles) and PRECIS simulation (solid line with circles) for the period 1979–1990. Units are in °C.

For consistency with the precipitation maps shown previously, the averaging period is 1979–1990. The PRECIS model captures the peak in Caribbean temperatures in August–September, and the gradient pattern of a cool north but warmer south Caribbean in NDJ and FMA. Also captured are the appearance, eastward advancement and subsequent retreat of the Caribbean warm pool from May through December (Wang and Enfield, 2001). As seen in the model, the warm pool appears first in the western Caribbean Sea in MJJ and eventually engulfs the region by the late rainfall season (ASO). In general, seasonal temperatures across the Caribbean basin are overestimated by 1–2 °C (with respect to NCEP) with some underestimation evident over Central America and portions of South America. Topography influenced variability (particularly over the higher altitude regions of Central and South America) is also discernible due to the finer scale of the regional model.

Figure 4 also shows the model biases with respect to the CRU observations (row 3). Again, the CRU minus ERA driven model maps are not shown due to their similarity. The cold bias over Central America and northern South America and the warm bias over the Caribbean are better depicted. The model underestimates temperatures by 1–2 °C over much of Central America except for the Yucatan Peninsula where there is an overestimation (up to 3 °C in FMA). Similarly, over northern South American, model simulated temperatures are up to 3 °C cooler, except for north Central Columbia, and coastal and northeastern Venezuela, where overestimation reaches up to 4 °C. The cold bias of the PRECIS model over South America is also seen in the maps of Alves and Marengo (2009). Over the Caribbean land masses, model temperatures are warmer than observations by approximately 1–4 °C dependent on season. The warm bias is greatest in the FMA and least in NDJ.

Copyright © 2010 Royal Meteorological Society

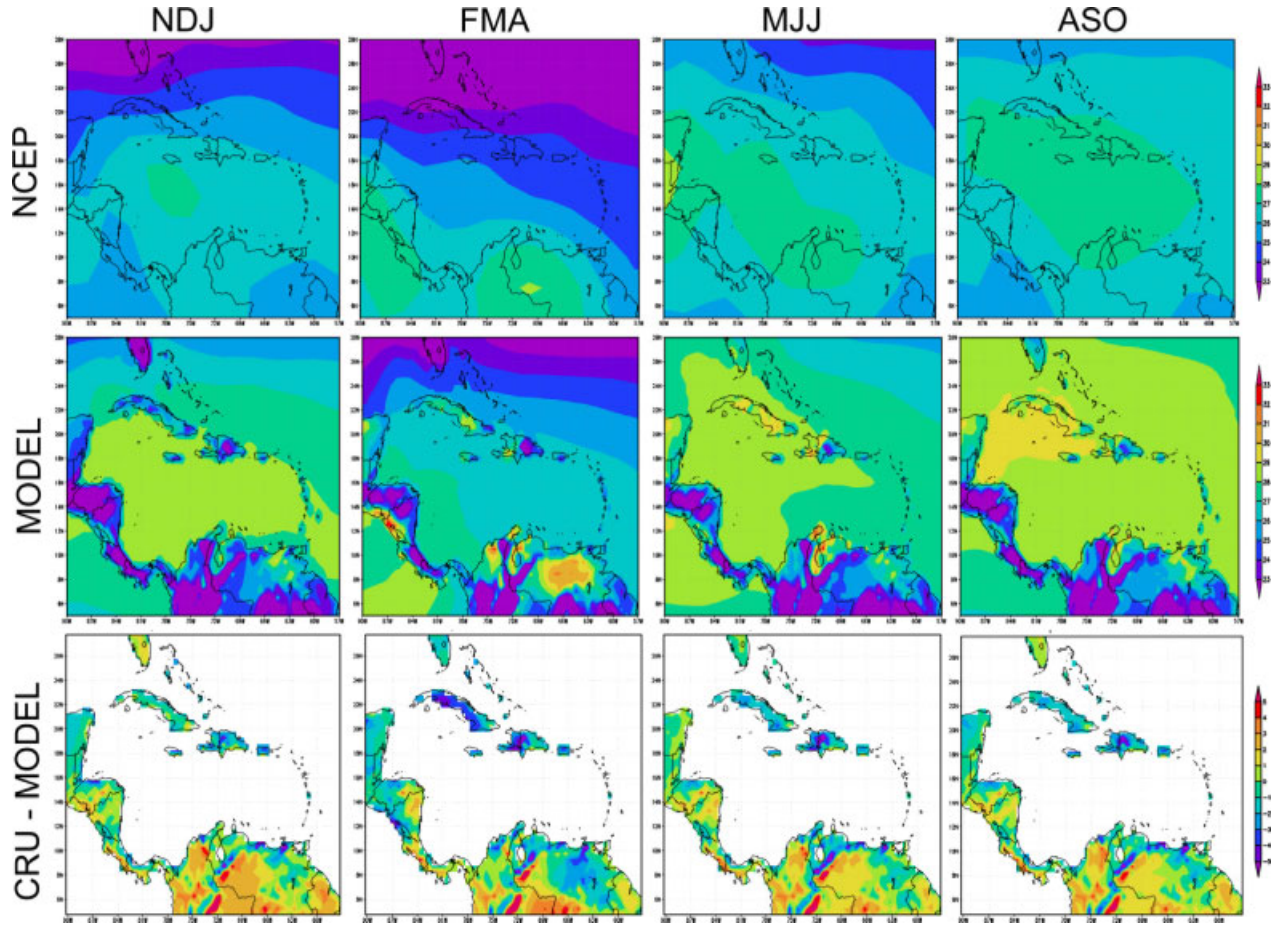


Figure 4. Diagram showing the spatial distribution of seasonal NDJ, FMA, MJJ and ASO temperatures, respectively, for NCEP–NCAR reanalysis (top row), PRECIS model simulated baseline (middle row) and CRU minus PRECIS model simulated baseline (bottom). All averages are for the period 1979–1990. Units are in °C. This figure is available in colour online at www.interscience.wiley.com/ijoc

Figure 3(b) indicates that the PRECIS RCM averaged over the entire domain reproduces the mean annual variation in temperature with the lowest temperatures occurring during the boreal winter months (December–February) and maximum during the boreal summer (July–September). The effective annual temperature range is also captured approximately 2.6 °C (model) versus 2.4 °C (observed). The model however overestimates NCEP–NCAR mean monthly temperatures by between 1 and 1.7 °C. The difference is greatest for boreal winter months and least for boreal summer months.

3.3. Extremes

Of the eight extreme indices analysed, only the simulated temperature extremes (TN10p, TX10p, TN90p, TX90p) bear any similarity to extremes calculated using daily data from the eight stations listed in Table II (not shown). TN90p and TN10p (TX90p and TX10p) are respective measures of the occurrence of very hot and cold nights (days). Whereas, the magnitudes of the RCM-derived temperature extremes were not comparable, the time series of their annual variation for overlapping periods were significantly correlated for most stations (not shown). For TN90p, correlations were significant and high (>0.60) for seven of the eight stations. The simulated temperature indices also showed increasing linear trends for the baseline period, though not all the linear trends were significant. An increasing linear trend is also noted by Peterson *et al.* (2002) for similar temperature indices calculated for the Caribbean basin as a whole.

There were, however, few similarities between the magnitudes and trends for the three rainfall indices and one dryness index when calculated using model and observed data. There are inherent difficulties in correctly simulating daily rainfall in any model, and the problem is compounded by the fact that the comparisons here are between grid box values and single data points. Table III shows the calculated magnitudes of R95, R10, Rx5 and CDD for the eight stations and for their corresponding model grid boxes. The first three indices are indicators of rainfall intensity and the last is a measure of dryness. A plus (minus) sign is placed beside each calculated value to indicate whether the general trend is increasing (decreasing) over the periods of analysis. None of the trends is, however, significant due to the strong interannual variability associated with the rainfall indices. A similar thing is noted by Peterson *et al.* (2002) for similar mean Caribbean rainfall indices that they calculated.

Copyright © 2010 Royal Meteorological Society

Table III. Table showing calculated magnitudes of rainfall extreme indices: R95, R10, Rx5 and CDD for eight Caribbean stations and for their corresponding grid boxes from ERA15 and baseline simulations respectively. The plus '+' and minus '−' signs represent a positive or negative linear trend, respectively, over the period of observation or simulation.

Stations	Observed (1970–1989)								ERA15 (1979–1992)								Baseline (1970–1989)							
	CDD	Trend	Rx5	Trend	R95	Trend	R10	Trend	CDD	Trend	x5	Trend	R95	Trend	R10	Trend	CDD	Trend	Rx5	Trend	R95	Trend	R10	Trend
Bahamas	23.30	−	168.14	−	355.54	+	40.65	+	21.43	+	146.54	−	277.24	−	41.29	−	18.60	+	142.55	−	295.23	−	53.50	−
Costa Rica	14.68	−	250.60	+	727.39	+	77.11	+	11.43	+	86.21	−	245.79	+	37.00	+	25.50	+	52.05	−	139.77	−	8.10	−
Cuba	30.60	C	172.76	+	318.83	+	33.85	+	40.50	+	74.68	−	141.55	−	10.00	−	31.60	+	77.04	−	151.33	−	12.45	−
Guadeloupe	NaN		NaN		NaN		NaN		14.50	−	81.21	−	212.19	−	21.50	−	11.25	+	82.92	−	211.30	−	37.00	−
Honduras	29.60	+	159.05	+	387.23	+	47.05	+	23.07	+	84.63	−	208.59	−	24.93	−	18.80	+	76.00	−	211.80	−	24.50	+
Jamaica	NaN		NaN		NaN		NaN		46.36	−	67.68	+	94.31	+	3.43	−	32.00	+	72.70	−	117.92	−	4.80	−
St. Lucia	21.50	+	199.34	−	495.36	+	59.93	+	16.50	+	55.10	−	202.50	−	38.50	−	13.05	+	49.26	−	199.95	−	43.55	−
Trinidad and Tobago	16.73	+	149.57	+	458.62	+	36.73	+	28.71	+	73.74	−	115.75	−	8.07	+	17.65	+	66.59	+	126.35	+	12.05	+

The signs of the modelled rainfall extremes suggest a tendency towards decreasing heavy rainfall and increasing dry days over the baseline period. It is the opposite tendencies, which are however reported by Peterson *et al.* (2002) and which are seemingly suggested by the station data. The model does not seemingly capture the rainfall extreme trends. We reiterate, however, that care must be taken when interpreting the results as only eight stations are analysed and the trends are not significant. A more detailed analysis of the model's ability to simulate extremes will be the subject of a future paper.

4. Projections

Annual and seasonal projections under the A2 (medium high) and B2 (medium low) SRES emission scenarios for the period 2071–2100 relative to the model baseline (1961–1990) are examined. The A2 SRES scenario represents a very heterogeneous world with continuously increasing global population and regionally oriented economic growth that is more fragmented and slower in comparison to other scenarios. The B2 scenario represents an emphasis on local solutions to economic, social and environmental sustainability with continuously increasing population (lower than A2) and intermediate economic development (Nakićenović, 2000). Assuming stationarity in model biases, changes seen are primarily due to climate change.

Annual (panel a) and seasonal spatial patterns (panels b through e) of change are presented in Figures 5 and 6 for rainfall and temperature, respectively, for the A2 scenario. In general the change patterns are similar for the B2 scenario but with smaller magnitudes (not shown). Changes in the monthly, seasonal and annual values of the Caribbean index are also presented in panel F. As an indication of the robustness of the change, the standard deviation is also plotted in panel F for both rainfall and temperature. The standard deviation is calculated using the CMAP and NCEP datasets for the 1979–1990 period and is plotted as a measure of typical change due to natural variability.

4.1. Rainfall

4.1.1. Annual

With the exception of the far northern latitudes (i.e. southern Florida, the Bahamas and northern Cuba), projections show a decrease in annual rainfall under both A2 (Figure 5(a)) and B2 scenarios (not shown) for much of the Caribbean. The decrease ranges from 25–50% and is largest over the Lesser Antilles and the Central Caribbean basin, under the A2 scenario, including Jamaica and Puerto Rico (i.e. ∼10–20°N). The pattern of drying is similar under the B2 scenario, but the largest change (∼50%) is now located in the Netherland Antilles. Under both scenarios, the northern edge of the Caribbean is becoming wetter: ∼25% for A2 and between 0–25% for the B2 projections.

Copyright © 2010 Royal Meteorological Society

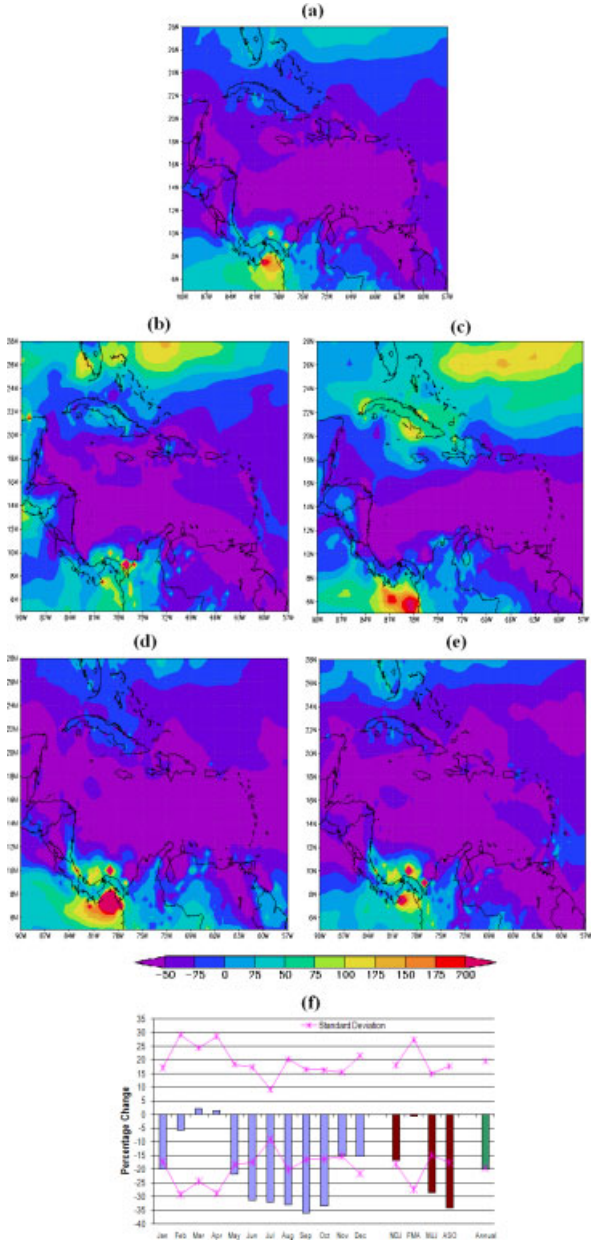


Figure 5. Rainfall projections for the period 2071–2100 relative to the period 1961–1990 baseline under the A2 scenario. Percentage change is presented. Panels (a), (b), (c), (d) and (e) represent annual, NDJ, FMA, MJJ and ASO, respectively. Panel (f) shows monthly, seasonal and annual changes calculated by averaging over the domain shown in (a)–(e). The solid line represents one standard deviation as calculated from the CMAP dataset. This figure is available in colour online at www.interscience.wiley.com/ijoc

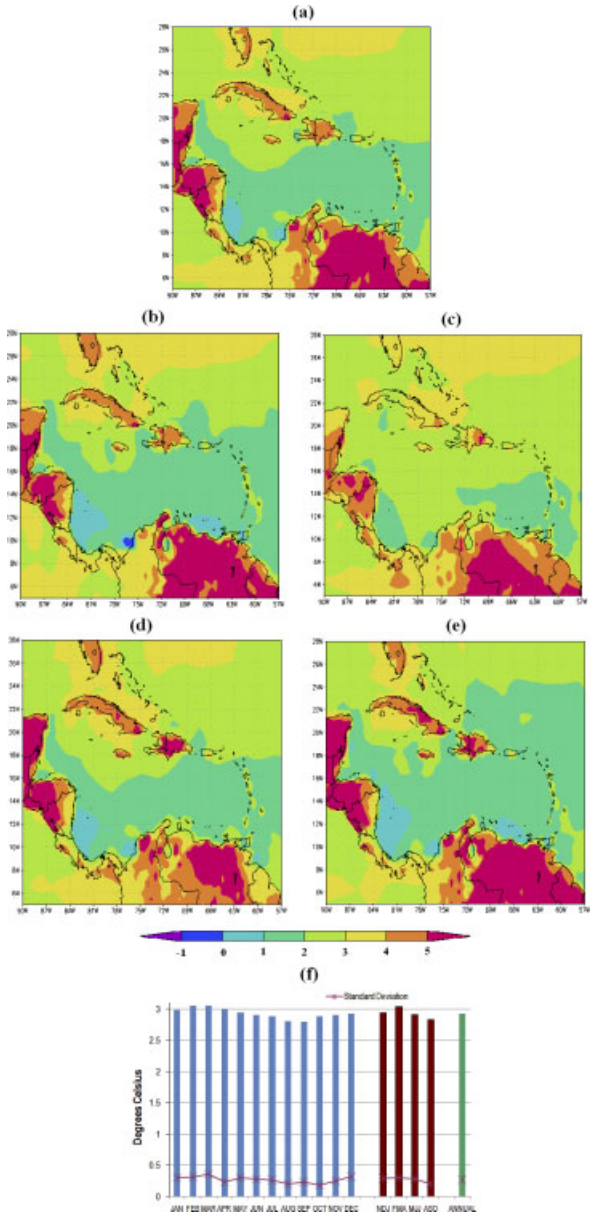


Figure 6. Temperature projections for the period 2071–2100 relative to the period 1961–1990 baseline under the A2 scenario. Absolute change is presented. Panels (a), (b), (c), (d) and (e) represent annual, NDJ, FMA, MJJ and ASO, respectively. Panel (f) shows monthly, seasonal and annual changes calculated by averaging over the domain shown in (a)–(e). The solid line represents one standard deviation as calculated from the NCEP–NCAR reanalysis dataset. This figure is available in colour online at www.interscience.wiley.com/ijoc

This spatial pattern of the changes is consistent with that obtained by Christensen *et al*. (2007) using 21 global models under the A1B SRES scenario. Of the 21 models, 15 models projected decreased annual rainfall over the Caribbean, excepting parts of the far north basin, from 2080–2099 relative to 1980–1999. Approximately ten models projected an increase over southern Florida. The results are also consistent with the annual precipitation decline projected by Nurse and Sem (2001). The annual rainfall total derived from the Caribbean index also shows a decrease of approximately 20% for the A2 Scenario [Figure 5(f)] and approximately 10% for the B2 Scenario (not shown). Though this lies within the range of GCM-based projected change for the region ($-6.8 \pm 15.8\%$) (Nurse and Sem, 2001), it is also comparable to the change seen in annual rainfall amounts in the recent historical record as indicated by the standard deviation (Figure 5(f)).

4.1.2. Seasonal

Projections of seasonal rainfall changes for the Caribbean for the period 2071–2100 under the A2 scenario are shown in Figure 5(b–e). The gradient pattern of a wetter

Copyright © 2010 Royal Meteorological Society

north–drier south Caribbean is a strong feature during the dry seasons NDJ and FMA. The projections indicate up to a 75% increase over the northern Caribbean (above 25°N) under the A2 scenario, even as the central Caribbean exhibits a strong decrease (∼50%) in rainfall. The wetter north–drier south pattern is absent in MJJ when uniform drying (∼50%) across the plotted domain is the trend, but begins to re-emerge in the late wet season (ASO). In ASO, the expanse of wetness is, however, greatly reduced in comparison to NDJ and FMA. The significance of the projected wetter north–drier south pattern during the dry season is discussed in the following section.

A drier Caribbean during MJJ and ASO (Figure 5(d–e)) is also noteworthy. Angeles *et al*. (2006) similarly show decreased summer rainfall over Cuba by mid-century using a fully coupled GCM. Christensen *et al*. (2007) show a robust drier Caribbean by the 2090s for a June–August season. A mechanism for the projected summer drying has been proposed by Neelin *et al*. (2003). We also discuss the summer drying further in the following section.

Simulated changes in the seasonal and monthly indices [Figure 5(f)] indicate that the general tendency is for drying over the Caribbean and adjacent regions in three of the four defined seasons by the 2071–2100 period. The change exceeds that due to natural variability for both MJJ (∼28 *vs* 15%) and ASO (∼35 *vs* 17%). The monthly indices further suggest that the tendency towards drying is robust for the entire period June–October when all the monthly changes projected are clearly outside the range of natural variability.

4.2. Temperature

4.2.1. Annual

Temperatures are projected to increase over the Caribbean (including Central and South America) under both the A2 [Figure 6(a)] and B2 scenarios (not shown). Projections are for 2–5 °C (2–4 °C) rise over the Caribbean region under the A2 (B2) scenario. The larger Caribbean islands, i.e. Cuba, Jamaica and Hispaniola, exhibit the greatest warming. The annual temperature change scenarios are comparable with IPCC projections of 1.5–4.5 °C increase in average global temperature (above pre-industrial levels) under the A1B by the end of the century (Solomon *et al*. 2007). The results also agree with increased temperatures projected using the Statistical DownScaling Model (Wilby *et al*., 2002) for stations in Trinidad (2.2 °C/1.6 °C), Barbados (2.3 °C/0.7 °C) and Jamaica (2.0–3.0 °C/1.5–2.3 °C) for the A2/B2 scenario (Chen *et al*., 2006).

The annual index shown in Figure 6(f) suggests an increase of approximately 2.9 °C over the domain. The change is well outside the range of natural variability as indicated by the one standard deviation value.

4.2.2. Seasonal

The seasonal temperature projections [Figure 6(b–e)] show increased temperatures across the Caribbean region including Central America and northern South America. The warming is strongest over land, particularly over Cuba, Jamaica, Hispaniola, Central America and northern South America, where the increase is approximately 2–5 °C (2–4 °C) under the A2 (B2) scenario across all seasons. The seasonal indices [Figure 6(f)] show that FMA and NDJ exhibit the strongest temperature response, i.e. approximately 3.1 and 2.9 °C, respectively, though across seasons the projections are within 0.5 °C of each other. As for the annual index, the temperature change in all months and in all seasons (irrespective of scenario) far exceeds that due to natural variability.

4.2.3. Extremes

Figure 7(a) shows the map of the Caribbean on which bar plots of R95 (very wet days) and Rx5 (maximum 5-day precipitation) for seven of the eight stations are superimposed. The plots show the magnitude of the index averaged over the baseline and future periods. Figure 7(b) is identical but for R10 (number of heavy precipitation days) and CDD (consecutive dry days). The general pattern is such that the far northern Caribbean stations (Bahamas and Cuba) and the Honduras station show increases in rainfall intensity in the future. This is true for R95 and Rx5 for all three stations, and for R10 (except for Cuba, which shows marginal decline). The northern Caribbean stations also show a decline in consecutive dry days by the 2071–2100 period [Figure 7(b)]. The opposite pattern is true for the remaining Caribbean stations. All show a decrease in the rainfall intensity indices and an increase in the dryness index. The patterns indicated by the seven stations are consistent with the mean projections for the basin (Section 4.1). It seems that the wetter north–drier south pattern of the 2071–2100 period is characterized by more (less) intense rainfall and less (more) dry days in the northern (southern) Caribbean basin. We consider, what this may mean in the following section.

5. Summary and discussion

The aim of this paper was twofold: to evaluate the performance of the PRECIS model in simulating observed climate variability over the Caribbean and to use it to produce climate change scenarios for the region for the 2071–2100 period. The PRECIS RCM shows reasonable skill in simulating 'present-day' rainfall and temperature variability over the Caribbean and adjacent regions. The simulated temperature climatology reproduces the summer maximum–winter minimum temperatures but with a bias ranging from +1 to +1.7 °C. The seasonal spatial patterns of temperature are also well simulated including the north–south temperature gradient in boreal winter months and the eastward expansion of the Caribbean warm pool from spring onwards.

Similarly, the simulated rainfall climatology of the central Caribbean basin (as represented by area averaged rainfall over the Caribbean index domain shown

Copyright © 2010 Royal Meteorological Society

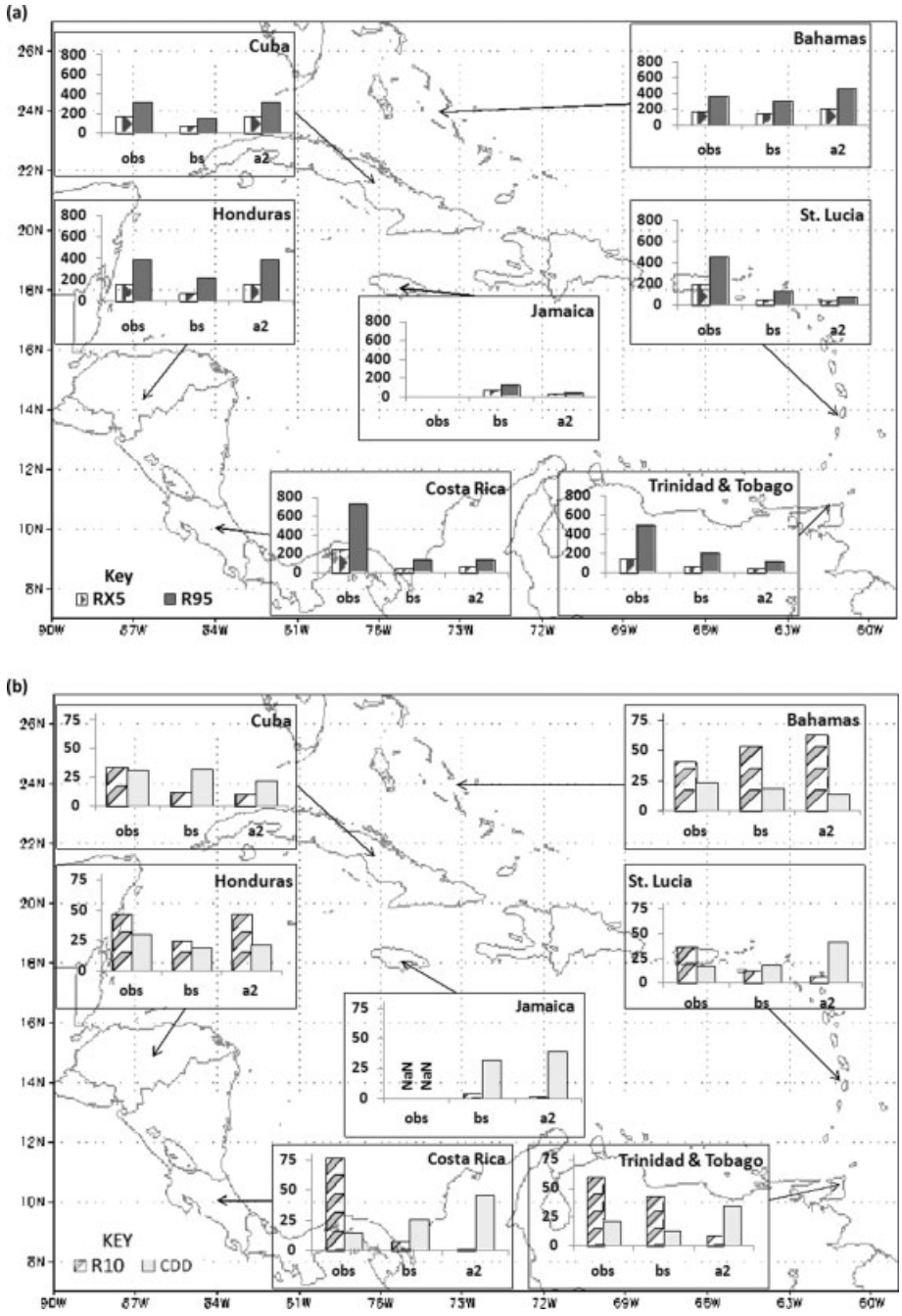


Figure 7. Observed and simulated (baseline and A2) magnitudes for extreme rainfall events indices: (a) maximum 5-day precipitation, Rx5, and very wet days, R95, (solid bar), (b) number of days precipitation was greater than or equal to 10 mm, R10 (striped bar) and the number of days precipitation was below 1 mm, CDD (solid bar), for seven Caribbean territories.

in Figure 1) captures the bimodal characteristics of Caribbean rainfall though overestimating the late season peak rainfall and displacing the rainfall maximum to November. Both the overestimation and the displaced peak are seemingly due to the model's eastward extension of a rainfall maximum found in the far southwest corner of the basin (off the coast of Panama) at this time, such that it now falls within the Caribbean index domain. This is seen in the seasonal maps of simulated rainfall (Figure 3). If, however, only land points are averaged, the overestimation disappears and the peak now occurs in October (not shown). Otherwise, the expected seasonal spatial patterns of rainfall for the Caribbean domain are well captured, not withstanding a dry bias over the Caribbean island masses.

The placement of the NDJ rainfall maximum south of Jamaica in NDJ is interesting and suggests that the model may be over or underestimating the strength of the Caribbean low-level jet (CLLJ). The CLLJ is similarly located and influences rainfall totals in its Caribbean entrance and exit regions and along the Caribbean coast of Central America, as well as moisture flux to the southeastern United States (Wang, 2007; Munoz *et al*., 2008; Whyte *et al*., 2008). Calculations of the magnitude of the

Copyright © 2010 Royal Meteorological Society

CLLJ index defined by Whyte *et al.* (2008) (not shown) reveal a slight overestimation of the winter strength by the PRECIS model, which could in part explain the NDJ pattern. It may also suggest a particular sensitivity of PRECIS simulated rainfall in the Caribbean to modelled trade wind speeds, which should be borne in mind when interpreting the future climates simulated by the model.

The annual and seasonal projections under the A2 and B2 scenarios reveal three other key features worth highlighting. Firstly, for 2071–2100, the annual rainfall is projected to increase north of 22 °N and decrease (∼25–50%) south of this demarcation. The pattern is even more pronounced during the dry seasons NDJ and FMA. This gradient pattern, already the dominant mode of NDJ and FMA rainfall variability (Giannini *et al.*, 2000; Spence *et al.*, 2004; Stephenson *et al.*, 2007), is linked to the Hadley overturning of the north tropical Atlantic. It is also the pattern manifested during the Caribbean dry season for warm phases of El Niño Southern Oscillation (ENSO) events (Stephenson *et al.*, 2007). The implication is that under a climate changed world marked by global warming, there may be a favouring of or possible strengthening of 'present-day' circulation patterns over the region – at least for the boreal winter months.

Secondly, by the 2071–2100 period, there is a projected drying (up to 35% under the A2 scenario) during MJJ and ASO, which is a basin-wide feature. The monthly indices indicate that the drying tendency is robust for June–October and in excess of the range of variability currently observed. This observation is in line with the consensus from previous GCM work that the drying signal during the summer months is a significant feature over the Caribbean and is very likely (following IPCC notation) to manifest in the future. This has strong implications for the use of water resources, especially when coupled with the previous idea of a probable drier dry season.

Given the previous observations about the likely link between trade wind speeds and rainfall in the Caribbean domain in the PRECIS model, it is noteworthy that the simulated CLLJ index shows an increase in the phenomenon's strength between June and August by the end of the century (not shown). Strengthening of the summer manifestation of the CLLJ is associated with a drier Caribbean basin (Whyte *et al.*, 2008) partially due to the increased vertical wind shear. Angeles *et al.* (2006) also noted moderate increases in wind shear during the Caribbean wet season by the end of the century. Again this is something worthy of further investigation (as is currently being done), especially as trade wind strength and the CLLJ are key components of a wider dynamical regime that is known to control the Caribbean wet season (Gamble and Curtis, 2008), which might seemingly be strengthened in the future.

Finally, it is noteworthy that Caribbean temperatures are projected to increase (1–4 °C) following global trends. The increased temperatures are projected for all locations in the domain and are irrespective of scenario. The changes over land are larger than over open water, and the magnitude of the increase exceeds by far due to natural variability.

It is clear from the analysis that the projected changes, should they materialize, are indicative of altered dynamical circulation patterns in both the dry and wet seasons. These would in turn lead to changes in the intensity and frequency of rainfall events as indicated by the projected changes in the extreme indices. The changes in the atmospheric dynamics that govern Caribbean climate under a much warmer world scenario need to be further investigated. It must also be borne in mind that the changes depicted in this paper, though consistent with GCM projections for the region, derive from simulations from only one regional model. Future work must involve the use of additional RCMs to engender greater confidence in the projections.

The analysis, however, does highlight the additional detail obtainable from the use of an RCM, e.g. differential rainfall and heating over land versus ocean points or variable patterns over land due to orography. Such detail is not available from GCMs. Scope exists, therefore, for using the projections from PRECIS to deliver more refined climates for climate impact studies, in turn enabling more tailored adaptation options to the threat of climate change within the Caribbean region.

Acknowledgements

This work was conducted as part of a collaborative effort between Cuba (Instituto de Meterologia de la Republica), Barbados (the Department of Computer Science, Mathematics and Physics, the University of the West Indies) and Jamaica (The Climate Studies Group Mona, The University of the West Indies). The project was funded by the Caribbean Community Climate Change Centre (Belize). Special thanks to the Hadley Centre (UK) for the PRECIS model support.

References

Aldrian E, Dümenil-Gate L, Jacob D, Podzun R, Gunawan D. 2004. Long-term simulation of Indonesian rainfall with the MPI regional model. *Climate Dynamics* **22**: 794–814, DOI: 10.1007/s00382-004-0418-9.

Alves LM, Marengo JA. 2009. Assessment of Regional Seasonal predictability using the PRECIS regional climate modeling system over South America. *Theoretical and Applied Climatology* **100**: 337–350, DOI: 10.1007/s00704-009-0165-2.

Angeles ME, Gonzalez JE, Erickson DJ III, Hernández JL. 2006. Predictions of future climate change in the Caribbean region using global general circulation models. *International Journal of Climatology* **27**(5): 555–569, DOI: 10.1002/joc.1416.

Ashby SA, Taylor MA, Chen AA. 2005. Statistical models for predicting rainfall in the Caribbean. *Theoretical and Applied Climatology* **82**: 65–80, DOI: 10.1007/s00704-004-0118-8.

Bloom A, Kotroni V, Lagouvardos K. 2008. Climate change impact of wind energy availability in the Eastern Mediterranean using the regional climate model PRECIS. *Natural Hazards and Earth System Sciences (NHESS)* **8**: 1249–1257.

Castro DM, da Rocha RP, Benzanilla-Morlot A, Alvarez-Escudero L, Reyes-Fernández JP, Silva-Vidal Y, Arritt RW. 2006. Sensitivity studies of the RegCM3 simulation of summer precipitation, temperature and local wind field in the Caribbean region. *Theoretical*

Copyright © 2010 Royal Meteorological Society

and Applied Climatology **86**: 5–22, DOI: 10. 1007/s00704-005-0201-9.

Chen AA, Rhoden CL, Taylor MA. 2006. Climate change science and future climate change scenarios. In *Climate Change Impact on Dengue: The Caribbean Experience*, Chen AA, Chadee DD, and Rawlins S (eds). Climate Studies Group Mona, University of the West Indies: Mona, Jamaica; 66–77.

Chen AA, Roy A, McTavish J, Taylor MA, Marx L. 1997. Using SST Anomalies to Predict Flood and Drought Conditions for the Caribbean. COLA Report 49.

Chen AA, Taylor MA. 2002. Investigating the link between early season Caribbean rainfall and the El Niño +1 year. *International Journal of Climatology* **22**: 87–106, DOI: 10.1002/joc.711.

Christensen JH, Hewitson B, Busuioc A, Chen A, Gao X, Held I, Jones R, Kolli RK, Kwon W-T, Laprise R, Magaña Rueda V, Mearns L, Menéndez CG, Räisänen J, Rinke A, Sarr A, Whetton P. 2007. Regional climate projections. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds). Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA; 847–940.

Dobler A, Ahrens B. 2008. Precipitation by a regional climate model and bias correction in Europe and Asia. *Meteorologische Zeitschrift* **17**(4): 499–509.

Gamble DW, Curtis S. 2008. Caribbean precipitation: review, model and prospect. *Progress in Physical Geography* **32**(3): 265–276.

Giannini A, Kushnir Y, Cane MA. 2000. Inter-annual variability of Caribbean rainfall, ENSO, and the Atlantic Ocean. *Journal of Climate* **13**: 297–311.

Hastenrath S. 1976. Variations in low-latitude, circulation and extreme climatic events in the tropical Americas. *Journal of Atmospheric Sciences* **33**: 202–215.

Islam S, Rehman N, Sheikh MM. 2009. Future change in the frequency of warm and cold spells durations over Pakistan simulated by the PRECIS regional climate model. *Climate Change* **94**: 35–45, DOI 10.1007/s10584-009-9557-7.

Jones RG, Hassell D, Hudson D, Wilson S, Jenkins G, Mitchell J. 2003. *Workbook on Generating High Resolution Climate Change Scenarios Using PRECIS.* UNDP: New York.

Jones RG, Noguer M, Hassell D, Hudson D, Wilson S, Jenkins G, Mitchell J. 2004. *Generating High Resolution Climate Change Scenarios Using PRECIS.* Met Office Hadley Centre: Exeter, UK.

Jury MR. 2009. A quasi-decadal cycle in Caribbean climate. *Journal of Geophysical Research* **114**: D13102, DOI:10.1029/2009JD011741.

Kalnay E, Kanamitsu M, Kistler R, Collins W, Deaven D, Gandin L, Iredell M, Saha S, White G, Woollen J, Zhu Y, Leetmaa A, Reynolds R, Chelliah M, Ebisuzaki W, Higgins W, Janowiak J, Mo KC, Ropelewski C, Wang J, Jenne R, Joseph D. 1996. The NCEP/NCAR 40-year reanalysis project. *Bulletin of the American Meteorological Society* **77**(3): 437–471.

Kotroni V, Lykoudis S, Lagouvardos K, Lalas D. 2008. A fine resolution regional climate change experiment for the Eastern Mediterranean: Analysis of the present climate simulations. *Global and Planetary Change* **64**(1–2): 93–104.

Kumar KR, Sahai AK, Kumar KK, Patwardhan SK, Mishra PK, Revadekar JV, Kamala K, Pant GB. 2006. High-resolution climate change scenarios for India for the 21st century Indian Institute of Tropical Meteorology. *Current Science* **90**(3): 334–345.

Marengo JA, Jones R, Alves LM, Valverde MC. 2009. Future change of temperature and precipitation extremes in South America as derived from the PRECIS regional climate modeling system. *International Journal of Climatology*, DOI: 10.1002/joc.1863.

Martis A, van Oldenborgh GJ, Burgers G. 2002. Predicting rainfall in the Dutch Caribbean – more than El Niño?. *International Journal of Climatology* **22**: 1219–1234.

Mearns LO, Giorgi F, Whetton P, Pabon D, Hulme M, Lal M. 2003. Guidelines for Use of Climate Scenarios Developed from Regional Climate Model Experiments. DDC IPCC TGCIA.

Moberg A, Jones PD. 2004. Regional climate models simulations of daily maximum and minimum near-surface temperatures across Europe compared with observed station data for 1961–1990. *Climate Dynamics* **23**: 695–715.

Munoz E, Busalacchi AJ, Nigam S, Ruiz-Barradas A. 2008. Winter and summer structure of the Caribbean Low-Level Jet. *Journal of Climate* **21**: 1260–1276.

Nakicenovic N, Swart R (eds).2000. *Special Report on Emissions Scenarios. A Special Report of Working Group III of the Intergovernmental Panel on Climate Change*. Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA; 599.

Neelin JD, Chou C, Su H. 2003. Tropical drought regions in global warming and El Niño teleconnections. *Geophysical Research Letters* **30**(24): 2275, DOI: 10.1029/2003GL018625.

New M, Todd M, Hulme M, Jones P. 2001. Precipitation measurements and trends in the twentieth century. *International Journal of Climatology* **21**: 1899–1922.

Nurse LA, Sem G. 2001. Small island states. In *Climate change 2001 – the scientific basis. Contribution of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)*. Houghton. JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Xiaosu D (eds). Cambridge University Press:Cambridge; 843–875.

Peterson TC, Taylor MA, Demeritte R, Duncombe DL, Burton S, Thompson F, Porter A, Mercedes M, Villegas E, Fils RS, Klein Tank A, Martis A, Warner R, Joyette A, Mills W, Alexander L, Gleason B. 2002. Recent changes in climate extremes in the Caribbean region. *Journal of Geophysical Research* **107**(D21): 4601, DOI: 10.1029/2002JD002251.

Rowell DP. 2005. A scenario of European climate change for the late 21st century seasonal means and inter-annual variability. *Climate Dynamics* **25**: 837–849.

Singh B. 1997a. Climate-related global changes in the southern Caribbean: Trinidad and Tobago. *Global and Planetary Change* **15**: 93–111.

Singh B. 1997b. Climate changes in the greater and southern Caribbean. *International Journal of Climatology* **17**: 10936–1114.

Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL. 2007. *Summary for Policymakers*. Cambridge University Press: Cambridge.

Spence JM, Taylor MA, Chen AA. 2004. The effect of concurrent sea surface temperature anomalies in the tropical Pacific and Atlantic on Caribbean Rainfall. *International Journal of Climatology* **24**: 1531–1541, DOI: 10.1002/joc.1068.

Stephenson TS, Chen AA, Taylor MA. 2007. Toward the development of prediction models for the primary Caribbean dry season, accepted. *Theoretical and Applied Climatology* **92**: 87–101, DOI: 10.1007/s00704-007-0308-2.

Tadross M, Jack C, Hewitson B. 2005. On RCM-based projections of change in southern African summer climate. *Geophysical Research Letters* **32**: L23713, DOI:10.1029/2005GL024460.

Taylor MA, Centella A, Charlery J, Borrajero I, Bezanilla A, Campbell J, Rivero R, Stephenson TS, Whyte F, Watson R. 2007. In *Glimpses of the Future: A Briefing from the PRECIS Caribbean Climate Change Project*. Caribbean Community Climate Change Centre: Belmopan, Belize.

Taylor MA, Enfield DB, Chen AA. 2002. Influence of the tropical Atlantic versus the tropical Pacific on Caribbean rainfall. *Journal of Geophysical Research* **107**(C9): 3127, DOI: 10,1029/2001JC001097.

Wang C. 2007. Variability of the Caribbean low-level jet and its relations to climate. *Climate Dynamics* **29**: 411–422.

Wang C, Enfield DB. 2001. The tropical Western Hemisphere warm pool. *Geophysical Research Letters* **28**(8): 1635–1638.

Whyte FS, Taylor MA, Stephenson TS, Campbell JD. 2008. Features of the Caribbean low level jet. *International Journal of Climatology* **28**: 119–128.

Wilby RL, Dawson CW, Barrow EM. 2002. SDSM – A decision support tool for the assessment of regional climate change impacts. *Environmental Modelling and Software* **17**: 147–159.

Wilby RL, Wigley TML. 1997. Downscaling general circulation model output: A review of methods and limitations. *Progress in Physical Geography* **21**(4): 530–548.

Xianfu L. 2006. Guidance on the development of regional climate scenarios for vulnerability and adaptation assessments within the Framework of National Communications from Parties not Included in Annex I to the United Nations Framework Convention on Climate Change, National Communications Support Programme, UNDP-UNEP-GEF New York, USA, 1–41.

Xie P, Arkin PA. 1997. Global Precipitation: A 17-year monthly analysis based on gauge observations, satellite estimates, and numerical model outputs. *Bulletin of the American Meteorological Society* **78**(11): 2539–2558.

Zhang Y, Yinlong X, Wenjie D, Lijuan C, Sparrow M. 2006. A future climate scenario of regional changes in extreme climate events over China using the PRECIS climate model. *Geophysical Research Letters* **33**: L24702, DOI:10.1029/2006GL027229.

Copyright © 2010 Royal Meteorological Society

Annex 39

J. J. Blackstock et al., *Climate Engineering Responses to Climate Emergencies* (Novim, 2009), pages 1-3



Novim

Climate Engineering Responses to Climate Emergencies

Jason J. Blackstock[†]
David S. Battisti
Ken Caldeira
Douglas M. Eardley
Jonathan I. Katz
David W. Keith
Aristides A. N. Patrinos
Daniel P. Schrag
Robert H. Socolow
and Steven E. Koonin[†,‡]

[†]*Report Lead Authors*
[‡]*Study Group Convener*

July 29, 2009

Santa Barbara, California

This report should be cited as either:

J. J. Blackstock, D. S. Battisti, K. Caldeira, D. M. Eardley, J. I. Katz, D. W. Keith, A. A. N. Patrinos, D. P. Schrag, R. H. Socolow and S. E. Koonin, *Climate Engineering Responses to Climate Emergencies* (Novim, 2009), archived online at: http://arxiv.org/pdf/0907.5140

OR

J. J. Blackstock et al., *Climate Engineering Responses to Climate Emergencies* (Novim, 2009), archived online at: http://arxiv.org/pdf/0907.5140

THE NOVIM GROUP

CLIMATE ENGINEERING RESPONSES TO CLIMATE EMERGENCIES

Public Report Released: **July 28, 2009**

Study Group Meeting: August 10 to 15, 2008

Study Group Participants:

Jason J. Blackstock[†], David S. Battisti, Ken Caldeira, Douglas M. Eardley, Jonathan I. Katz, David W. Keith, Aristides A. N. Patrinos, Daniel P. Schrag, Robert H. Socolow and Steven E. Koonin[†,‡]

[†]*Report Lead Authors* [‡]*Study Group Convener*

TABLE OF CONTENTS

EXECUTIVE SUMMARY ..... **III**

PRELUDE: THE CONTEXT OF THE "SHOULD" DEBATE ABOUT CLIMATE ENGINEERING RESEARCH ..... **V**

1 INTRODUCTION AND CONTEXT **1**

1.1 THE POSSIBILITY OF CLIMATE EMERGENCIES 1
1.2 CLIMATE ENGINEERING AS A POTENTIAL—BUT UNCERTAIN—RESPONSE TO CLIMATE EMERGENCIES 2
1.3 REDUCING THE UNCERTAINTIES: THE FOCUS AND LIMITED SCOPE OF THIS STUDY 3

2 TECHNICAL CONSIDERATIONS FOR CLIMATE ENGINEERING INTERVENTIONS **4**

2.1 THE POTENTIAL UTILITY AND LIMITATIONS OF SHORTWAVE CLIMATE ENGINEERING INTERVENTIONS 4
2.2 GENERAL DESIGN OBJECTIVES FOR SHORTWAVE CLIMATE ENGINEERING SYSTEMS 17
2.3 ENGINEERING CONTROL VARIABLES FOR STRATOSPHERIC AEROSOLS 19
2.4 PHASES OF RESEARCH, DEVELOPMENT AND DEPLOYMENT FOR SHORTWAVE CLIMATE ENGINEERING 24
2.5 MAINTAINING INTERVENTIONS AND THE RISKS OF STOPPING ONCE STARTED 27

3 REDUCING THE UNCERTAINTIES FOR STRATOSPHERIC AEROSOLS **30**

3.1 A COMPREHENSIVE RESEARCH AGENDA 30
3.2 THE VALUE AND LIMITATIONS OF FIELD TESTING 42

4 IMPLICATIONS FOR THE SOCIO-POLITICAL DIMENSIONS OF CLIMATE ENGINEERING **44**

APPENDIX: PRELIMINARY EVALUATION OF STRATOSPHERIC LOFTING METHODS **46**

AIRCRAFT 46
GUNS 46
ROCKETS 48
CHIMNEYS 48
BALLOONS 50

BIBLIOGRAPHY **52**

LIST OF FIGURES

FIGURE 1 SCHEMATIC OVERVIEW OF SHORTWAVE CLIMATE ENGINEERING (SWCE) CONCEPTS 9
FIGURE 2 INITIAL CLIMATE MODEL RESULTS FOR A GLOBALLY UNIFORM SWCE SCENARIO 12
FIGURE 3 GLOBAL TEMPERATURE IMPACT OF AEROSOLS FROM THE 1991 MOUNT PINATUBO ERUPTION 14
FIGURE 4 PHASES OF SWCE RESEARCH, DEVELOPMENT AND DEPLOYMENT 29
FIGURE 5 OUTLINE OF A COMPREHENSIVE RESEARCH PROGRAM FOR STRATOSPHERIC AEROSOL SWCE 41

Study Group Participants

Dr. Steven E. Koonin*	Study Group Leader; Chief Scientist, BP; former Provost, Caltech
Dr. Jason J. Blackstock	Research Scholar, International Institute for Applied Systems Analysis (IIASA); Fellow, Centre for International Governance Innovation
Dr. David S. Battisti	Professor of Atmospheric Sciences, University of Washington
Dr. Ken Caldeira	Staff Scientist, Carnegie Institution for Science, Stanford University
Dr. Doug M. Eardley	Professor of Physics, Kavli Institute for Theoretical Physics, UCSB
Dr. Jonathan I. Katz	Professor of Physics, Washington University
Dr. David W. Keith	Director, ISEEE Energy and Environmental Systems Group, at the University of Calgary
Dr. Aristides A. N. Patrinos	Former Director of the Office of Biological and Environmental Research, DOE Office of Science; President of Synthetic Genomics
Dr. Daniel P. Schrag	Professor of Earth and Planetary Sciences, Harvard University; Director of the Harvard University Center for the Environment
Dr. Robert H. Socolow	Professor of Mechanical & Aerospace Engineering, Princeton Environmental Institute, Princeton University

**Steven E. Koonin is currently the Under Secretary for Science at the US Department of Energy*

Acknowledgements

The study participants and the Novim organization are grateful for the hospitality of the Kavli Institute for Theoretical Physics (KITP) at the University of California, Santa Barbara (UCSB) during the course of this study. Special thanks are extended to: Dr. David Gross (KITP Director); Michael Ditmore (Novim Executive Director); and Jim Knight (Novim Executive Vice President). The authors of this report are also grateful to our numerous colleagues who provided invaluable feedback on early drafts of this report.

1 INTRODUCTION AND CONTEXT

1.1 The Possibility of Climate Emergencies

The recent Fourth Assessment Report (AR4) of the *Intergovernmental Panel on Climate Change* (IPCC) concluded with "*very high confidence*" that anthropogenic accumulations of greenhouse gases (GHGs) in the atmosphere are affecting the Earth climate.[6] AR4 also documented a range of scientifically measured impacts on human and natural environments due to the current warming. As anthropogenic GHG concentrations continue to rise, their environmental impacts will increase.

However the sensitivity of the climate system to continued increases in atmospheric GHG concentrations remains significantly uncertain. AR4 placed the "*likely*" (66% likelihood) global mean temperature increase due to a doubling of CO_2 from pre-industrial levels at between 2ºC and 4.5ºC, while also noting that "values substantially higher than 4.5°C cannot be excluded."[7] This very broad range means that it is not currently possible to define a "safe" level of atmospheric CO_2,[8] because the future rate, magnitude, and distribution of climate change impacts are all far from certain. There is no guarantee that the previously observed trend of gradually intensifying consequences will continue. Indeed, the significant reduction in arctic summer sea ice coverage during the summers of 2007 and 2008 (~30% lower coverage than predicted by recent linear trends)[9] highlights the possibility that non-linear feedbacks in the climate system could accelerate these impacts.[10,11]

It is possible that international efforts to stabilize CO_2 concentrations will be sufficient to prevent or delay the worst climate impacts, that the world will warm only another 2°C or 3°C, that ice sheets will melt slowly, and that most of the consequences will be gradual, allowing smooth adaptation by human societies and natural ecosystems. However, it is also possible that even with concerted near-term efforts and cooperation on emissions reductions, the climate system could change quickly and unexpectedly, or could change smoothly, yet with consequences that are both severe and unanticipated. For example, the Greenland and West Antarctic ice sheets could disappear more rapidly than currently projected and the impacts of a warmer world on humans and natural ecosystems—ranging from rapidly increasing sea level to more frequent and stronger storms—could be more severe than current median predictions.[12]

We define *climate emergencies* as those circumstances where severe consequences of climate change occur too rapidly to be significantly averted by even immediate mitigation efforts. Given the long lifetime of CO_2 in the atmosphere, even aggressive near-term mitigation efforts would take several decades to stabilize and begin reducing atmospheric CO_2 concentrations.

---

[6] IPCC-2007b

[7] Ibid, page 38.

[8] Apart from the impossible (in the near-term) goal of the pre-industrial level of 280ppm.

[9] NSIDC-2007.

[10] For one example of a postulated positive climate feedback related to the loss of arctic sea ice, see: Lawrence-2008.

[11] The IPPC AR4 refers specifically to the possibility of "large-scale singularities" in the climate system that rapidly increase the rate and impacts of climate change: IPCC-2007b, page 65.

[12] It is beyond the scope of this report to discuss the myriad possibilities for such climate change impacts. For a comprehensive review of potential impacts see: IPCC-2007a.

Consequently, mitigation can at best ameliorate consequences of climate change only over a similar multi-decade period.

While offering no predictions about the likelihood of either climate emergencies or gradual climate change (or anything in between),[13] we recognize that there is now a non-negligible possibility of a climate emergency in one form or other. Serious consideration of potential responses to such an eventuality is therefore important and reasonable.

1.2 Climate Engineering as a Potential—but Uncertain—Response to Climate Emergencies

Intentional intervention in the climate system has long been discussed as one approach to deal with the effects of rising GHG concentrations. Such "climate engineering" concepts (also known as "geoengineering") vary widely in design and specific objective. Existing concepts range from those aimed at directly reducing atmospheric GHG concentrations, to those targeted at averting the consequent global warming by reducing the amount of solar radiation absorbed by the Earth, and even include some aimed at simply altering the regional to global scale distribution of climate change impacts.[14,15]

This study considers only climate engineering concepts that might serve as rapid palliative responses to global climate emergencies (*i.e.* having a significant palliative impact within several years of deployment.) This eliminates concepts aimed at directly reducing atmospheric GHG concentrations (*e.g.* large-scale reforestation, ocean-iron fertilization, atmospheric scrubbing of CO_2, *etc.*) because, similar to mitigation efforts, they would take several decades to have a substantial impact on the climate system.[16]

In contrast, concepts for modestly reducing the incoming shortwave solar radiation absorbed by the Earth would have a prompt cooling impact on the climate system.[17] Moreover, previous investigations suggest that the direct economic costs to deploy any one of several such *shortwave climate engineering* (SWCE) concepts could be very low by international standards (order of $30B annually, or ~0.05% of current global GDP.)[18]

We currently understand very little about either the potential utility or the risks of reducing absorbed solar radiation. This limited understanding stems most immediately from the very limited number of technical investigations that have been conducted to date, but also, and perhaps irreducibly, from the inherent complexity of the climate system and biosphere. Basic understanding is sufficient to conclude that a simple decrease of the solar constant can compensate for the increase in global average temperature caused by anthropogenic GHG

---

[13] Readers are referred to IPCC AR4 for recent consensus estimates of scenario probabilities: IPCC-2007b.

[14] For a basic taxonomy of climate engineering (or geoengineering) concepts, please see Figure 1 on page 12.

[15] For a detailed review and history of climate engineering concepts up to 2000 see: Keith-2000.

[16] Significant technical difficulties are associated with rapidly removing large quantities CO_2 for the atmosphere. Proposed approaches for removing carbon dioxide from the atmosphere include concepts such as enhancing biological uptake through fertilization or chemical removal and sequestration with engineered systems. However, even if such efforts were to become economically competitive with low-carbon energy systems, the scale required to make a significant impact on the existing stock of carbon in the surface ocean-atmosphere system is so large that reducing the atmospheric carbon dioxide concentration by a significant amount more quickly than several decades is essentially impossible.

[17] Natural events such as the Mt. Pinatubo eruption in 1991 have conclusively demonstrated the immediacy of such cooling impacts due to a temporary increase in the Earth's albedo. See, for example: Soden-2002.

[18] NAS-1992; Schelling-1996; Keith-2001; Barrett-2008.

emissions, but would not fully eliminate all impacts of climate change. For instance, temperature compensation at the regional scale would not be perfect, and other climate parameters currently perturbed by atmospheric GHGs—most notably ocean acidity—would remain largely unaffected. But beyond these basic observations, we know essentially nothing about the net combined impacts of shortwave climate engineering and elevated GHGs on a wide range of other climate and ecological parameters (*e.g.* regional precipitation, atmospheric and oceanic circulation, patterns of interannual variability, net ecological productivity, etc) or about the extent to which various SWCE concepts might be optimized to address them.

This large uncertainty makes the near-term deployment of any full-scale SWCE concept highly risky—unanticipated negative impacts on human and ecological systems could overshadow the expected benefits. Indeed it is this high level of risk that has largely deterred serious consideration of these concepts to date (as discussed above in the Prelude to this report.)

But given the possibility of extreme climate emergencies discussed above, it is important that the best technical information and judgment be applied in assessing the risk-effectiveness of deploying any SWCE concept. Our study is a first attempt to outline a research agenda that would clarify and might reduce the uncertainties in such an assessment.

1.3 Reducing the Uncertainties: The Focus and Limited Scope of this Study

Our weeklong study focused on the question:

> **"What program of scientific and engineering research over the next decade would maximally reduce the technical uncertainties associated with potential shortwave climate engineering responses to climate emergencies?"**

Balancing limited study time against a desire for depth and rigor, we focused our detailed technical analyses exclusively on the injection of aerosols[19] into the stratosphere to increase the Earth's shortwave albedo (reflectivity.) Previous evaluations of such concepts—particularly those involving the stratospheric injection of sulfate aerosols similar to those from volcanic eruptions—have already suggested the basic engineering and economic feasibility of such ideas.[20] Moreover, a recent body of preliminary scientific investigations[21] of this family of concepts provides a solid foundation upon which to define a comprehensive research program for reducing uncertainties.

Our focus on stratospheric aerosols does not imply that we consider it to be the only viable shortwave climate engineering concept worthy of consideration (although, with our present state of knowledge, we do judge it among the most feasible and potentially useful.) Rather, our detailed evaluation of this one family of concepts aims to provide both: (1) general insights into some issues related to *any* shortwave climate engineering proposal (presented mainly in Part 2 of this report); and (2) an example and template of the kind of systematic program necessary to reduce uncertainties in other types of potential interventions (presented mainly in Part 3 of this report.) Examples of alternative SWCE concepts are included with references in Figure 1.

---

[19] We consider in this study the full range of proposed (and possible) aerosols that could be injected into the stratosphere to increase the Earth's albedo.

[20] NAS-1992; Crutzen-2006.

[21] For references and a summary discussion of the recent scientific investigations, please see: Rasch-2008b.

Annex 39 bis

A. Cashman et al., "Climate Change in the Caribbean: The Water Management Implications", *The Journal of Environment & Development*, 2010, pp. 42-67

The Journal of Environment & Development
19(1) 42–67
© 2010 SAGE Publications
Reprints and permission: http://www.sagepub.com/journalsPermissions.nav
DOI: 10.1177/1070496509347088
http://jed.sagepub.com

Climate Change in the Caribbean: The Water Management Implications

Adrian Cashman, PhD[1], Leonard Nurse, PhD[1], and Charlery John, PhD[1]

Abstract

Concerns over the status of freshwater availability in the Caribbean region and in particular the eastern Caribbean states have been expressed for at least the past 30 years. There is a growing realization that availability will be vulnerable to extremes of climate behavior and increasing demand for water. Climate modeling for the Caribbean region under a range of scenarios suggests a continuation of a warming in average temperatures, a lengthening of seasonal dry periods, and increases in frequency of occurrence of drought conditions. Using information from the most recent IPCC report and regional downscaling, the authors suggest what some of the macrolevel changes in temperature and rainfall might be and the implications for water resources availability. This article evaluates the existing availability of water resources, the implications of the most recent climate change modeling for the Caribbean region, and the impact of on existing service provision strategies.

Keywords

climate change, water resources, water management, scarcity, vulnerability, social impacts

Freshwater resources rank very high on the priority list of small island developing states (SIDS), given the sensitivity and vulnerability to extremes of climatic behavior (UNEP, 2004). Concerns over the status of freshwater availability in the Caribbean region and in particular the eastern Caribbean states have been expressed for at least the past 30 years (Caribbean Environmental Health Institute [CEHI], 2002). In spite of the significant progress that has been made in extending the coverage of water supply and sanitation services, there are increasing challenges in maintaining access, coverage, and quality standards. In the face of population pressures, urbanization, economic

[1]University of the West Indies

Corresponding Author:
Dr. Adrian Cashman Centre for Resource Management and Environmental Studies (CERMES), University of the West Indies, Cave Hill Campus, P. O. Box 4, Barbados, West Indies, BB11000
Email: adrian.cashman@cavehill.uwi.edu

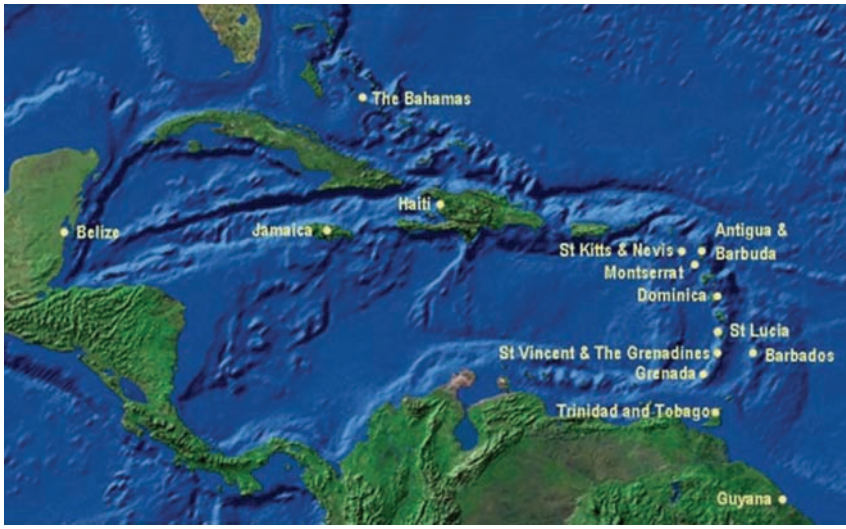


Figure 1. Caribbean region

development, and growth in tourism, pressures on water resources have increased significantly. Many Caribbean states are increasingly vulnerable to the dual challenges of increasing demand for water and climatic variability where even a slight reduction in rainfall would have serious consequences (Intergovernmental Panel on Climate Change [IPCC], 2007a; UNEP, 2003). Climate modeling for the Caribbean region under a range of scenarios suggests a continuation of warming in average temperatures, a lengthening of seasonal dry periods, and increases in frequency of occurrence of drought conditions. Major emerging concerns with respect to climate change include a limited capacity to adapt, flooding, saltwater intrusion, limited storage capacity, all contributing to increasing water scarcity (Arnell, 2004).

The ability of Caribbean states to cope with a growing water stress imbalance and the consequences for their social and economic well-being needs to be explored. Caribbean states have high levels of indebtedness and are economically vulnerable to the impacts of adverse climatic events (CDB, 2004). At the same time, demand for water is growing rapidly in all economic and social sectors. Using information from the most recent IPCC report and regional downscaling, we identify the likely macro-level changes in temperature and rainfall and the implications for water resources availability. This article seeks to evaluate the existing availability of water resources, projections of potential demand trajectories, and the impact on existing service provision strategies, and critiques some of the proposed responses to tackle water scarcity, such as desalination. The potential social and economic effects associated with increasing water resources stress are outlined and discussed.

General Background

In the Caribbean, as elsewhere, the ability to manage water resources and services and to respond to changing conditions is a function of the prevailing macroeconomic, institutional, and political circumstances. Many of the crosscutting environmental and development-related matters having an impact on water management affecting the region are dealt with in a piecemeal fashion, with the possible exception of climate change (Brown, Geoghegan, & Renard, 2007). Most countries in the wider Caribbean region have sought to initiate policy and institutional efforts to mitigate the negative aspects of development and demographic change. However, among other things, the high debt burden of many of the countries in the region has in some cases led to restrictions on the ability of the state to invest in public services, such as water management and services (CANARI, 2005). This is despite the fact that many of the countries have been ranked in the high- and middle- income categories according to the World Bank.

Almost all Caribbean states continue to encourage tourism, which makes up approximately half of the region's earnings from goods and services (ECLAC, 2005). Although there are restrictions, large-scale resorts continue to be developed in the region as a way of attracting ever more tourist-related revenue. Hotel tourism places huge demands on water resources and due to its economic importance tends to be privileged over other consumers. It is paradoxical that countries experiencing some of the highest rates of water scarcity are also some of the most attractive in terms of tourism, and therefore, experience the highest rates of increased demand for water (Brown et al., 2007).

In contrast to the importance given to tourism, the importance of agriculture in many economies has declined as has the percentage of the economically active population involved in agriculture (Ringler, Rosengrant, & Paisner, 2000). Nevertheless, in some cases efforts are being made to encourage the diversification of agricultural production (Ministry of Economic Affairs and Development Barbados, 2007). Globally, agriculture constitutes the single biggest user of water. Agriculture will continue to play a role in national economies; however, even after increasing attention being given to food security and the deveopment and active use of ecofriendly biofuels, the demands on water resources from agriculture are unlikely to decrease significantly. Furthermore, agricultural practices and land conversion have contributed to watershed degradation and pollution that have implications for both water quantity and quality.

Demographic patterns are increasingly having both a direct and indirect impact on water resources. With limited land available for an increasing number of uses and users, there has been a noticeable increase in concentrations of people in environmentally sensitive areas such as coastal zones and hillsides. Urbanization, a growing middle-class, and increased migration towards urban areas trigger an increased demand for water, and concurrently, increase problems associated with stormwater management, urban runoff, and waste management, and again lead to the pollution of water sources and the reliability of supplies. These in turn affect consumers, water users, and key economic

sectors and raise the cost of ensuring safe water supplies (Brown et al., 2007). This can be especially problematic where countries rely on a single source of water, for example, groundwater. One of the defining characteristics of SIDS is the close relationship between the environment and the rapid movement of impacts through that environment from "ridge to reef."

Water Resources and Consumption

Geographically the wider Caribbean region sits between the North American coast of Florida and the South American mainland, spread out as an arc of islands varying in size and topography. The region has a maritime tropical climate with wide variation in rainfall, influenced by topography and size of landmass. Seasonal variability of rainfall is marked by a distinct dry period, usually December to March/April and peak rainfall coinciding with the hurricane season of June to November, especially at the start and end of the season.

The lack of geographic homogeneity makes the drawing of any general observations about water resources problematic. Some rely solely on groundwater, whereas for others rainfall and topography allow the utilization of rivers and streams.

Information on the available water resources is scarce, as in many parts of the region there is no designated responsible central agency and a lack of trained and available personnel, equipment and monitoring systems, operating procedures, and management information systems necessary for the collection and collation of resource and consumption data. Indeed, it is not unknown for water service providers to have sparse reliable data on supply and demand. One water manager observed that though his water authority had good records of their own water production, there were no records or data of production by private producers or any proper appreciation of consumption patterns (personal communication). This is reflected to some extent in Table 1.

The above table indicates that at least in theory the availability of adequate water resources is not a constraint. Indeed, only three of the reported countries are considered water scarce with water scarcity being defined as being less than 1000 m^3 of total renewable water resources per person per year (Falkenmark, Lundqvist, & Widstrand, 1989), though this is a very crude measure. However, the total exploitable water resources, which are available to be utilized to support development taking into consideration the economic, environmental, and physical factors, are usually significantly smaller than the natural water resources. Depending on particular circumstances, the percentage can lie anywhere between 15% and 85 % (e.g., for Malta it is 30%). The scarcity of water in the Caribbean can also be illustrated using an approached developed by Falkenmark (Falkenmark & Rockström, 2005) in which the current level of mobilization of water resources is plotted against the availability of water. Using FAO *Aquastat* data, Figure 2 illustrates the relative social and technical water stress in the wider Caribbean region.

In Figure 2, the diagonal line indicates an assumed renewable water requirement of 1000 m^3 per person per year, for all activities by humans directly using renewable

Table 1. Caribbean States Water Statistics

Country	Total Renewable Water Resources Km^3/Year	Total Renewable Water Resources Per Head of Population m^3/Capita/Year	Total Withdrawals Per Capita m^3/Capita/Year	Percentage of Agricultural Use	Percentage of Industrial Use	Percentage of Domestic Use	Desalination Mm^3/a
Antigua & Barbuda	0.052	702	78.13	20	20	60	3.3
Barbados	0.080	294	334.6	22	44	34	44
Belize	18.560	69, 756	597.6	20	73	7	6.9
Cuba	38.120	3, 358	727.5	69	12	19	
Dominica	—		218.4				
Dominican Republic	20.990	2, 333	313.5	66	2	32	
Guyana	241.000	313, 802	2 147.0	97	1	2	
Haiti	14.030	1, 641	120.5	94	1	5	
Jamaica	9.404	3, 482	156.1	49	17	34	0.5
Puerto Rico	7.100	1, 814					
St. Kitts & Nevis	0.024	571					
St. Vincent & Grenadines	—		85.78				
Trinidad & Tobago	3.840	2, 929	238.8	6	26	68	36.5

Note: There are no data reported for Grenada and St. Lucia.
Source: FAO aquastat database, water scarce countries shown shaded <1000 m^3/capita.

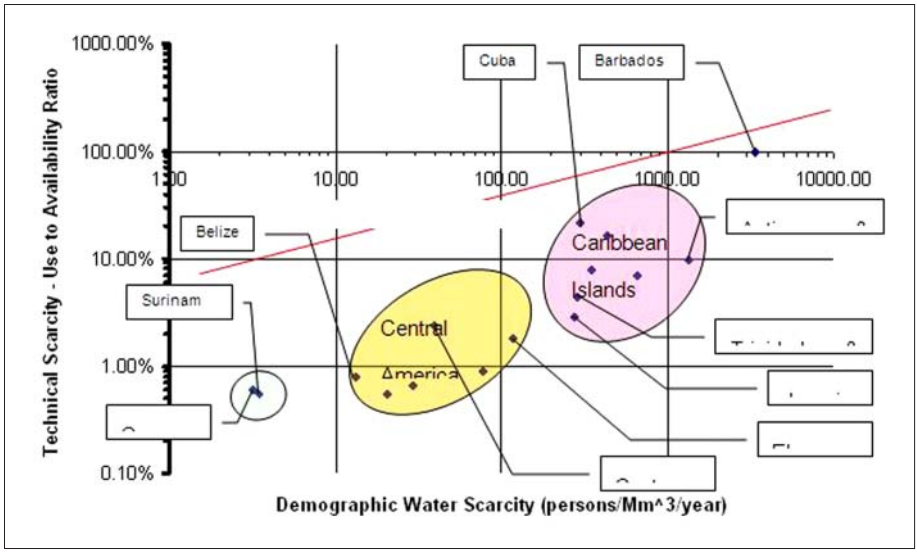


Figure 2. Social and technical water stress (after Falkenmark & Rockstorm, 2005)

water resources. According to Falkenmark, particularly critical are those countries that (a) have more than 20% mobilization of water resources due to the high investment needs required to make more water accessible for use, and (b) have more than 600 persons per flow unit. Falkenmark also highlights coping capability and financial means as further determinants that compound the problems of scarcity. One of the conclusions reached by Falkenmark and Rockström was that water scarcity is linked to substantial withdrawals or a low coping capability, limiting the prospects for an increase of withdrawals. They highlight the critical position of North Africa and Western and Southern Asia in this respect, which, if plotted on the graph, would lie somewhere between the Caribbean Islands cluster and Barbados. By these measures, Barbados, followed by most other Caribbean Islands, can currently be seen as a water-stressed and water-scarce state. The likelihood is that with increasing population and social trends Caribbean island states will become evermore water scarce, making additional increases in supply very expensive and environmentally sensitive.

However, it is not a question of total amounts of water resources available through a year, rather it is about the seasonality of the availability and the ability to capture peak season precipitation and make it available at other times of the year. This is a function of the nature of the resource available (groundwater or surface water) as well as infrastructural deficiencies, for example, high rates of unaccounted water, insufficient supply network capacity to meet demand, and inadequate storage capacity. Some countries that experience a high degree of seasonality in their rainfall patterns and uneven distribution of resources in time and space have invested in storage systems as a means of smoothing out both seasonal and interannual variability and redistributing water to when

Table 2. Progress Toward MDG Target 7 as at 2004

Country	Percentage of Population With Improved Drinking Water Coverage	Percentage of Population With Household Connection	Percentage of Population With Improved Sanitation Coverage
Anguilla	60	45	99
Antigua & Barbuda	91	84	95
Bahamas	97	70	100
Barbados	100	100	100
Belize	91	81	47
Bermuda	—	—	—
British Virggin Islands	98	97	100
Cuba	91	74	98
Dominica	97	87	84
Dominican Republic	95	80	78
Grenada	95	82	96
Guyana	83	53	70
Haiti	54	11	30
Jamaica	93	70	80
Montserrat	100	—	96
St. Kitts and Nevis	99	77	95
St. Lucia	98	75	89
St. Vincent and the Grenadines	—	—	—
Trinidad ND Tobago	91	77	89
Suriname	92	81	94

Source: WHO/UNICEF, 2006.

and where people wanted it. Whereas arid, rich countries such as the United States and Australia have built over 5000 m^3 of water storage per person, and middle-income countries like South Africa, China, and Mexico can store about 1000 m^3 per person, India by comparison can only store 200 m^3 (Cashman and Ashley, 2008). At present, there is no comparable figure available for Caribbean Island states, but it is likely that the per capita storage figure is closer to that of India than Mexico or South Africa.

It is already known that many of the island states experience difficulties in meeting demands at certain times of the year. In ,Barbados demand already exceeds the total annual renewable freshwater resource (CEHI, 2002), meaning the country is reliant on desalination to meet the shortfall. Antigua and Barbuda is reliant on desalination and rainwater harvesting for a large part of its supply. In other instances, for example, Grenada, St. Lucia, and St. Vincent, and the Grenadines, demand exceeds supply during the dry months, and water shortages are experienced even in Dominica (USACE, 2004). Estimates indicate that the reduction in available resources can currently be 40% or more in the dry season. On islands such as Bequia and others in the Grenadines, where

the main source of supply is "roof water," fluctuations in rainfall patterns means that every year local supplies run out and have to be supplemented by water shipped in by the government (Durrant, 2007). In addition, periodic droughts have affected even water-rich countries such as Guyana and Trinidad (Caribbean Environmental Health Institute [CEHI], 2007a; *Daily Nation*, April 2007).

This pattern of periodic shortfall in supply contrasts with the generally high levels of access to water supply and sanitation that are reported. The majority of Caribbean states have near-universal access to safe water, particularly in urban areas, and access to basic sanitation (see Table 2; WHO/UNICEF, 2004). In other words, most Caribbean states are on track to achieve the Millennium Development Goal 7 target of halving, by 2015, the proportion of people without sustainable access to safe drinking water and basic sanitation. However, the definitions used say little about the reliability and adequacy of potable supply or sanitation and not all people who do have access to these facilities actually use them, for various reasons (WHO/UNICEF, 2004). In most states, sewerage services with primary levels of wastewater treatment service cover less than 20% of the population and are usually confined to the capital cities and major towns. The earlier gains made in providing water services are being undermined by aging infrastructure and the difficulties of keeping pace with rising demands placed on the systems, especially by urban and tourism-related developments. The extent and impact of disparities in distribution and access to water services has been, with a few exceptions, underresearched (see Mycoo, 2007; Schneiderman & Reddock, 2004).

Some Caribbean states have over the last decade made efforts to adapt the institutional arrangements in their water sectors but as might be expected, and given the disparities between states in the region, these vary. Water resource sitatuion varies between states, with some regions having very little to show in terms of policy and organizational revamp since the mid-20th century and others showing significant organizational and institutional changes (Cashman & Daniel, 2008). Water service provision remains an activity that is undertaken by governments, usually in the form of a statutory authority or government-owned corporation. In few instances, forms of divesture, such as privatization, have been tried (e.g., St. Lucia, Trinidad, Tobago, and Belize), but difficulties were encountered with the enterprises being taken back into state ownership. More successful have been the efforts to separate service provision from economic and environmental regulatory functions (e.g., Trinidad and Tobago, Grenada, St. Lucia, Dominica, Jamaica, Anguilla, and Barbuda). This has not yet placed these water service providers on a firmer financial footing or improved their operating efficiency, partly because the governments continue to see water provision as a social service and are reluctant to implement cost-recovery policies.

On the other hand, there has been a widespread acceptance, especially among water sector professionals, of the concept of integrated water resources management (IWRM; UN Water, 2008). This is in part due to efforts by the likes of the Global Environmental Facility—UNEP Integrated Watershed and Coastal Areas Management Project (IWCAM) and the work of the Global Water Partnership, to mention just two. The principles of IWRM include the recognition that water is a finite resource and an integral

part of ecosystems; human activities affect the productivity and functioning of water resources; water resources need to be managed at an appropriate level geographically and through the active participation of stakeholders; women have a central role to play in water management; water should be equitably accessible; the management of water needs to be coordinated and integrated across different levels, sectors, and institutions; and water has an economic value and should be recognized as an economic as well as a social good (Pangare, Pangare, Shah, Neupane, & Rao, 2006).

In at least three countries, the principles of IWRM have been either incorporated into national plans and policies or there are plans to incorporate them (UN Water, 2008). Furthermore, the importance of water management to the region was also highlighted through the Caribbean Community (CARICOM) Council for Trade and Economic Development (COTED) convening a special meeting in 2008 to chart a way forward with respect to the better management of water resources and service delivery. Perhaps one of the consequences of the advocacy of IWRM within the Caribbean region has been a growing realization on the part of policy makers that there is an urgent need to address the underinvestment in water infrastructure (CEHI, 2007b, 2009) and as evidenced by recent lending for water infrastructure by organizations like Inter-American Development Bank and the Caribbean Development Bank. However, the ability to invest in infrastructure improvements and organizational capacity building is constrained by difficulties associated with achieving cost recovery and competition from other sectors for financial support from governments.

In many of the countries consumption is constrained by factors such as the seasonal effects on water resources and intermittent supply (CEHI, 2007a). There are also the perverse effects. The low tariffs that seem to be endemic to much of the region, fail to signal to consumers the scarcity and value of water. At the same time, water service providers can have rates of unaccounted or nonrevenue water up to 60%, depending on whose figures are accepted, which in itself is an indication of the serious lack management information. Unmet demand for water is not uncommon; for example, it has been reported that only 14% of Trinidadians received an uninterrupted water supply and that the difference between estimated demand and actual supply in 2000 was 11% (Schneiderman & Reddock, 2004). Recently, Trinidad's Water and Sewerage Authority announced that it wants to invest in increased storage and construct a new national water transmission network in order to achieve "water for all" (*Guardian*, April 14, 2008). Thus, any calculation of the real level of demand is problematic. What can be inferred though is that the demand for water, whether fully realized or not, will grow. The factors that will drive this will be population demographics and economic development. The populations of many of the islands are set to rise in the medium term (United Nations, 2006) and an increasing proportion will become urbanized. At the same time, urban populations especially will become economically better off, which will translate into changed life styles, expectations, and higher standards of living and consumption. Governments are committed to trying to meet the Millennium Development Goals, which has implications for water services provision and hence demand. More land will be brought under irrigated agriculture and as a part of their national

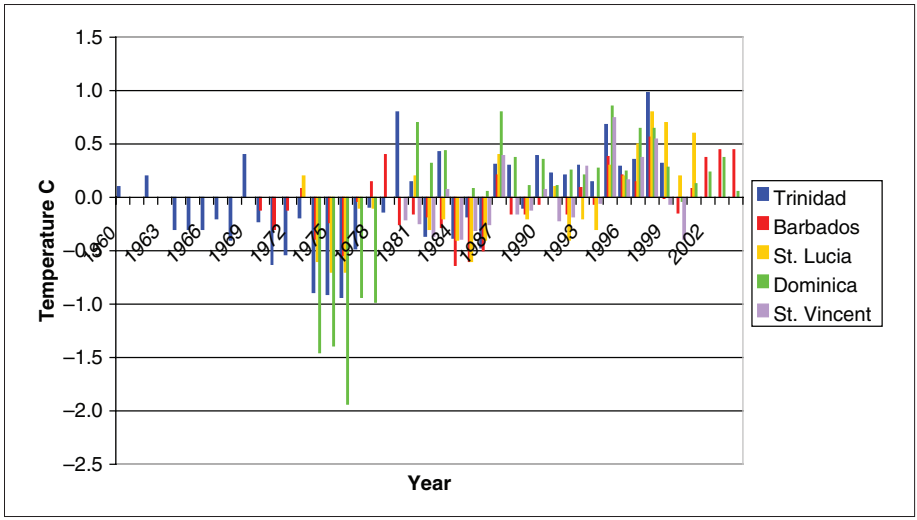


Figure 3. Deviations from mean annual temperature as recorded by the National Meteorological Services in Trinidad, Barbados, St. Lucia, Dominica, and St. Vincent, respectively

plans many island states are seeking to continue to promote industrial development and growth in tourism.

A preliminary estimate for Barbados, for example, indicates that potential water demand could increase by nearly 50% over present levels of consumption. Often peak levels of demand coincide with the dry season. With demand for water set to increase throughout the region, even without the effects of climate change the existing problems arising from the seasonality of water resources would be exacerbated.

Climate Change Impacts and Water Resources

The recently released fourth assessment report of the Intergovernmental Panel on Climate Change projects a bleak future for water resources availability in regions such as the Caribbean. The report suggests that *decreases* in mean annual precipitation (in some cases by as much as 20%) are likely[1] in the regions of the subtropics (see also Figure 3 for the Caribbean basin). Moreover, the report indicates unequivocally that on account of human-induced thermal expansion of the ocean surface and the melting of land ice, global mean sea level will continue to rise at a rate of 1.0 to 7.0 mm/year for many decades into the future (IPCC, 2007a). This rate of rise is approximately 10 times higher than the average rate of rise in the previous 3,000 years. In the case of the Caribbean region, a recent model that runs under a variety of climate scenarios suggest that sea level will continue to rise for the next several decades at between 5.0 and 10.0 mm

[1]In the IPCC Fourth Assessment Report this represents a confidence level of at lest 90 per cent.

per year (IPCC, 2007a). Though this rate of rise may appear to be quantitatively small, the effect will be disproportionately great on low-lying coastal areas, such as those in the Caribbean, where aquifer size is partly controlled by the size of the land mass.

In the specific case of the Caribbean, sea levels have risen at a rate of approximately 1 mm/year during the 20th century. Together with a projected decrease in rainfall, rising sea levels will lead to salinity intrusion into coastal and groundwater aquifers and thus reduce freshwater availability. However, the effect of *eustatic* sea-level rise on the adjacent land mass is complicated by the fact that vertical crustal changes are occurring on some Caribbean islands, as a result of tectonic processes (Farrell, Moseley, & Nurse, 2007). For example, available records suggest that in Trinidad the sea level in the north of the island is rising at roughly 1 mm/year (the average for the region); however, in the south, sea level appears to be rising at approximately 4 mm/year. This must be of great concern to the small islands of the Caribbean, given that global sea levels are projected to continue rising by up to 7 $mm/year^{-1}$ during the 21st century.

Recent results from studies carried out by the Institute of Meteorology in Cuba and the University of the West Indies (Taylor et al., 2007) have indicated that the mean temperatures of individual Caribbean territories have demonstrated an upward trend during the last three decades. This trend is driven largely by the steady increase in daily minimum temperature values (see Figure 3). The studies also showed that the frequency of droughts has increased significantly, whereas the frequency of other extreme events in the region seems to be changing with flooding events and hurricane passage through the region increasing since the mid-1990s (Taylor et al., 2007).

From the results of the regional climate modeling project for the Caribbean region, which was undertaken jointly by the University of the West Indies and the Institute of Meteorology using the United Kingdom Hadley Centre's PRECIS model, the main conclusions about changes in average temperatures were that by 2080 an annual warming of between 1° and 5° C would be experienced through the Caribbean, depending on the region and scenario. The warming would be greater in the northwest Caribbean territories of Cuba, Jamaica, Hispaniola, and Belize than in the eastern Caribbean island chain. Also, there would be greater warming in the summer months than in the cooler and traditionally drier earlier months of the year.

Recent projections from a macroscale hydrological model using the IPCC SRES scenarios suggest that many Caribbean islands are likely to become increasingly water stressed in the future, as a result of climate change (see Figure 4), irrespective of the climate scenario employed (Arnell, 2004; Taylor et al., 2007). The A2 Scenario is based on a world of independently operating, self-reliant nations; continuously increasing population; regionally oriented economic development; and slower and more fragmented technological changes and improvements to per capita income. The B2 Scenario is based on assumptions of continuously increasing population, but at a slower rate than in A2; emphasis on local rather than global solutions to economic, social, and environmental stability; intermediate levels of economic development; and less rapid and fragmented technological changes. The A1B Scenario is based on the assumption of a balanced emphasis on all energy sources (IPCC, 2007a).

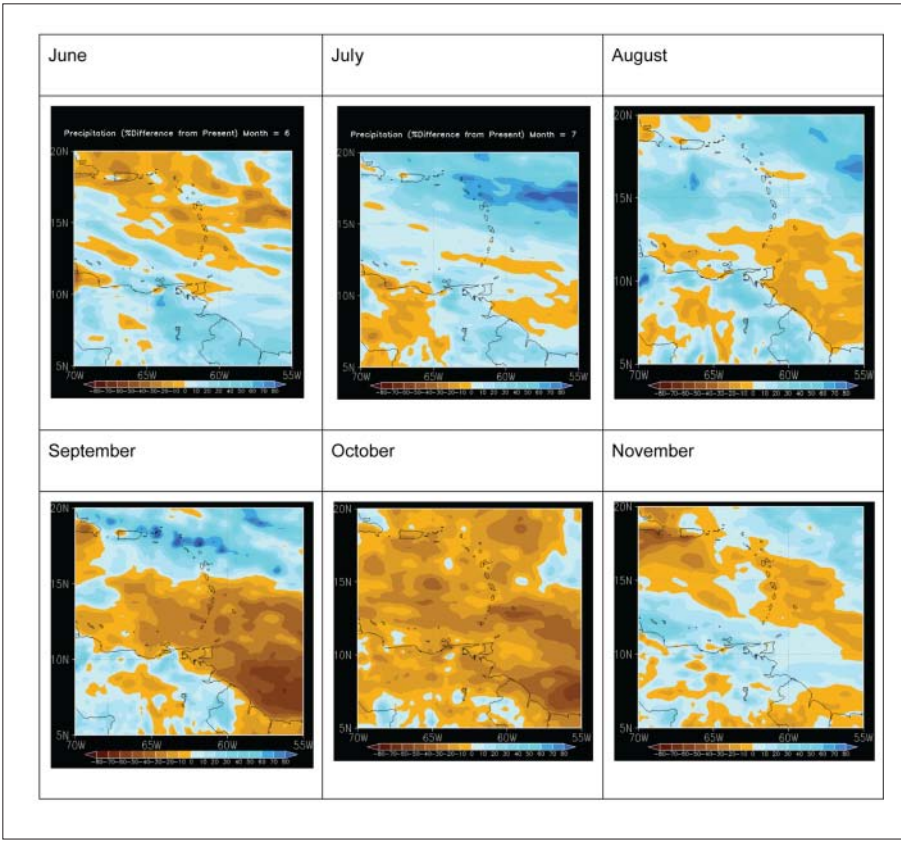


Figure 4. Changes in monthly rainfall patterns, A1B Scenario 1990s-2070s (earth simulator's super-high resolution GCM; Japan's Meteorological Research Institute)

Figures 4 to 7 show the changes in monthly rainfall patterns for a particular IPCC SRES scenario derived using the PRECIS model. The changes are shown as a percentage deviation from the mean monthly precipitation using the period between 1960 and 1999 as the baseline. The percentage deviations are shown in 10% intervals and are differentiated in the figures by increasing color intensity; that is, the deeper the color the greater the deviation from mean monthly precipitation. The increasing intensity of blue indicates the projected percentage increase in monthly precipitation, mapped across the Caribbean Region, whereas an increasing intensity, from yellow to brown, indicates decreasing precipitation, mapped across the Caribbean region.

The pattern that is emerging from the modeling work into changes in annual average precipitation carried out suggests a drying across the Caribbean basin. The decreases in rainfall range from 25% to 50% depending on the scenario and part of the Caribbean basin. For example, using the 1960-1999 baseline climate period, the model

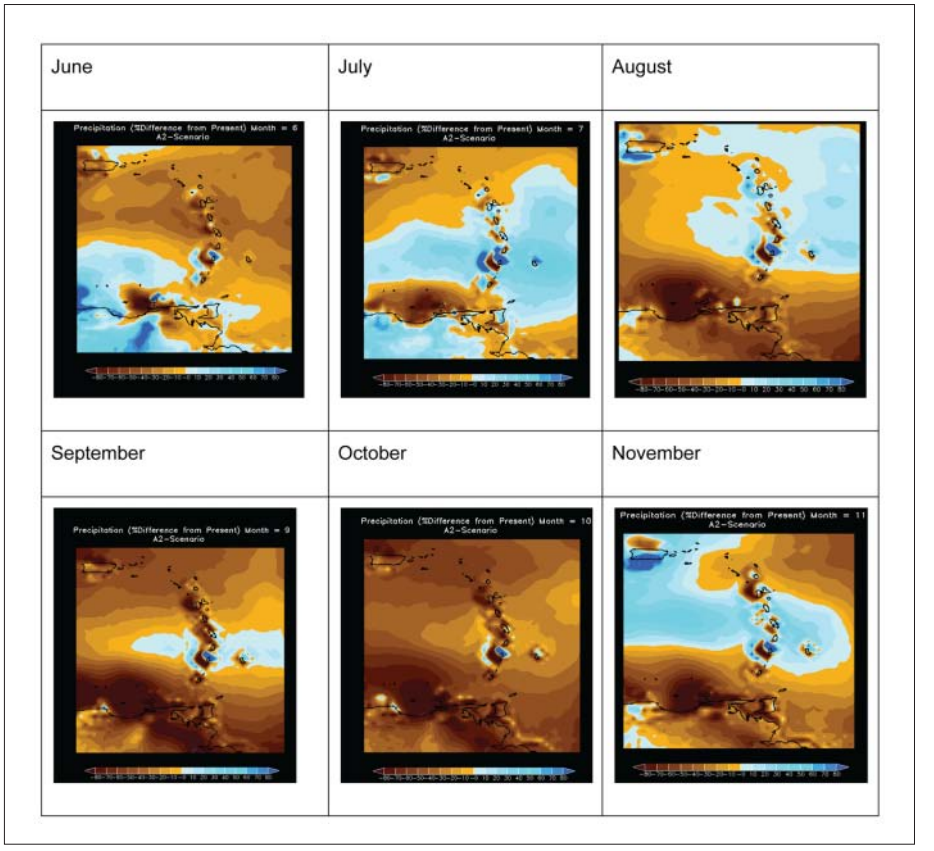


Figure 5. Changes in monthly rainfall patterns, A2 Scenario 1990s-2070s, as simulated by the U.K. Hadley Centre's PRECIS regional climate model

shows that the southern Caribbean region and the islands from St. Kitts to Martinique will have the largest percentage of decreases relative to the mean precipitation by the 2080s. On the other hand, the exception to the overall drying trend is in the far north of the Caribbean, including western Cuba and the southern Bahamas plus Costa Rica and Panama, all are up to 25% wetter under the scenarios. The effect of climate change appears to be to enhance the existing climatic pattern, making the wet and dry zones wetter and drier, respectively, during the first 4 to 6 months of the year. However, for the months from May to October, the entire Caribbean region is up to 25% drier. The changes in average rainfall show a pronounced north–south gradient in rainfall change during the January-to-April dry season, whereas the summer drying is set to become more severe during the wet season (Taylor et al., 2007).

Despite the widely varied conditions that drive the different climate scenarios, there is a large degree of agreement between the different climate models with respect

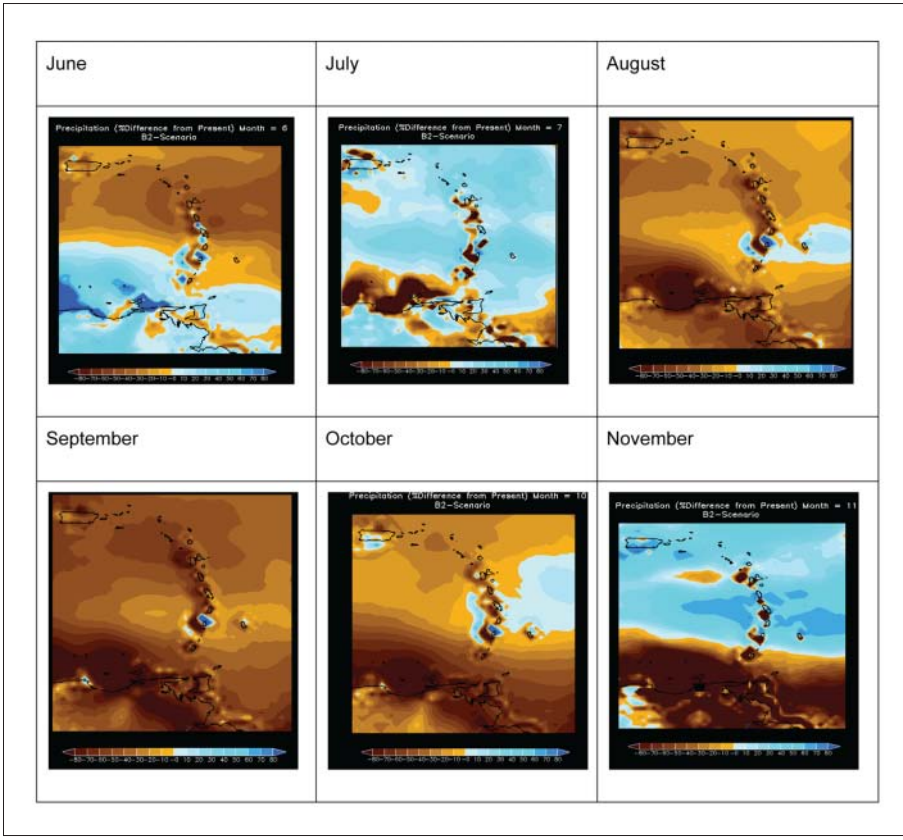


Figure 6. Changes in monthly rainfall patterns, B2 Scenario 1990s-2070s, as simulated by the U.K. Hadley Centre's PRECIS regional climate model

to rainfall patterns in the Caribbean. In the case of the Eastern Caribbean under all three climatic scenarios examined (A1B, A2, and B2), the projections are for a substantially drier wet season (July to November) as shown in Figure 1, an even drier dry season (March to April), and a marginally wetter spell at the end of the year. For the purposes of comparison, Figures 4 and 5 show the monthly changes in rainfall patterns over the eastern Caribbean for climate scenarios A2 and B2, respectively.

Discussion

Stress Factors

There are multiple processes that control water quantities, quality, and flow regimes, but in terms of water supply two issues are crucial: the changes in average run-off supply and changes in the frequency and severity of extreme events (flooding and

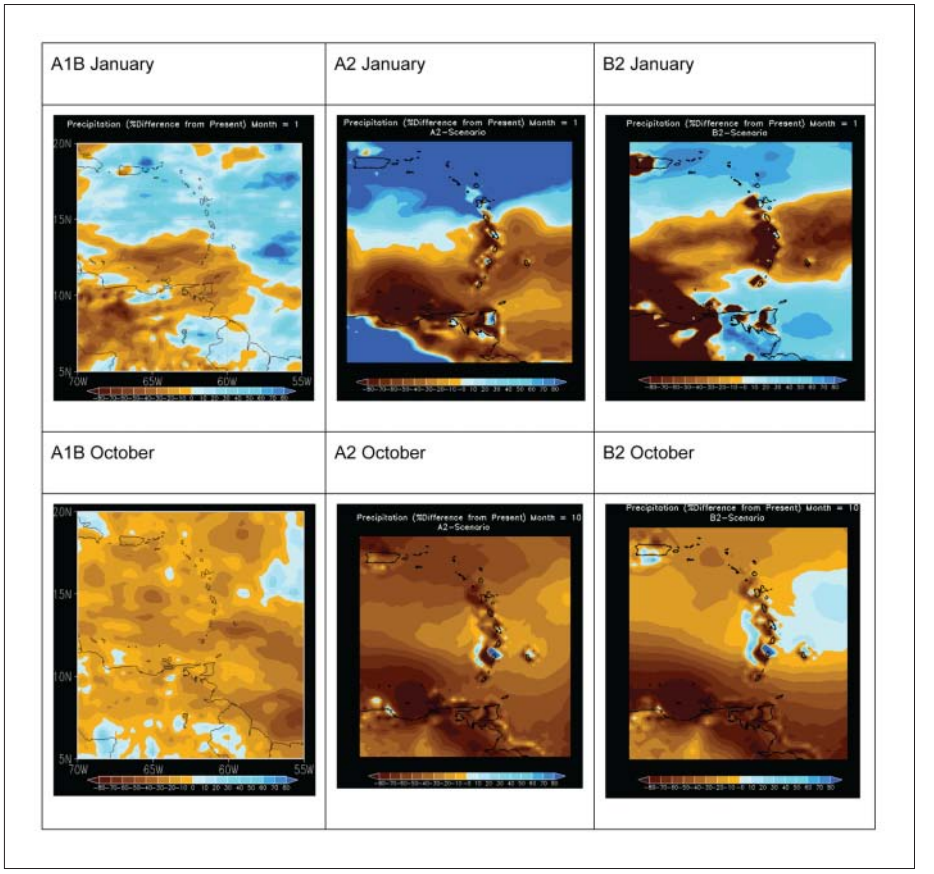


Figure 7. Comparative changes in monthly rainfall across scenarios A1B, A2, and B2

drought). Although the extent of these changes is not clear, this work provides some insight into the potential severity of changes if appropriate adaptation strategies are not implemented. Other work has already suggested that climate change may already be causing long-term shifts in seasonal weather patterns, and hence, the run-off production that characterizes renewable freshwater supply (freshwater). Together, general warming and rainfall deficits bring about changes in vegetation and soils. This too could have adverse implications for groundwater recharge though current understanding of this topic is poor and little research has taken place so far (Alley, 2001). Water balance is not easily determined for island systems, and on average, groundwater recharge normally requires 20% to 25% of rainfall, which is not easily retained on islands (MEA, 2005a).

Research from Caribbean and other jurisdictions has shown that climate-related extreme events are also likely to have an adverse effect on the availability of freshwater

supplies. The effect of warm spells and heat waves (e.g., during El Nino events) could lead to higher evaporation losses and reduced water quality due to an increase in the incidence of various phenomena, for example, algal blooms (IPCC, 2007b). Similarly, an increase in the frequency of drought projected for the Caribbean region will also serve to exacerbate existing water stress (Arnell, 2004; IPCC, 2007). It is also well established that salinity intrusion into groundwater lenses resulting from a combination of sea-level rise and overabstraction is already posing a threat to the quality and availability of freshwater supplies on many islands.

Moreover, contamination of ground and surface water frequently occurs following the passage of tropical storms, cyclones, and heavy precipitation episodes, sometimes rendering the available water unfit for human consumption for long periods, particularly in regions such as the Pacific (Terry, 2007), the Caribbean (Arnell, 2004; IPCC, 2007), and South Asia (Manton et al., 2001; Mirza and Ahmad, 2005). In the case of countries like Barbados, Grenada and the Bahamas, more than 80% of the potable water is abstracted from groundwater aquifers and pumped to the reservoirs; supply is almost periodically disrupted due to power outages caused by tropical storms, and other extreme weather events would also add to the challenges already faced by local water resource managers.

More intense rainfall events, in addition to potentially giving rise to increased flooding, including likely flooding in urban and periurban areas, will adversely affect water quality, with consequent implications for public health. Changes in both patterns of flow and residence time of water in catchments affect water quality regardless of quantity. Increased levels of turbidity through increased erosion would mobilize higher levels of contaminants and pollution, requiring greater levels of treatment that water utilities may not be able to cope with during increasingly frequent extreme (high run-off) seasons. This could exacerbate existing difficulties due to lack of sanitation as well as adequate and appropriate drinking water treatment. As noted (IPCC, 2007b; chapter 3) there are no studies that analyze the impact of climate change on biological water quality from the developing countries' perspective.

As the rate of demand is already exceeding the rate of supply, most of the islands are likely to experience increasing water deficits. It is worth pointing out that climate change–induced water scarcity is likely to be a feature of most small islands, not just those in the Caribbean. For instance, a study commissioned by the World Bank (2000) shows that a 10% decrease in mean rainfall by 2050 would be equivalent to a 20% reduction in the extent of the freshwater aquifer on the Tarawa Atoll, Kiribati in the Pacific. Furthermore, model outputs for Bonriki Island, Tarawa, and Kiribati indicated that a 25% decrease in rainfall combined with a 50 cm rise in sea level could cause the freshwater lens to contract by approximately 65% (World Bank, 2000).

Although little detailed work has been carried out on the effects of the most recent climate change scenarios on the water resources of individual islands and Caribbean states, a few general inferences may be made on the basis of on-going climate modeling of the Caribbean basin. The modeling, as noted earlier, indicates, irrespective of any scenario, region wide, a significant decrease in overall rainfall, especially during the

important rainy season, of up to 30% over the period from 1990s to 2070s may occur. The effective lengthening of the dry season period, coupled with reductions in received rainfall, higher temperatures, and rates of evapotranspiration, will not only cause greater ecological stress but also lead to what are likely to be significant reductions in available water resources, and by implication, higher levels of water stress for those countries reliant on surface water resources, such as Dominica, Grenada, Jamaica, St. Lucia, St. Vincent, and Trinidad and Tobago.

The changes in precipitation patterns will also affect run-off characteristics. A recent report in *Nature* speculated that changes in climate through their impact on vegetation may further contribute to the severity of flooding during intense rainfall events (Betts et al., 2007). More intense rainfall events will result in flashier run-off and potentially greater occurrence of flash flooding. Furthermore, land cover and use changes have also altered, which in turn intensify the patterns of run-off, giving rise to additional forms of pollution with consequent impacts on human health, aquatic ecosystems, and biodiversity (freshwater) that would be exacerbated under the impact of climate change. Less overall rainfall and higher rates of run-off would lead to a corresponding decrease in water available for recharging groundwater aquifers as well as higher transport and pollutant loads. A decrease in overall rain and higher run-off will not only affect groundwater aquifers but also those reliant on other forms of rainwater capture and harvesting. This would either be due to quality considerations or an inability to capture sufficient amounts of the run-off. This would affect among others countries such as Antigua & Barbuda, Barbados, the Grenadines, Jamaica, St. Kitts and Nevis.

Socioeconomic Effects

There are multiple challenges that all countries face from climate change and the impact on water resources, and its management is just one facet. The impact on water issues should not be seen in isolation and as separate from other impacted spheres of concern, for example, health or economic development, as these are all factors that can contribute toward resilience and "climate-proofing." Managing water resources more intelligently is just one aspect of a bigger picture. However, low-income countries will face the greater challenge as more intelligent management must go hand in hand with strong leadership. Climate change that increases variability and event intensity will impose substantial costs on poor countries, both in terms of the adverse effects and the cost of creating adequate institutional and infrastructural adaptations (Muller, 2007). The impacts of extreme events on human and social welfare are likely to affect more severely countries with low adaptation capacity (IPCC, 2007b, chapter 3).

Caribbean island states will be vulnerable as a result of a lack of relevant information, data gathering, and monitoring; institutional weaknesses in responding to a changing environment; and difficulties in mobilizing and making available resources (IPCC, 2007b, chapter3). Add to this increasing water scarcity, even in the absence of climate change, it is likely to become a serious constraint on development, and by extension, the ability of governments to respond to the challenges of climate change

(MEA, 2005b, chapter 7). More often, increasing water scarcity and variability of supply have given rise to numerous development challenges that governments have struggled to address. These include increased levels of competition for water between different economic activities, people, and ecosystems; the increasing use of non-sustainable supplies or the development of costly alternatives; limits to economic growth that curtail activities and require the use of more expensive substitutes; and pollution and public health problems (Furlong & Gleditsch, 2003; Miguel, Satyanath, & Sergenti, 2004).

Though the availability of water is a function of climate, the ability to harness and manage water resources and provide water services depends more on other factors. These include technical expertise, adequate institutional arrangements, as well as adequate financial arrangements for the provision and support of water services. Climate change leads to additional costs for the water sector that it may not be able to absorb (IPCC, 2007b, chapter 3) and thus be taken into account in designing future infrastructure. Therefore, water investments should be designed to perform under future climate regimes. Furthermore, Ravenga and Cassar (2002) suggested that current approaches to the provision of water services, the lock-in to existing infrastructure, and weak regulatory and enforcement regimes have limited the effectiveness of water resources management. In this context, climate change as it pertains to water resources management may make an already bad situation worse.

Without much further research it is difficult to provide anything other than a qualitative overview of the possible social and economic impacts that would be associated with the climate changes outlined earlier. At a macroeconomic scale average public debt for Caribbean countries is almost 100% of GDP (Duncan, 2005), whereas per capita economic growth in GDP is expected to be between 2% and 3% average for the Caribbean region (World Bank, 2005). With respect to levels of poverty, income, inequality and human development index, the picture is more varied with significant instances of deprivation coupled with generally high rates of unemployment and underemployment (Duncan, 2005), which contribute to the vulnerability of some states. In addition, outmigration rates, especially among the better educated, tend to be high, coupled with low enrolment rates in tertiary education, which thus weakens the region's capability for achieving economic growth.

On most Caribbean islands, land size is relatively small and large numbers of the populations live in close proximity to the coastal areas. UNFCCC (2008) predicted that "a future of more severe storms and floods along the world's increasingly crowded coastlines is likely." Flooding will have immediate impacts on water resources and human populations. Water and sanitation systems would be disrupted and overburdened, thus contaminating water supplies, leading to the risk of increased exposure to water-related diseases (Water Aid, 2007). In addition, indirect health challenges include malnutrition arising from disruption to agriculture and food insecurity. Some governments would be able to cope better than others, which is linked to economic performance, institutional resilience, and other sociodemographic factors.

Agriculture may well be one of the hardest-hit sectors by climate change (Water Aid, 2007). The divergence of dependence of economies on agriculture through the Caribbean will reinforce an unequal distribution of impacts. Warmer temperatures and changes in land cover and use would lead to increased evapotranspiration, thus making the need for water more acqute particularly in times of water scarcity. The impact on currently produced crops, agricultural productivity, and hence, the viability of farming as an economic activity in the Caribbean region, has not been researched in detail as yet. However, one example is Cuba, where the impact of climate change on rice production indicated that overall per-hectare yields would decrease, with the gains in rainfed production failing to offset the decrease in flooded rice production yields (Taylor et al., 2007). At the same time, changes in climate may induce susceptibility to new forms of crop and livestock diseases and pests (Water Aid, 2007; MEA, 2005a, chapter 23).

Against this background, we consider the examples of rainwater harvesting and desalination and possible social and economic effects. For those reliant on rainwater harvesting, an obvious adaptation strategy to climate change would be to invest in more storage where it already exists, in order to require the provision of storage for new developments and to encourage greater uptake where rainwater collection does not exist. It is unlikely, however, that existing building regulations will be updated to take into account the need for greater storage. There are also questions of policing and enforcement of existing regulations, especially because these are seen by builders and developers as adding to costs. Though rainwater collection systems have stood the test of time in their ability to meet water needs, one of the most significant barriers to their adoption and use lies in the attitude and perception of householders and communities.

Those householders who rely most on rainwater collection systems for domestic supply, for example, in the Grenadines include a significant number in lower income and disadvantaged groups. In the case of Bequia in the Grenadines, for example, residents have to appeal to the government for assistance in the form of "water boats" to be able to meet their basic water requirements during the dry season (Durrant, 2007). With very low household incomes, such communities are the least able to afford to adopt adaptation strategies due to high costs involved in implementing such strategies. An alternative strategy would be to extend existing communal collection and distribution systems, which would require either community financing or government-led interventions. The former has similar drawbacks as before, whereas the latter, that is, reliance on the state, may be an uncertain prospect, and added to that, there would also be questions over financing, costs to the community, operation, and equity considerations. On the other hand, those who are better off economically, even when they are better placed to respond, may well be disinclined to do so. Interviews with home occupants in Barbados has indicated a certain resistance to the adoption of rainwater systems (Hegazi, Mouck, & Cashman, 2007). First, there are expectations that it is the responsibility of the state to ensure the adequacy of their water services. Second, there

may be a reluctance to invest in adapting their homes and businesses, especially if this entails having to self-operate an associated pump and purification system.

Climate change, for those communities and households that rely on rainwater collection systems as their primary source of supply, is likely to reduce the reliability of such systems in the absence of investment. Reduced reliability could also pose more problems in the form of health hazards, additional physical burdens, and livelihoods affected by reduced income levels. These would affect disproportionately the poor, the young, and the elderly, as well as women (Schneiderman& Reddock, 2004). Conversely, for those communities that do not make use of rainwater collection systems, a failure to change attitudes will compound the adverse impacts of climate change by placing even greater demands on existing systems of resource management and service provision.

An increasingly popular strategy has been to invest in desalination plants as a way of countering seasonal or persistent water resource shortages. This is the route that Water and Sewerage Authority (WASA) in Trinidad has embarked upon through its proposal to build five desalination plants (Guardian, 2008). However, such a strategy is unlikely to be suitable under all circumstances. Small communities in many instances will not be able to afford the full cost of desalinated water, and if the cost does go up, it will be those who are least able to afford the costs will be the most severely affected. On the other hand, governments may be reluctant to subsidize some communities at the expense of others, especially when faced with the sorts of financial constraints outlined previously. It is also expected that energy costs will continue to rise (Andrieu, 2005) and as desalination is an energy-intensive process, the costs of production will also rise. If such costs are passed on to the consumer, then, once again, it is those low-income and vulnerable households, where expenditures on necessities make up a proportionally large part of household budgets, which will be most adversely affected. A recent study has also pointed out the environmental problems in the form of increased greenhouse gas emissions and damage to coastal and marine environments (WWF, 2007). Caribbean states, by making increasing use of desalination, could indirectly be suffering an adverse impact on marine resources that support fishing and tourism, the two mainstays of many island economies.

Any underpricing of desalinated water could well be at the expense of other options. The question is, whether it is more cost effective to accept losses of anything up to 50% or more from water systems, in comparison to options such as desalination. Furthermore, the location of desalination plants in vulnerable coastal areas exposed to the effects of extreme events may well contribute to increased infrastructural fragility, at precisely the time when more robust adaptable solutions should be implemented.

Further Considerations and Conclusions

Although much more work needs to be carried out, it is already possible to draw some general conclusions regarding the implications for water management arising from climate change. Irrespective of climate change scenario, the water resources of the

Caribbean basin are going to come under increasing pressure. The likely decrease in rainfall, lengthening of dry seasons, and temperature increases will result in less available water resources throughout the region. Decreases in monthly rainfall in the peak rainfall months could be as much as 50% under certain circumstances. At the same time, it will not be possible (nor is it desirable) to turn back the economic development clock, which implies that demand for and consumption of water will continue to rise. In spite of clear evidence pointing to water stress in some countries, water stress has not acted as a constraint on planned developments, as countries appear to be trying to go the desalination way to get out of their water availability predicament.

In our brief review of the available literature, it does not appear that governments or water service providers in the region are considering the possibility of long-term water shortages while embarking on other development plans. In the first instance, many countries in the Carribean region lack the necessary basic data, the human resources, or the financial capacity to be able to undertake such work necessary to tackle water scarcity in the longer term. There can be little doubt that better water management practices will be the key to adapting to climate change–induced impacts on water resources, the demand for water services, and the avoidance of the manifold consequences arising from poor or inadequate water management. The prescription for managing the impact of climate change on water is the adoption of the philosophy and methodology of Integrated Water Resources Management IWRM (GWP, 2007; World Water Forum, 2006; IPCC, 2007b, chapter 3). Such an approach recognizes the importance of combining infrastructural and institutional responses and changing the way agriculture, industry, and human settlement patterns are managed. Although the interpretation of IWRM varies considerably, there is general agreement that it includes concepts of good environmental stewardship and the coupling of land management policies and practices with water governance in the context of political, socioeconomic, and administrative systems (Eakin & Lemos, 2006).

As has been indicated, the issue of water management has found its way into the CARICOM agenda providing a timely regional focus. Also an increasing number of Caribbean states are putting in place water policies that make explicit mention of IWRM, and some have started preparing master water plans for the first time, taking climate change into account. Although climate change and the resultant water scarcity are an important issue, especially for the Caribbean (Bates, Kundzewicz, Wu, & Palutikof, 2008) region, just as much emphasis needs to be placed on the way existing water resources and services are managed to address current problems as well as to anticipate evolutionary changes. In this respect, there should be a greater emphasis placed on "no regret" actions. These are actions that commonsense and good management practice would suggest should be undertaken as a priority, which, if undertaken, would also constitute adaptation to climate change. In this respect, we would conclude that there are actions that can be undertaken even without the need for major organizational, legal or policy changes and which represent value-for-money investments.

Steps that we believe would build capacity include the following measures:

- The robustness of existing water supplies needs to be enhanced by increasing the available storage.
- Greater attention must be paid to the maintenance of the existing water service infrastructure and the simultaneous implementation programs to reduce unaccounted-for water.
- The resilience of existing schemes can be enhanced by promoting and adopting appropriate water harvesting and reuse measures and technologies.
- Financial incentives must be put in place to improve water use efficiency in the same way that incentives are offered to the tourist industry.
- CARICOM must take the lead by encouraging regional governments to complete their water use efficiency plans, as mandated at the 2002 Johannesburg World Summit on Sustainable Development (WSSD, 2002).

At the organizational level, CARICOM should build on the 2008 COTED water management initiative and provide leadership and encouragement for the adoption and implementation of IWRM strategies and realignment of the water sector. CARICOM needs to consider regional mechanisms to share resources to supplement the limited technical and managerial capabilities that some states face. This could create opportunities and openings and make a contribution to stemming the outflow of expertise from the region and at the same time addressing concerns over the availability, quality, and reliability of information sources to support better management planning (GEF-IWCAM, 2008).

International as well as national lending and development agencies have supported a range of water resources and water management studies and projects throughout the Region. In this respect, we would make three recommendations:

1. That they exercise due diligence to ensure that the programs they are supporting are sound and relevant, reflecting the needs of the recipients;
2. That climate change is explicitly factored in the development and execution of programs;
3. That specific measures for training and capacity building, such as requirements for substantial involvement of local professionals, consultants, and others, must be included as prerequisites for the approval of programs.

In this respect the valuable experiences that research studies undertaken by the Caribbean Climate Change Center under their Main Streaming Adaptation to Climate Change program needs to be maximized.

We see the potential for encouraging nongovernmental bodies such as the Caribbean Water and Wastewater Association (CWWA), the Caribbean Basin Water Management Partnership, and Global Water Partnership–Carribean, among others, to develop and expand their training role. In this respect, there is also a need to complement this

and encourage regional academic institutions, such as the University of the West Indies, to expand their existing programs and simultaneously develop innovative approaches (e.g., through distance education programs) that address specific water sector needs. The major obstacle here is making the necessary finances available and sustaining them over a period of time. This cannot be achieved only with the resources available in the Carribean region; international agencies need to be engaged with as well. Perhaps this too is a potential brokering role for CARICOM to play.

Declaration of Conflicting Interests

The authors declared that they had no conflicts of interests with respect to their authorship or the publication of this article.

Funding

The authors received no financial support for the research and/or authorship of this article.

References

Alley, W. M. (2001). Groundwater and climate. *Ground Water, 39*, 161.

Andrieu, M. (2005). *Long-term trends and the demand for infrastructure*. Paris: Organization for Economic Cooperation and Development.

Arnell, N. W. (2004). Climate change and global water resources: SRES emissions and socio-economic scenarios. *Global Environmental Change, 14*, 31-52.

Bates, B. C., Kundzewicz, Z. W., Wu, S., & Palutikof, J. P. (Eds.). (2008). *Climate change and water* (Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat). Geneva, Switzerland: IPCC.

Betts, R., Boucher, O., Collins, M., Cox, P., Falloon, P., Gedney, N., et al. (2007). Projected increase in continental runoff due to plant responses to increasing carbon dioxide. *Nature, 448*, 1037-1041.

Brown, N., Geoghegan, T., & Renard, Y. (2007). *A situation analysis for the wider Caribbean*. Gland, Switzerland: IUCN.

Carribean Natural Resource Institute. (2005). *Governance and civil society participation in sustainable development in the Caribbean* (CANARI Policy Brief No. 7). Trinidad and Tobago: Author.

Cashman, A., & Ashley, R. (2008). Costing the long-term demand for water sector infrastructure. *Foresight, 10*(3), 9-26.

Cashman, A., & Daniel, J. (2008). *Water policy development in the Caribbean: An overview of developments, IWRM and the incorporation of climate change*. Fourth Caribbean environmental forum on "Climate change, water and sanitation: A shared responsibility" held from June 23 to 27, 2008, at Grenada Trade Centre, Grand Anse, Grenada.

Caribbean Development Bank. (2004). *Annual economic review 2004*. Barbados: Author.

Caribbean Environmental Health Institute. (2002). *Water and climate change in the Caribbean*. Castries, St. Lucia: Author.

Caribbean Environmental Health Institute. (2007a). *Background information*. Castries, St. Lucia: Author.

Caribbean Environmental Health Institute. (2007b). Road map towards integrated water resources management planning for Grenada. Castries, St. Lucia: Author.

Caribbean Environmental Health Institute. (2009). Road map towards integrated water resources management planning for Barbados. Castries, St. Lucia: Author.

Duncan, N. (2005). *Highlights of a time to choose: Caribbean development in the 21st century*. Paper presented at "The Challenges of the Contemporary Caribbean," 7th General Assembly, Panama City, Panama.

Durrant, S. (2007). *Monitoring the effect of below average precipitation on water resources in Paget Farm, Bequia, Grenadines*. MSc Research report submitted to Center for Resource Management and Environmental Studies, Barbados.

Eakin, H., & Lemos, M. (2006). Adaptation and the state: The challenge of capacity building under globalization. *Global Environmental Change, 16*, 7-18.

Economic Commission for Latin America and the Carribean. (2005). *Economic Survey of the Caribbean 2004-2005* (LC/CAR/L.52/Rev.1). Available from http://www.eclac.org.lc

Falkenmark, M., Lundqvist, J., & Widstrand, C. (1989). Coping with water scarcity requires micro-scale approaches: Aspects of vulnerability in semi-arid development. *Natural Resources Forum, 13*, 258-267.

Falkenmark, M., & Rockström, J. (2005). Balancing water for humans and nature: The new approach of ecohydrology. London: Earthscan.

Food and Agricultural Organization. (2007). *Aquastat*. Retrieved June 19, 2007, from http://www.fao.org/ag/agl/aglw/aquastat/

Furlong, K., & Gleditsch, N. P. (2003). The boundary data set. *Conflict Management and Peace, 20*, 93-117.

Farrell, D., Moseley, L., & Nurse, L. (2007). *Managing water resources in the face of climate change: A Caribbean perspective.* Proceedings of the 8th Annual Sir Arthur Lewis Institute of Social and Economic Studies (SALISES) Conference, UWI, St. Augustine, Trinidad, March 26-28, 2007.

Global Environment Facility and Intergrating Watershed and Coastal Area Management (GEF-IWCAM). (2008). *Indicators mechanism workshop*. A conference held from March 10 to 12, 2008, in Ocho Rios, Jamaica.

Global Water Partnership. (2007). Climate *change adaptation and integrated water resource management— An initial overview* (Policy Brief No. 5). Stockholm, Sweden: GWP.

Hegazi, F. Mouck, J., & Cashman, A. (2007). *An analysis of water supply and consumption*. An unpublished McGill/UWI report.

Intergovernmental Panel on Climate Change. (2007a). Climate change. (2007). *The physical science basis—summary for policy makers*. Cambridge, UK: Cambridge University Press.

Manton, M. J., Della-Marta, P. M., Haylock, M. R., Hennessy, K. J., Nicholls, N., Chambers, L. E., et al. (2001). Trends in extreme daily rainfall and temperature in Southeast Asia and the South Pacific, 1961-1998. *International Journal of Climatology, 21*, 269-284.

Ministry of Economic Affairs and Development. (2007). *National strategic plan of Barbados 2006 -2025*. Barbados: Bridgetown.

Miguel, E. S., Satyanath, S., & Sergenti, E. (2004) Economic shock and civil conflict: An instrumental variables approach. *Journal of Political Economy, 112*, 725-753.

Mirza, M. M. Q., & Ahmad, Q. K. (Eds.). (2005). *Climate change and water resources in South Asia*. Leiden, Netherlands: A. A. Balkema Publishers.

Muller, M. (2007). Adapting to climate change: Water management for urban resilience. *Environment and Urbanization, 19*, 99-113.

Mycoo, M. (2007). *Diagnosis of Trinidad's water problems—mid-1980s to mid-1990s* (Water Policy No. 9, pp. 73-86).

Pangare, V., Pangare, G., Shah, V., Neupane, B., & Rao, P. (2006). *Global perspectives on integrated water resources management: A resource kit*. New Delhi, India: Academic Foundation

Ravenga, C., & Cassar, A. (2002). *Freshwater trends and projections focus on Africa*. Retrieved June 11, 2009, from http://www.wwf.org.uk/filelibrary/pdf/africa_freshwater.pdf

Ringler, C., Rosengrant, M., & Paisner, M. (2000). *Irrigation and water resources in Latin America and the Caribbean: challenges and strategies* (EPTD Discussion Paper No. 64). Washington, DC: International Food Policy Research Institute.

Schneiderman, J. S., & Reddock, R. (2004). Water, women and community in Trinidad, West Indies. *Natural Resources Forum, 28*, 179-188.

Taylor, M. A., Centella, A., Charlery, J., Borrajero, I., Bezanilla, A., Campbell, J., et al. (2007). *Glimpses of the future: A Briefing from PRECIS Caribbean climate change project*. Belmopan, Belize: Caribbean Community Climate Change Center.

Terry, J. P. (2007). *Tropical cyclones and impacts in the South Pacific*. New York: Springer.

United Nations. (2006). *World population prospects: The 2006 revision population database*. Retrieved June 19, 2007, from http://www.esa.un.org/unpp/

United Nations Environment Program. (2003). *GEO Latin America and the Caribbean: Environmental outlook 2003*. Mexico: Author.

United Nations Environment Program. (2004). *UNEP's assistance in the implementation of the Barbados programme of action for the sustainable development of small island developing states*. The Hague, Netherlands: Author.

United Nations Framework Convention on Climate Change. (2008). *Feeling the heat future effects: A question of degree*. Retrieved May 21, 2008, from http://unfccc.int/essential_background/feeling_the_heat/items/2905.php.

UN Water. (2008, May). *Status report on integrated water resources management and water efficiency plans*. Prepared for the 16th session of the Commission on Sustainable Development in May 2008. New York.

United States Army Corps of Engineers. (2004). *Water resources assessment of Dominica, Antigua, Barbuda, St. Kitts and Nevis*. Mobile, AL: Author.

Vörösmarty, C., Lévêque, C., & Ravenga, C. (2005). Fresh water. R. Hassan, R. Scholes, & N. Ash (Eds.), *Ecosystems and human well-being: Current state and trends—findings of the conditions and trends working group* (pp. 165-207).

WHO/UNICEF. (2006). *Meeting the MDG drinking water and sanitation target: The urban and rural challenge of the decade*. Geneva/New York: Authors.

World Bank. (2000). *Cities, seas and storms: Managing change in Pacific Island economies: Vol. 4: adapting to climate change*. Washington, DC: Author.

World Bank. (2005). *Global economic prospects*. Washington DC: Author.

World Water Forum. (2006). Retrieved June 1, 2006, from http://www.worldwaterforum4.org.mx/

World Wildlife Fund. (2007). Making Water. Desalination: option or distraction for a thirsty world? Sydney, Australia.

World Summit on Sustainable Development**.**(2002). Available from http:www.johannesburg-summit.org

Bios

Adrian Cashman is a lecturer in water resources management whose interests include the governance of water resources and policy development in response to drivers such as climate change. He has more than 25 years of international experience in water management in government and the private sector.

Leonard Nurse is a senior lecturer whose research focuses on the impact of climate change on small island environments, human impact on coastal dynamics and, integrated coastal management. He is a member of the Intergovernmental Panel on Climate Change.

John Charlery is a meteorologist turned lecturer in computer science with interests in the areas of simulation and dynamic modeling. He runs the climate-modeling laboratory at UWI where the emphasis is on regional climate modeling over the Caribbean.

Annex 40

C. Karakosta et al., "Technology transfer through climate change: Setting a sustainable energy pattern", *Renewable and Sustainable Energy Reviews,* 2010, pp. 1546-1557

Renewable and Sustainable Energy Reviews 14 (2010) 1546–1557

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Technology transfer through climate change: Setting a sustainable energy pattern

Charikleia Karakosta *, Haris Doukas [1], John Psarras [1]

National Technical University of Athens, School of Electrical and Computer Engineering, Energy Policy Unit of the Management & Decision Support Systems Laboratory (EPU-NTUA), 9, Iroon Polytechniou str., 157 80 Athens, Greece

ARTICLE INFO

Article history:
Received 26 May 2009
Accepted 2 February 2010

Keywords:
Technology transfer
Sustainability
Climate change
Renewable energy

ABSTRACT

Climate change mitigation is considered as a high priority internationally and is placed in the top of the agenda for most politicians and decision makers. The key challenge is that low-carbon sustainable technologies need to be adopted both by developed as well as developing countries, in an effort to avoid past unsustainable practices and being locked into old, less sustainable technologies. Technology transfer (TT), as an important feature of both the United Nations Framework Convention on Climate Change (UNFCCC) and its Kyoto Protocol can play a key role. TT can allow countries to move quickly to environmentally sound and sustainable practices, institutions and technologies. Indeed, the transfer or innovation process must be fast enough, to reduce global vulnerability to climate change. The aim of this paper is to analyse the TT challenges and emerging opportunities under the new climate regime, in terms of the process of innovation into an existing energy system, the related barriers and the supporting diffusion mechanisms. Good practices for renewable energy are also presented and discussed by both the developed and the developing countries in this respect.

© 2010 Elsevier Ltd. All rights reserved.

Contents

1. Introduction . . . 1546
2. Basic concepts . . . 1547
3. Contours of advances and development . . . 1549
4. Technology transfer process conflicts . . . 1551
5. The distance between theory and practice . . . 1551
   5.1. Diffusion mechanisms and implementation programmes . . . 1551
   5.2. Paradigms of good practices . . . 1552
   5.3. Financial support systems and support programmes . . . 1554
   5.4. Emerging opportunities and threats under the CDM . . . 1554
6. Conclusion . . . 1555
   Acknowledgements . . . 1555
   References . . . 1555

1. Introduction

The origin of transferring sustainable energy technologies in the context of the international climate co-operation and in particular from industrialised countries to developing countries lies in Article 4.5 of the United Nations Framework Convention on Climate Change (UNFCCC). The Article 4 states that developed country Parties and other developed Parties included in Annex II to take "all practicable steps to promote, facilitate and finance, as appropriate, the transfer of, or access to, environmentally sound technologies and know-how to other Parties, particularly developing country Parties", and to "support the development and 'enhancement of endogenous capacities and technologies of developing country Parties", and calls on other Parties and organisations to assist in facilitating the transfer of such technologies [1].

* Corresponding author. Tel.: +30 210 7722084; fax: +30 210 7723550.
E-mail address: chkara@epu.ntua.gr (C. Karakosta).
[1] Tel.: +30 210 7722084; fax: +30 210 7723550.

1364-0321/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.rser.2010.02.001

Achieving the ultimate objective of the UNFCCC, as formulated in Article 2,[2] will require technological innovation and the rapid and widespread transfer and implementation of technologies, including know-how for mitigation of greenhouse gas (GHG) emissions. Transfer of technology for adaptation to climate change is also an important element of reducing vulnerability to climate change.

This technological innovation must occur fast enough and continue over a period of time to allow greenhouse gas concentrations to stabilize and reduce vulnerability to climate change. Technology for mitigating and adapting to climate change should be environmentally sound technology (EST) and should support sustainable development (SD).

SD on a global scale will require radical technological and related changes in both developed and developing countries. Economic development is most rapid in developing countries, but it will not be sustainable if these countries simply follow the historic polluting trends of industrialised countries. Rapid development with modern knowledge offers many opportunities to avoid bad past practices and move more rapidly towards better technologies, techniques and associated institutions. The literature indicates that to achieve this developing countries require assistance with developing human capacity (knowledge, techniques and management skills), developing appropriate institutions and networks, and with acquiring and adapting specific hardware.

Technology transfer (TT), in particular from developed to developing countries, must therefore operate on a broad front covering these "software" and "hardware" challenges, and ideally within a framework of helping to find new sustainable paths for economies as a whole. A key element is choice. Hence, the development of societal and organisational structures that enable well-informed choices of technologies which promote climate stability, adaptation to the effects of climate change and SD is essential. To a large extent, the state of the environment today is the result of the technological choices of yesterday. Similarly, the state of the environment in the future will be determined largely by the technologies we choose today.

The key challenge in this respect is that low-carbon sustainable technologies need to be adopted both by developed as well as developing countries, which requires that developing countries avoid past unsustainable practices and being locked into old, less sustainable technologies. Instead, TT should allow them to move quickly to environmentally sound and sustainable practices, institutions and technologies. The transfer or innovation process must be fast enough to reduce global vulnerability to climate change. In this process the clean development mechanism (CDM) of the Kyoto Protocol [2] could play a key role as it is focussed on low(er) carbon technology transfers to developing countries.

The process of technology transfer is informed by a range of literature on innovation, development, behavioural change and economic development. This paper draws on some of this literature and analyses the TT challenges and emerging opportunities within the new climate regime, in terms of the process of innovation into an existing energy system, the related barriers and the supporting diffusion mechanisms. Successful practices for the promotion of renewable energy are also presented and discussed by both the developed and the developing countries in this respect.

[2] Article 2 – Objective "The ultimate objective of this Convention and any related legal instruments that the Conference of Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilisation of greenhouse gas concentrations in the atmosphere at such a level that would prevent dangerous interference with the climate system. Such a level should be achieved within a timeframe sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner".

Apart from the introduction, the paper is structured along five sections. First, it is worth reviewing at TT in more detail from a conceptual view. In the following sections, some of the developments of the theories in this area and the implications for TT process and paradigms of TT good practices for renewable energy are traced. Finally, the last section is the conclusions, which summarizes the main points that have arisen in this study.

2. Basic concepts

Several types of technologies that could assist with addressing the problem of climate change already exist. The challenge is how to make them readily available where they are needed most. Although TT is a common feature of many sectors of human activity these days, the idea of actively encouraging it is a fairly recent one. Transfer has only really been seen in practice in the second half of the 20th century, prior to which technological advance was viewed (and of course, to some extent is still viewed) as synonymous with power, both military and economic, and was closely guarded.

Technology transfer may appear a relatively simple process. Assuming the classical "economic" view of technology – as "objects" that can be moved around – transfer can be as simple as the sale or purchase of industrial equipment. However, inherent to this view of TT – as a "one shot" relocation of a fully blown technology from one economic and cultural context to another – is that it creates and maintains dependency on the part of the recipient. If transfer is to lead to a more satisfactory outcome, and one which is more in line with the ends of sustainable and equitable development, a much wider approach is required.

Schnepp et al. [3] define technology transfer as "... a process by which expertise or knowledge related to some aspect of technology is passed from one user to another for the purpose of economic gain". In the case of the transfer of low-carbon technology, the economic benefits that Schnepp et al. highlight include the mitigation of the future costs associated with climate change [4] as well as any financial benefits to the companies involved in the transfer process.

TT from the countries and companies that developed them to other countries and entities that could put them to good use in reducing GHGs has been an important theme in international deliberations leading to the UNFCCC. The Convention, signed at the United Nations Conference on Environment and Development (UNCED) in 1992, came into force in 1994, and requires (Article 4.1.c) the parties to UNFCCC, "to promote and cooperate in the development, application, diffusion, including transfer, of technologies, practices, and processes that control, reduce, or prevent anthropogenic emissions of greenhouse gases" [1].

The Intergovernmental Panel on Climate Change (IPCC) report on *Methodological and technological issues in technology transfer* [5] contains a broad definition of TT. They define technology transfer in terms of a set of processes "covering the flows of know-how, experience and equipment, for mitigating and adapting to climate change amongst different stakeholders such as governments, private-sector entities, financial institutions, non-governmental organizations (NGOs) and research/education institutions". Transfer includes diffusion of technologies and technological cooperation across and within countries. The term is usually applied to transfers from North to South, but as Brewer points out [6], it neglects the fact that some developing countries have climate friendly technologies which could be transferred from South to North and also from South to South.

According to the IPCC [5], technology transfer involves the process of "learning to understand, utilise and replicate the technology including the ability to decide which technology to transfer and adapt it to local conditions and integrate it with indigenous technologies".

Table 1
The relative importance of type of financial flow to TT pathway.

TT pathway	Government	Private sector	Community
Cross-border movement of personnel	–	+++	–
Foreign direct investment	+	+++	–
Foreign portfolio equity investment	+	++	+
Government assistance programmes	+++	–	++
Joint ventures	+	+++	–
Licensing	++	+++	–
Loans	++	+++	–
Meetings, workshops, conferences and other public forums	+	–	+++
NGOs	+	–	+++
Open literature (journals, magazines, books and articles)	+	+	+++
Trades in goods and services (includes purchases, sales, exports and imports)	+	+++	–

(+) Minor, (++) secondary, (+++) primary component of pathway.

The term technology transfer refers to both the transfer of knowledge and of the hardware. Knowledge can be comprised of explicit technical scientific knowledge about the principles of how a technology might work. Such transfers also need to involve knowledge about the practicality of the technology to make it work under a range of circumstances. Then, when a technology is being transferred through an organisation, such as a manufacturer, there is tacit knowledge associated with the procedures associated with the organisation. For the host developing country, there are similar knowledge requirements with additional need for people who can interface with the host country organisations and people who can understand and have knowledge about the systems into which the technology is being transferred with its supply and support chains.

Of course, knowledge is not enough for a complete transfer of the technology. There also needs to be consideration of the host country social capital for the skills and expertise needed and host country technology base in terms of manufacturing capacity, supply chain capacity, end-of-life/waste disposal, institutional capacity and sustainability of the whole process and the social networks between them. For the technology innovation to deliver benefits to the communities within the host developing country, it is also imperative that local organisations buy themselves in the investment and that communities are involved in the technology implementation process.

IPCC considers only North–South transfers and breaks down some of the elements of the processes involved [5]. It recognises a diversity of stakeholders in the process and identifies the following key actors: project developers, technology owners, technology suppliers, product buyers, recipients, users of the technology, financiers and donors, governments, international organisations, NGOs, and community groups. They do not mention research organisations, trade organisations and educational institutions, though these are also important in supporting the transfer process.

IPCC points out that technology transfer can take place in a number of ways and lists the following [5]: directly between government agencies, within vertically integrated firms, and partnerships across a network of information service providers, business consultants and financial firms.

The IPCC report also recognises that the pathways for transfer will depend on the country context, sector and type of technology [5]. However, they explicitly mention pathways for interaction, such as government assistance programmes, direct purchases, licensing, foreign direct investment (FDI), etc. and classify pathways into three primary types:

- Government-driven pathways are technology transfers initiated by government to fulfil specific policy objectives.
- Private-sector-driven pathways primarily involve transfers between commercially oriented private-sector entities, and have become the dominant mode of technology transfer.
- Community-driven pathways are those technology transfers involving community organisations with a high degree of collective decision-making.

Table 1 illustrates the importance of the different types of financing to various transfer routes.

Moreover, in addition to the ways in which TT can take place and the pathways for transfers, the IPCC report also identifies five basic stages within the processes involved in technology transfer: assessment, which includes identification of needs and choice of technology, agreement, implementation, evaluation and adjustment, and replication (Fig. 1). The stakeholders involved and the specific decisions and actions taken at each stage differ greatly depending upon the pathway. Based on the analysis of the interests and influences of different stakeholders at each stage it is possible to determine how various barriers to TT might be overcome. It is

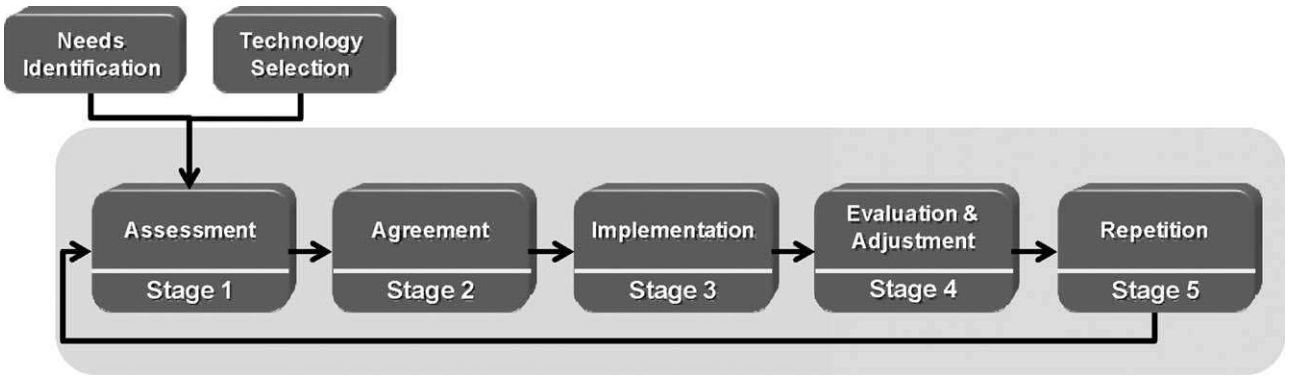


Fig. 1. The process of TT.

emphasised that the processes are complex and not necessarily sequential. The above-mentioned stages, from assessment of conditions of transfer to replication, which represent the transfer to the local energy market, are also essential when aiming at technology transfer via the CDM.

The IPCC quite rightly emphasises that there is no fixed prescription for enabling TT and that activities have to be grounded in the stakeholder and country context, as well as the technology scale and type. However, they focus on three main activities, which are considered to make a significant contribution to overcoming barriers, namely capacity building; enabling environment; and mechanisms for transfer.

There is no doubt that TT has been much encouraged by the development of multinational corporations seeking to expand their markets, and has been facilitated by developments in communications and changes in legislation on intellectual property rights. However, there are other important forces of change, including actions by multilateral organizations such as the United Nations, and by governmental and NGOs. Such organizations are concerned with promoting development that is more sustainable and equitable than in the past, and have identified TT, especially from industrialized to developing countries, as an important element in this process.

3. Contours of advances and development

The technology transfer process for a sustainable energy technology involves a process of innovation into an existing energy system. Innovation, whether social or technical, has been studied from the point of view of an industrialised developed country with the innovation taking place within its existing systems. Technology transfer, on the other hand, involves innovation from one country to another country, which may be more or less well developed. The innovation chain involves both the processes of research and development and the commercialisation of the technology, including its social acceptance and adoption.

The importance of social capital for successful innovation, in terms of the multiple stakeholder collaborative learning and knowledge transfer activities, has been pointed out by the National Systems of Innovation (NSIs) approach developed by Lundvall et al. [7]. Other important aspects of such national innovation systems can be found at regional, technological and sectoral levels within a country. As Lundvall et al. [7] point out, innovation system ideas are rooted in development theories [8] and so it is appropriate to make a connection between technology transfer aspects to developing countries and development theories.

When analysing economic change in developing countries, development theories used to emphasise the role of institutions, whereas in developed countries markets were assumed to dominate. In developing the theory further, it became evident that the development of new technology was an interaction between the user sectors and the producer sectors within a country. However, in the context of technology transfers from industrialised to developing countries, such as with the CDM, one possible model is that less developed countries are the user sectors and industrialised countries the producer sectors. Other possibilities, of course, are that less developed countries are both producers and users of technologies, such as in unilateral CDM and in South–South transfers (e.g. technologies produced China and implemented in CDM projects in other countries in Southeast Asia).

Further studies on NSIs showed that success in innovation relate to long-term and close interaction with external agents [9]. It was also realised that trust, loyalty and power relationships of the players in the market are important [10], which led to the focus on 'interactive learning' and that is the basis for the current focus on networks and mechanisms for innovation. It also supports the above-mentioned IPCC emphasis on the influence of differences in country contexts on technology transfer. For example, how firms and organisations from different countries interact depends on the differences between countries in terms of languages and mores, trust and transfer of tacit knowledge. In this respect, institutional aspects such as norms, habits and rules play an important role, as has been emphasised by Johnson [11], who stated that institutions play a key role in the process of relationship building and building of trust and that the regulatory and legal environment round an existing market, such as property rights, contract laws corporate law arbitration, and labour market institutions will have an effect on this.

Innovation systems have two main dimensions: the structure of the system and the institutional set up. The structure of the system is concerned about what is produced and what are the competences developed by the system, while the institutional aspect is concerned with how the production innovation and learning actually occurs within the system.

Lundvall specifically recommends the NSI approach for less developed countries as innovations are based on everyday activities in firms and abilities of ordinary people [10]. However, the study emphasises that the rate of change based on short-term financial criteria in markets has serious consequences for maintaining the social capital upon which the development of intellectual capital depends. In the authors view, the short-term financial focus ignores the value of longer term ecological implications and this has a negative impact on the innovation system.

Innovation according to Schumpeter [12] would involve firstly the demonstration of a technology and then the diffusion of the technology in space and over time. Thus, a new 'technology' is adopted by the market and is disseminated throughout that market. Of course, the process of adoption is complex and also involves some behavioural change on the part of the receiver. This means that people must make an effort to actively seek out and adopt the technology and adapt to its requirements. The efficiency of this adoption process will depend on people's experience, values and perceptions, but also on the economic, social and political environment.

Rogers and Shoemaker [13] and Ostland [14] developed a sociological/psychological theory of diffusion of innovations which has been widely applied to innovation of new technologies. Rogers [15] defines diffusion as: "the process by which an innovation is communicated through certain channels over time among the members of a social system". He derives three concepts from the theory: diffusion, adoption and innovativeness. Adoption refers to the famous S-shaped curve where the innovation, e.g. technology is adopted by more and more of the social system until it saturates the system. The rate of diffusion of the technology is the time taken to move from low numbers of adoption to the saturated level as also described by Gruebler [16]. Innovativeness is related to the personal characteristics of the individual who may be willing to change. Five stages of 'innovativeness' for individuals are identified and these stages correspond to the S-shaped diffusion curve [15]. These stages are innovators (first to adopt); early adopters; early majority; late majority; and laggards (last to adopt).

A review of the application of diffusion theory is provided by Rogers [15,17,18]. Key factors in the adoption process, which will affect the outcome, are identified. These factors include personality traits, attitudes, and socio-demographic factors, the nature of the social system, and their perception of the attributes of the innovation. These in turn require consideration of the communication system between the social actors and also the constraints of the social system. Social psychology is concerned with the links between the individual and society. Rogers [15], like Lundvall [10],

emphasises the social processes involved in diffusion and the nature of the social system. He proposes that system norms that reflect cultural patterns of behaviour have an important role in determining responses to innovation. Thus studying local practices and the barriers that these produce as well as incentives for adoption of an innovation can provide a foundation for progress in innovation acceptability and acceleration compared to the normal top down approach.

Rogers and Shoemaker [13] also introduced five types of perceptions that were identified from their study of innovations. These perceptions will have an effect on the decision to adopt the innovation and will thus affect the overall rate of adoption. The perception of the innovation is affected by the following psychological characteristics:

- *Relative advantage*: the perception of how much better the innovation is relative to the status quo.
- *Compatibility*: the perception of how well the innovation fulfils the person's needs, values and past experience.
- *Complexity*: how easy it is to understand and use.
- *Trialability*: the possibility of being able to try out the innovation on a limited basis before adoption.
- *Observability*: how clearly can the results of the innovation be seen?

The effort made by Bauer [19] and Ostland [14] has added to this list the characteristic of:

- *Risk*: the expected probability of economic personal or social problems resulting from adoption (see also Guagnano et al. [20]).

This can be modified to:

- *Perceived risk*: the perception of the social, physical and functional risks of the innovation [21].

Rogers and Shoemaker [13] also found that the relative importance of relative advantage, compatibility, trialability and observability were higher compared to perceived risks and complexity for adopters. Demographic factors were also found to be important with age and income being a key. Young and highly educated professionals on high incomes tended to be adopters.

Observability and trialability have been the subject of contention as some studies failed to find these aspects important. However, this is technology dependent and further work understanding the role of demonstration programmes was conducted by Shama and Wisenbilt [21] and Leonard-Barton [22].

Developments from Rogers' original work linked diffusion theory with social network theory [23] to account for the social interactions, which also affect the decision to adopt and innovate. This links to the effort by Lundvall [10] on National Systems of Innovation. In addition, the six factors identified above (including risk) can be disaggregated into subfactors, which could explore the complexity of the decisions being made. Trialability, however, was distinct in this respect.

Shama and Wisenbilt [21] postulated a refinement of the factors based on a review of the literature and the studies carried out. These are economic feasibility; reliability, maintenance and safety; legal and regulatory issues, and regional aspects.

One of his insights was that financial barriers may not be a good indicator, as what is important is the relative advantage over the status quo, which he pointed out will only be manifest over time. Using life cycle costing with energy savings and payback times is problematic as it involves consideration of system efficiency, location, energy prices, income level and uncertainties in future prices for energy services.

Hobday [24] points out that successful developing countries are good at linking up to the National Systems of Innovation in more developed countries. The NSI approach with its focus on norms, habits and rules within a country is particularly useful where there is a need to take account of local and traditional knowledge. In many developing countries, such knowledge is largely not documented and lodged solely in local competences [25]. Lundvall et al. [7] stress that the approach has been applied mainly to industrialised countries and it will be important to consider the effect of globalisation on the possibilities to build innovation systems in developing countries.

An aspect that has been identified as currently lacking in the NSI approach is that it does not handle the potential for power struggles and conflicts over income within the innovation interactive learning focus. Such problems could offset the co-operation and communication aspect of innovation development, or as Gu and Lundvall [26] state: "interactive learning possibilities can be blocked and competences destroyed for political reasons" and "counteractive policies are needed as is stability in the financial and macroeconomic fiscal and monetary policies". To further improve innovation systems, there is a need for long-term competence building in firms and society. Gu and Lundvall [26] recommended a cross-policy strategy with elements from social, employment, education, science, energy and environmental policies.

Gu and Lundvall [26] propose that production capital and intellectual capital are easily reproduced, but that natural and social capital are not. Therefore, focussing only on production and intellectual capital and neglecting natural and social capital is not sustainable.

The above has shown that innovation systems theory has developed from analysis of existing systems in the industrialised countries to a focus on the role of social capital in the form of multi-stakeholder networks for collaboration, interactive learning and transfer. However, it should not be applied directly to developing countries without taking account of their particular context.

Gu and Lundvall [26] suggested that the main requirements for innovation within a country are:

- Formal rules in market regulations and planning;
- Informal norms rules and values that shape collaboration ways or compete;
- Strong and diversified systems;
- Well developed structural and institutional support, e.g. legal, education, regulatory;
- Competence building systems;
- Interactive learning systems 'where agents communicate and cooperate in the creation and utilisation of new economically useful knowledge'; and
- Capacity building for learning for all levels of society.

Conflict can arise because something is replaced and power and income can be lost from one set of people and transferred to innovators. There can be deliberate moves to block the innovation process for this reason. Policies to minimise these opportunities are needed, in particular in developing countries that may be more vulnerable to this. In addition, in international co-operation aspects, issues of knowledge transfer can emerge, such as in the case of monopolistic electricity utilities blocking market entry for renewable technologies.

With respect to the role of energy technologies in innovation, studies have shown that energy systems are subject to inertia and lock-in effects [27,28] and that introduction of renewable energy technologies involves informal organisational and behavioural norms [29]. Winskel et al. [30] show that "Organisations operate in embedded socio-technical networks and tend to re-invest in

established competences: disruptive technologies (e.g. renewable energy technologies) rarely make sense to incumbents so their development tends to be left to small outsider organisations''. Indeed, key stakeholders usually tend to consider technologies that they are not familiar with as low priority. This in turn may have implications on how technology transfer processes should proceed.

Therefore, it has been argued that policy interventions are needed to make firms consider alternative energy technologies [31]. According to Reijnders [32], there is a need for policy to support a technology push and feed-in market pull for effective system building. Therefore, widespread support for renewables at the preparatory stage is an essential precursor for policy intervention to facilitate industrial growth.

Studies of other energy systems also indicate that developing a new technology requires a long period of learning and network building in the experimental phase with sustained policy support to maintain a range of different designs and to avoid lock-in round unsuccessful designs. According to Bergek and Jacobsson [33], creating and maintaining this 'Design Variety' requires an inclusive style of system building. Social acceptance plays an increasing role in the market development of an innovation. Wustenhagen et al. [34] postulated that there are three main elements of social acceptance: a broad general public acceptance in principle for renewable energy technologies, effective policies for new investors, and collaborative decision-making on spatial planning.

4. Technology transfer process conflicts

Gruebler [16] examined the process of technology transfer in terms of the patterns of diffusion of innovation at a macro level. He found that, for a range of technological innovations, they all followed the three stages of invention, diffusion and saturation, as identified earlier by Schumpeter [12]. He also uses the well-known S-shape diffusion curve [35] for social or technological change to show that the time between the initial invention/demonstration to adoption varies with how radical the change is in terms of the sociological and organisational and institutional system changes involved. In addition, these innovations were accompanied by other critical innovations. For example, the development of road systems goes in parallel with the development of oil pipelines for supplying the fuel for the cars. Gruebler [16] also showed that diffusion is also a spatial phenomenon with areas that adopt an innovation later, do so faster, but with less penetration.

Gruebler [16] points out that the cycle of invention, diffusion and saturation followed by a new invention which substitutes for the original 'technology' tends to go through a period of crisis in transitional periods when the old system is saturating and the new is still at the early stages of innovation. Saturation leads to a decline in the rate of technical and social change leading to a slowdown in economic growth. This transitional period lasts for some time before a period of accelerating rates of change occurs. These economic growth periods seem to correlate with the emergence of a cluster of interrelated innovations leading to new products, markets, industries and infrastructures supported by social and organisational processes.

Barriers to technology transfer have been identified by many researchers [5,36]. However, looking at the transfer processes as a system, particular to the type of technology, scale of the technology and country context, means that barriers are more related to blockages in the flows through the system or a lack of supporting and enabling institutions. Due to the complexity of the technology-transfer process, different factors on the macro and micro levels determine the actual flow of technology [5,37].

Geographically, most TT takes place within the countries that generate the technologies, which means within or between industrialized countries. Barriers to the spread of proven ESTs exist in almost all sectors, in developed and developing countries, and in countries with economies in transition. There is no preset pattern of barriers that will be encountered in all transfers of technology and their identification, analysis and prioritization must be suited to the situation if they are to be overcome. Commonly encountered barriers identified in the IPCC [5] include lack of information, insufficient human capabilities, political and economic barriers such as lack of capital, high transaction costs, lack of full cost pricing, trade and policy barriers, lack of understanding of local needs, business limitations such as the aversion to risk felt by some financial, institutions and inadequate environmental codes and standards.

An important barrier to technology transfer is the potential lack of commercial viability. In general, technology imported from industrialised countries is more efficient but also more expensive than technology manufactured locally, and it therefore requires higher initial investment costs. This is of particular importance for the transfer of EST [38]. Furthermore, as a result of their typically early commercialisation stage, EST are often considered riskier than existing commercial technologies [39].

Even if commercial viability allowed a deal that involved technology transfer, it might not be executed because of a lack of information about the investment opportunity, a lack of confidence in the information, and high transaction costs for obtaining reliable information and negotiating the deal [37]. Furthermore, since technology providers tend to lack knowledge about recipients' local needs and technological capabilities, technology available on the world market is often not appropriate, e.g. due to size differences of the required and the available technologies [40].

Frequently, a lack of access to capital hinders technology recipients from getting an investment financed [41]. Firms might not be able to find an investor because of the insufficient infrastructure of financial markets in many developing countries or the high interest rates of up to 30–40% per year [36]. Moreover, investors sometimes overestimate the investment risks, thus leaving sound and theoretically profitable investment projects without the necessary funding [38].

The above barriers are closely linked to the institutional framework that a country provides as Schneider et al. [42] describes in the following examples. For instance, trade restrictions through tariffs and non-tariff barriers are limiting a technology's commercial viability. Access to capital is more restricted if investors are worried about political risks and consider enforcement of the regulatory framework as weak. With respect to lack of information, a high level of corruption complicates obtaining the right information and thus raises transaction costs. Thus, stability of the political system, sound economic policy and regulatory frameworks, legal security, trade openness, and a low level of corruption are important elements of an enabling environment suitable for attracting foreign technology [5].

5. The distance between theory and practice

5.1. Diffusion mechanisms and implementation programmes

In order to help overcome the barriers to technology transfer and implementation mentioned above, several approaches and mechanisms can be used. These are described below:

- *National Systems of Innovation*. In the literature it has been suggested that technology innovation and diffusion would take place more efficiently through so-called National Systems of Innovation (NSIs) which create an enabling environment for sustainable technology transfers by integrating capacity building

and access to information [43]. Subsystems and the quality of interconnections within them can successfully influence technology transfer. The concept of NSIs can be enhanced through partnerships with international consortia. Partnerships would be system oriented, encompass all stages of the transfer process, and ensure the participation of private and public stakeholders, including business, legal, financial and other service providers from developed and developing countries.

- *Official Development Assistance (ODA)* is an important mechanism for technology transfer to developing countries, and it could also assist in improving policy frameworks and capacity building. There is increasing recognition that ODA can best be focused on mobilizing and multiplying additional financial resources [5].
- The *Global Environment Facility (GEF)* is the financial mechanism of the UNFCCC (managed by the World Bank and UNDP) and is a key multilateral institution for transfer sustainable energy technologies transfer. The GEF currently targets incremental, one-time investments in mitigation projects that test and demonstrate a variety of financing and institutional models for promoting technology diffusion, thus contributing to a host country's ability to understand, absorb and diffuse technologies.
- *Multilateral Development Banks (MDB)* could, thereby requested by governments: take increased account of the environmental consequences of the programmes that they support, develop programmatic approaches to lending that remove institutional barriers and create enabling environments for private technology transfers, and establish partnerships in NSIs.
- The *UNFCCC* addresses technology transfers from industrialised to developing countries in its Article 4.5. In addition, the CDM under the Kyoto Protocol is also considered an important mechanism for technology transfer to developing countries [5].
- *Research, Development and Demonstration (RD&D) policies* aim at alleviating technical barriers and reducing costs by improving materials, components, system design and tools for installers and users. During the past 15 years, only 7.7% of RD&D budgets in IEA member countries was devoted to renewable energy technologies. Solar heating and cooling represents only 0.55% against 2.68% for solar PV. Wind power, geothermal energy and concentrated solar power receive even less money, which suggests that public R&D funding is somehow inversely proportional to the energy potential [44].

In addition to these concepts and mechanism, governments can support market deployment of sustainable energy technologies through a wide array of policies, from outreach and raising awareness to training to certification of components and systems at national or international levels, to various financial incentives to reducing import tariffs. Outreach programmes are necessary to raise awareness of potential customers of the possibilities of sustainable energy technologies, e.g. through successful demonstration projects. Training, especially of engineers and installers, is also a key component of comprehensive support programmes to market deployment. For instance, lack of knowledge of solar-based technologies of most professionals in energy service companies, architects, building developers and other energy experts and key actors is an important barrier to diffusion of these technologies. This training should not focus only on the technical aspects, but also involve sales and marketing experts, and would enable a broadening of assessing a technology from a sole focus on 'pay back time' to a broader set of product evaluation criteria.

Governments, industry associations and regional authorities can furthermore develop certification systems for sustainable energy technology equipment. Another way to make customers, especially large installations, more confident about a technology is through guaranteed-result schemes. Finally, purchase of technologies in collaboration with other installations could reduce time and costs of the procurement, as well as reduce the risks for manufacturers. Ultimately, co-operative technology procurement could accelerate technology innovation. Westling [45] provides several examples of energy end-use projects where the utilisation of the technology procurement method in Sweden led to energy reductions of 30–50%.

Energy service companies may also offer third party financing to overcome the 'split incentives' barrier, which relates to situations in which funding for investment and funding for running costs are not compatible at the decision maker's level.

Most industrialised country governments have put in place policies to financially support the dissemination of renewable energy technologies. This support is generally justified by focussing on the ancillary benefits from implementing such technologies, such as increased security of supply and reduced pollution of local air. In addition, government support to such technologies could contribute to creating economies of scale so that costs could be reduced. It could also reduce the distortions that may arise when cost structures of different technologies differ [46].

Tax credits and grants usually constitute the core of the public policies to support the dissemination of sustainable energy technologies, alongside qualification of materials guaranteeing performances. These could take the forms of feed-in tariffs or (possibly tradable) obligations for installations to increase the share of renewable energy sources in their energy mixes (e.g. through green certificates). Some EU countries have developed energy saving certificates or 'white certificates' systems, which require producers, suppliers or distributors of electricity, gas and oil to undertake energy efficiency measures for the final users that are consistent with a pre-defined percentage of their annual energy deliverance. White certificates can be tradable.

5.2. Paradigms of good practices

Following the assessment of barriers to technology transfer and possible ways and programmes to help overcome these barriers, this section describes success stories and good practices for the promotion of renewable energy in both the EU and the developing countries. Several examples how government policies and programmes in combination with involvement of the private sector can be effective in sustainable energy technology transfer and implementation are presented in this respect.

Paradigms of good practices for the promotion of renewable energy in the EU are the following:

- *The Netherlands – energy-saving equipment and renewable energy*. The Netherlands aims to reduce its dependence on fossil fuels and to create an economy that is both efficient and sustainable in terms of its energy use. One of the ways to reach that goal is to stimulate investments in energy-saving assets and renewable energy sources. Through this programme, implemented jointly by SenterNovem and the Dutch Tax authorities, Dutch companies investing in energy efficient equipment and renewable energy sources can receive a compensation of 44% of the investment costs by deducting these costs from their fiscal profits [47]. The maximum amount that can be received from the tax authorities is €108 million per year. In order to be eligible for tax deduction, the equipment applied must be on the 'Energy List' and the investment should be reported to the Dutch Investment Schemes and Arbitrary Depreciation Office (located in Breda) within 3 months after the purchase.
- *Greece – solar thermal systems*. In Greece, solar energy applications are almost exclusively used for water heating and with 300 ha (2005 figures) the country is the second solar collector market in the EU (after Germany). The Greek domestic market had a significant growing rate of 11 ha per year [48]. The

Guaranteed Sola Results (GSR) concept that was applied in Greece with these important impacts had the form of 'third party financing': besides the user and the manufacturer of the solar system, a third party is introduced which, in practice, is an Energy Service Company (ESCO), whose role is to finance the solar system; supply the technical expertise; monitor the working order and results of the solar system; and ensure system maintenance. The user pays the ESCO an amount that is directly related to the amount of energy supplied by the solar system. Once the financial investment of the ESCO has been returned, the user becomes the sole owner of the installation. In this way, the energy user can exploit a solar system without an initial investment/risk and the ESCO has the incentive to maintain the equipment until the return on the capital investment has been achieved.

- *Denmark – wind energy*. In Denmark, the first wind electricity target is found in "Energy 21" (the plan of the Danish Government for sustainable development of energy in Denmark): 60,000 windmills to supply 10% of Denmark's electricity by the year 2000 [49]. Interestingly, this production share target was achieved about two years before the target date. Another programme was introduced in 1990 with the aim to build 100 MW of wind power capacity [50], which was followed up in 1996 when the government and the utilities signed an agreement for the installation of 200 MW of wind power capacity. In 1998, utilities signed another agreement to install 750 MW of offshore wind turbines before 2008. The agreement is considered the first phase of a programme to reach 4000 MW before 2030 [51]. Investment incentives have been also very important, in this respect. Since 1979 citizens who installed wind turbines were partly reimbursed till 1989, after about €37.6 million (€-equivalent) that had been granted [52]. Research has been funded by the *Danish Energy Research Programme*, with about €1.6 million spent on new turbines research in 2001 [53]. Funding was also provided to test stations and dissemination of knowledge and advice [54]. Privately owned offshore wind turbines were funded under the "Development of New Renewable Energy Technologies".
- *Germany – solar photovoltaics (PV)*. The total PV capacity in Germany increased from 70 MW in 1999 to 115 MW in 2000, an expansion of almost 65% in one year (in 2001, around 20,000 solar installations were installed in Germany). Growth continued reaching an installed capacity of 258 MW and a generation potential of about 190 GWh in 2002 and about 260 GWh in 2003 [55]. Nowadays, Germany has the largest share of installed PV in the EU. In general, renewable energy technologies play an important role in the German energy policy, both at national and regional levels. Most German regions have energy policies, targets and support mechanisms designed to encourage the development of renewable energy (e.g. Berlin's energy policy). Especially, PV has benefited from support from regional governments. Incentives for renewable energy are provided by the 'Electricity Feed in Law' of 1991 and it successor (in April 2000) the 'Renewable Energy Law – feed-in tariff'. For PV systems built before the end of 2001 a feed-in tariff of €0.59/kWh will be paid, which will be gradually reduced over time by 5% per year [55].

Additional paradigms of good practices for the promotion of renewable energy in the developing countries are the following:

- *Morocco – solar heaters*. Only in a few developing countries, notably Morocco and Tunisia, international support through the GEF has been provided for solar thermal technologies. The number of solar water heaters in Morocco has strongly increased from about 20,700 in 1998 to about 111,300 in 2004. This growth can partially be attributed to a GEF project implemented by UNDP [59]. Since an analysis of the existing market showed that the growth of solar water heater use was hindered by the low quality and reliability of previous solar water heaters, the project has been designed to focus on improving product quality and reliability. Part of the project focuses on training governmental agencies and private firms to promote, evaluate, and install solar hot water systems. Moreover, the project shows improved technology standards to assemblers and manufacturers, how to apply these standards and procedures to training architects and engineers, and how to develop codes of practices for constructors, installers, and plumbers [59].
- *Chile – hydro energy*. The Chile Quilleco Hydroelectric CDM Project consists of a 70 MW run-of-river hydropower plant, located on the Laja River, 8 km downstream of the existing Rucue hydropower plant [56]. The project will generate on average about 422 GWh of electricity per year, with a firm power capacity of approximately 47 MW. The project will feed into the Central Interconnected System through a 0.5 km 220 kV transmission line connected to the Central Interconnected System. The Netherlands Clean Development Mechanism Facility will purchase 100 $ktCO_{2e}$ of CERs each year between 2008 and 2012, and additional CERs produced by the project will be retained by the firm Tractebel [57].
- *China – wind energy*. In 2000, the GEF approved a USD 12 million grant to China to help develop wind power generation and reduce GHG emissions. The grant is only one component of a USD 98 million investment project that is designed to help China diversify its energy resources and reduce its dependence on coal. The project is estimated to add 78 MW of electricity generation from three new wind farms in Dabancheng, Fujin and Xiwaizi. The present installed capacity of wind power generation in China is 265 MW, which is about 1% of the country's known wind energy potential [58]. This amount could increase due to the 'Key Points of the Program for Development of New Energy and Renewable Energy Industry in the 2000–2015 Period', which aims at a renewable energy production of 43 million toe by 2015 (by then, 2% of the country's aggregate energy demand) [60].
- *Kenya – hydro energy*. The Tungu-Kabiri community micro hydropower project in the rural area around Mount Kenya demonstrates how the use of micro hydropower can bring development to rural areas in Africa. About 96% of the rural population in Kenya still lacks access to grid-based electricity. A pilot project initiated by *Practical Action* in Kenya has shown the potential for decentralised micro hydro schemes to provide access to electricity. In Tungu-Kabiri, rural Kenya, almost 200 households have formed a commercial enterprise to own and operate the micro hydropower plant, which they constructed and continue to maintain themselves. The micro hydro plant now supplies electricity to a number of local enterprises and households, thereby contributing to improving the quality of life in the area. This project has shown that micro hydropower can effectively meet the energy needs of poor off-grid communities. It has also demonstrated that communities are willing to invest time and money for improved energy services, and can organise themselves to build and operate a micro hydropower plant [61].
- *Thailand – biomass energy*. In Thailand, biomass represents a significant energy generating potential, in particular in co-generation (CHP). As of January 2003, the total installed CHP-based electric generating capacity in Thailand was 3.6 GWe, which accounted for 7.8% of the total installed power capacity in the country. 15% of installed CHP-based electric generating capacity was based on biomass [62]. In 1992, the Thai Government announced a policy to stimulate private-sector participation in the electricity generation industry, especially via

small power plants. As of today, the 1992 SPP program has resulted in 246 biomass-based SPP projects which supply electricity to the national grid [63]. Through the EC-ASEAN COGEN Programme, the Asian Institute of Technology (AIT) promoted the implementation of biomass power and CHP projects in Southeast Asia between 1992 and 2004. Under the Programme, more than 20 biomass projects were implemented in the sugar, palm oil, rice and wood industries with capacities ranging from 500 kWe to 41 MWe. AIT is also working to promote the sugar sector in Thailand through a project financed by the European Commission under the EU-Thailand Economic Co-operation Small Projects Facility.

As presented in the previous paragraphs, the private sector has the capacity to mobilise the funds required to address pressing energy needs, but incentives to do so, as well as legislation to create a stable investment climate, need to be provided by governments. This is particularly important in developing countries where the perceived risks of technology investments are generally higher and investments are more difficult to attract [64].

5.3. Financial support systems and support programmes

This paragraph summarises a number of policy measures that governments can take to provide incentives for investments in sustainable energy technologies. These measures have already been developed and applied in the EU and the experience thus gained could be fed into technology support programmes in developing countries, possibly in combination with the CDM. It must be noted that the below categorisation into four groups is a fairly simple presentation of the real energy incentive policy landscape in Europe, which also contains several mixed systems with elements from each of the categories (the description of tax incentives shows an example of such combinations):

- *Feed-in tariffs exist in most of the member states*. Under feed-in tariff systems domestic producers of 'green' electricity receive a market price for the electricity that they produce and on top of that, in order to be able to achieve an acceptable internal rate of return, they are paid a specific price per kWh produced as a subsidy. The latter component is called the feed-in tariff and is usually set for a number of years. Generally, the green power producers receive the full price per kWh from electricity companies, usually distributors, who are subsequently compensated for that by the government. These schemes have the advantages of investment security and the possibility of fine-tuning,[3] so as to promote mid- and long-term technologies. On the other hand, they are difficult to be harmonised at the EU and there is a risk of over-compensation if the tariff remains the same while electricity production costs of a particular technology reduce because of learning effects. A variant of a feed-in tariff scheme is the fixed-premium mechanism, which offers a fixed premium or environmental bonus on top of normal or spot prices for electricity generated by renewable energy technologies [65].
- *Under the green certificate system*. Currently, in Sweden, the UK, Italy, Belgium and Poland, a green certificate system is operational which also has the aim to compensate green electricity producer for the difference between the costs of production and the market price for electricity (the non-profitable part). Unlike feed-in tariff, under a green certificate system the compensation takes place in the form of certificates that end users (or power producers using fossil-fuel-based technologies) must purchase from green electricity producers. Utilities could generate these certificates by switching from fossil fuels to renewable energy sources in their own electricity production, but they could also buy such certificates from green electricity producers. End users can be also asked to submit green certificates by the end of the year, showing that they have purchased the required amount of green electricity during that year. In case, a utility or end user is not able to submit the required amount of certificates by the end of year, a penalty must be paid for non-compliance. These penalty revenues are generally either used for research and development of renewable technologies, or transferred the general government budget. Technologies with a long-term sustainable energy potential, but which require higher initial costs, are not easily developed under such schemes.
- *Pure tendering procedures*. Under a tendering procedure, the government places a series of tenders for the supply of green electricity which is then supplied on a contract basis at the price resulting from the tender. The price that the producers receive, again, is based on the market price for electricity (which end users pay) with on top of that a compensation for the non-profitable part (which the government pays as part of the tender contract). While tendering systems theoretically make optimum use of market forces, their stop-and-go nature does not contribute to stable investment conditions. There is also a risk that low bids may result in projects not being implemented. Within the EU, tenders for green electricity mainly take place in France and Ireland. France has recently changed its system to a feed-in tariff scheme combined with a tendering programme in some cases. Ireland has recently announced a similar move.
- *Systems based only on tax incentives*. Within the EU, green electricity support systems based purely on tax incentives are only applied in Malta and Finland. In most other cases (e.g. Cyprus, UK, and the Czech Republic), tax incentives are used as an additional policy tool.

5.4. Emerging opportunities and threats under the CDM

Technology transfer is not an explicit objective of the CDM, but the CDM can contribute to technology transfer by financing emission reduction projects using technologies currently not available in the host countries. Currently, the CDM is the only market-based mechanism aimed at triggering changes in the pattern of emission-intensive activities in developing countries. While its primary goal is to save abatement costs, the CDM is also considered by many as a key means to boost technology transfer and diffusion. If the technology used in the project is not available in the host country but must be imported, the project leads, de facto, to a technology transfer [5].

The participants must complete a project design document that describes the proposed CDM project. An independent "Designated Operational Entity" (DOE) must validate a proposed project to ensure that it meets all of the requirements of a CDM project. As part of the validation process the DOE must solicit public comments on the proposed project. Once public comments are requested for a project it is considered to be in the CDM pipeline.

A definition of "technology transfer" is not provided to project participants, so each project is free to use its own interpretation of "technology transfer". However, from the claims it is clear that project participants overwhelmingly interpret technology transfer as meaning the use of equipment or knowledge not previously available in the host country for the CDM project. Nevertheless, technology transfer is claimed for some projects with very simple technology (e.g. solar cookers), while no technology transfer is claimed in other projects where it might be expected (e.g. cement).

[3] Fine-tuning in this context refers to flexibility within the system to allow for adjustments (fine-tuning, but not wholesale changes or elimination of polices) a regular predetermined time schedule if circumstances change.

The characteristics of the host country might affect the incidence of technology transfer for CDM projects. A larger (larger population or larger economy) host country might already use a technology and/or have the expertise for a given project type. Similarly, a richer host country, higher per capita GDP, might already use a technology and/or have the expertise for a given project type.

A host country can incorporate technology transfer requirements into its criteria for approval of CDM projects. In addition, host country characteristics, such as tariffs or other barriers to imports of relevant technologies, perceived and effective protection of intellectual property rights (IPR), and restrictions on foreign investment, can have an impact on technology transfer.

Foreign participants might express a preference for technology they are familiar with or technology suppliers might agree to purchase/accept Certified Emission Reductions (CERs) from a project as a marketing strategy. Such practices would lead to technology transfers from buyer countries.

Technology transfer is found to be very heterogeneous across project types [66], varying significantly in terms of the reliance on imported technology, the mix of equipment and knowledge, and the source countries for the technology.

Therefore, an essential aspect that remains to be seen since the CDM entered into force (2000) is how important the mechanism has been in terms of stimulating the transfer of sustainable energy technologies to developing countries. An extensive literature has been developed covering a wide range of aspects related to CDM, such as assessments of CDM potential and development [67–71], CDM projects' sustainability impact studies [72] indicatively.

The problem of how the CDM promotes technology transfer is complicated and the transfer of environmentally sound technologies in the context of climate change mitigation is the subject of an extensive literature, such as [37,73]. However, only a few studies deal with the assessment of CDM's contribution to technology transfer, mainly by assessing empirical work based on project design document (PDD) evaluations [40,42,66,74], while there are only a few studies dealing with technology transfer through CDM projects using a quantitative approach [74–77]. These studies find that technology transfer is occurring to some extent. In addition to this, while the performance of CDM institutions impacts the number of CDM projects, the technology-transfer content of those projects is, rather, driven by its compatibility with the host country national priorities and related conditions. Limited and sporadic are the efforts supporting policy makers in trying to direct CDM towards national Sustainable Development priorities [78–81].

6. Conclusion

The review has provided many insights for technology transfer to developing countries. Energy systems in most developing countries, even in least developed countries, tend to have large-scale infrastructure and institutional inertia, similar to those in industrialised countries. Changing investments in energy infrastructure to low-carbon alternatives and more decentralised energy generation and making industry more efficient could be hampered by ingrained habits and training, as well as pressures from industrialised countries to buy their older technologies.

If there is a possibility of leapfrogging, then concerted efforts would need to be made to overcome the lag times built into changing long-term infrastructure systems or of circumventing them. Currently available high-carbon or older technologies tend to be cheaper and more affordable for developing countries and play to the existing experience and know-how.

The role of social capital in terms of the multi-stakeholder networks in innovation systems needs to be recognised and explicitly fostered. Short-term financial criteria can undermine this resource and that natural and social capital cannot easily be renewed.

Power and lack of trust in markets can block change as can be seen in the behaviour of monopolistic electricity utilities (whether overtly privatised or not) towards distributed energy and new sources and the use of intellection property and other methods for blocking innovation. Economic losses from innovations will affect some existing market players who will therefore resist innovation. As Winskel et al. [30] point out "Organisations operate in embedded socio-technical networks and tend to re-invest in established competences: disruptive technologies, e.g. renewable energy technologies rarely make sense to incumbents so their development tends to be left to small outsider organisations".

The need for the country and technology context has been shown in the NSI approach to be grounded in the institutional settings within the country relating to cultural norms and rules and firm-to-firm interactions.

Rogers' work on the key factors affecting perceptions for decisions to adopt an innovation showed that these included relative advantage, compatibility, complexity, observability, trialability and risk. Early adopters tended to be young, highly educated professionals.

These key perceptions of new technologies need to be addressed, and in addition awareness of the existence of the new options. In the short term, small-scale new technologies may have more opportunity to enter these markets.

Presently, the CDM concentrates on single projects, mostly in isolation of the host country's national and technology context, and does not address technology transfer on any scale. It currently does not foster the supporting systems needed to enhance adoption of a new technology, and it can therefore only address part of the process. The isolated installation of projects is useful for only the very early stage of demonstration of an invention, but the real technology transfer processes will require much more effort. The CDM should be adapted to deliver more TT through improvement of the country system for adoption of low-carbon technologies.

For real TT a more programmatic approach to the CDM needs should be invoked so that a portfolio of projects can be introduced that is designed to explore the range of circumstances and applications in the host country, supported by complementary programmes to foster the knowledge transfer systems and knowledge transfer networks needed for success.

Acknowledgement

Ms. Charikleia Karakosta wishes to acknowledge with gratitude the Alexander S. Onassis Public Benefit Foundation for supporting her PhD research.

References

[1] United Nations, Division for Sustainable Development. Agenda 21: The Report of the United Nations Conference on Environment and Development, Chapter 34: Transfer of environmentally sound technology, cooperation & capacity-building. Rio de Janeiro: Earth Summit, UN; 1992.
[2] United Nations. The Kyoto Protocol to the United Nations Framework Convention on Climate Change. Geneva, Switzerland. Available at: http://unfccc.int/resource/docs/convkp/kpeng.pdf; 1998.
[3] Schnepp O, Bhambri A, von Glinow MAY. United States-China technology transfer. Englewood Cliffs, NJ: Prentice-Hall. ISBN: 013949975X; 1990.
[4] Ockwell D, Lovett JC. Fire assisted pastoralism vs. sustainable forestry-the implications of missing markets for carbon in determining optimal land use in the wet-dry tropics of Australia. Journal of Environmental Management 2005;75(1):1–9.
[5] IPCC – Intergovernmental Panel on Climate Change. In: Metz B, Davidson O, Martens JW, Van Rooijen S, Van Wie Mcgrory L, editors. Methodological and technological issues in technology transfer. Cambridge, UK: Cambridge University Press; 2000. p. 432.
[6] Brewer TL. International climate change transfer: new paradigm and new policy agenda. Available at: http://www.usclimatechange.com/; 2007.

[7] Lundvall BA, Johnson B, Andersen ES, Dalum B. National systems of production, innovation and competence building. Research Policy 2002;31:213–31.
[8] Hirschman AO. The strategy of economic development. New Haven, CT: Yale University Press; 1958.
[9] Rothwell R. The characteristics of successful innovators and technically progressive firms (with some comments on innovation research). R&D Management 1977;7(3):191–206.
[10] Lundvall BA. Product innovation and user-producer interaction. Industrial development research, series no. 31. ISBN 87-7307-304-0. Aalborg: Aalborg University Press; 1985.
[11] Johnson B. Institutional learning. In: Lundvall BA, editor. National innovation systems: towards a theory of innovation and interactive learning. London: Pinter Publishers; 1992. p. 23–44.
[12] Schumpeter JA. Business cycles: a theoretical, historical and statistical analysis of the capitalist process: vols. I and II. New York/Toronto/London: McGraw-Hill Book Company; 1939.
[13] Rogers EM, Shoemaker FF. Communication of innovations: a cross-cultural approach, 2nd ed., New York: The Free Press; 1971.
[14] Ostland LE. Interpersonal communication following McGovern's Eageleton decision. Public Opinion Quarterly 1974;37:601–10.
[15] Rogers EM. Diffusion of innovations, 3rd ed., New York: The Free Press; 1983.
[16] Gruebler A. Time for a change: on the patterns of diffusion of innovation. In: Ausubel JA, Langford HD, editors. Technological trajectories and the human environment. Washington, DC, USA: National Academy Press; 1997. p. 14–32.
[17] Rogers EM. Diffusion of innovations, 4th ed., New York: The Free Press; 1995.
[18] Rogers EM. Diffusion of innovations, 5th ed., New York: The Free Press; 2003.
[19] Bauer RA. Consumer behavior as risk-taking. In: Hancock RS, editor. Dynamic marketing for a changing world. Chicago: American Marketing Association; 1960. p. 389–98.
[20] Guagnano G, Hawkes GR, Acredolo C, White N. Innovation perception and adoption of solar heating technology. Journal of Consumer Affairs 1986; 20(1):48–64.
[21] Shama A, Wisenbilt J. Values of voluntary simplicity: lifestyle and motivation. Psychological Reports 1984;55:231–40.
[22] Leonard-Barton D. Voluntary simplicity lifestyles and energy conservation. Journal of Consumer Research 1981;8:243–52.
[23] Darley JM, Beninger JR. Diffusion of energy-conserving innovations. Journal of Social Issues 1981;37(2):150–71.
[24] Hobday M. Innovation in East Asia. London: Edward Elgar; 1997.
[25] Ernst D, Lundvall BA. Information technology in the learning economy: challenges for developing countries. Aalborg, Denmark: Danish Research Unit for Industrial Dynamics (DRUID) working paper 97-12; 1997.
[26] Gu S, Lundvall BA. China's innovation system and the move toward harmonious growth and endogenous innovation. Innovation Management Policy & Practice 2006;8(1/2):1–25.
[27] Unruh GC. Understanding carbon lock-in. Energy Policy 2000;28(12):817–30.
[28] Unruh GC. Escaping carbon lock-in. Energy Policy 2002;30(4):317–25.
[29] Karnoe P. The social process of competence building. International Journal of Technology Management 1996;11(7–6):770–89.
[30] Winskel M, Mcleod Wallace AR, Williams R. Energy policy and the institutional context: marine energy innovation systems. Energy Policy 2006;33(5):365–76.
[31] Rip A, Kemp R. Technological change. In: Rayner S, Majone EL, editors. Human choices and climate change. Ohio, Columbus: Batelle Press; 1998. p. 327–99.
[32] Reijnders L. Imports as a major complication: liberalisation of the green electricity market in the Netherlands. Energy Policy 2002;30(9):723–6.
[33] Bergek A, Jacobsson S. The emergence of a growth industry: a comparative analysis of the German, Dutch and Swedich wind turbibe industries. In: Metcalfe S, Canter U, editors. Change, transformation and development: Schupeterian perspectives. Heidelberg: Physica/Springer; 2002 . p. 197–228.
[34] Wustenhagen R, Wolsink M, Buerer MJ. Social acceptance of renewable energy innovation: an introduction to the concept. Energy Policy 2007; 35:2683–91.
[35] Hobsbawn E, Rude G. Captain swing: a social history of the Great English agricultural uprising of 1830. New York: W.W. Norton and Company; 1973.
[36] Ellis J, Kamel S. Overcoming barriers to clean development mechanism projects. COM/ENV/EPOC/IEA/SLT(2007)3. Paris, France: OECD/IEA; 2007.
[37] Worrell R, Berkel Van Fengqi Z, Menke C, Schaeffer R, Williams RO. Technology transfer of energy efficient technologies in industry: a review of trends and policy issues. Energy Policy 2001;29:29–43.
[38] Wilkins G. Technology transfer for renewable energy overcoming barriers in developing countries. London: Earthscan; 2002.
[39] Ockwell D, Watson J, MacKerron G, Pal P, Yamin F, Vasudevan N, et al. UK-India collaboration to identify the barriers to the transfer of low carbon energy technology. London: Department of Environment, Food and Rural Affairs; 2007.
[40] Dechezleprêtre A, Glachant M, Ménièrea Y. The clean development mechanism and the international diffusion of technologies: an empirical study. Energy Policy 2008;36:1273–83.
[41] Tébar Less C, McMillan S. Achieving the successful transfer of environmentally sound technologies: trade-related aspects. In: Environment, J.W.P.o.T.a., editors. OECD Trade and Environment working paper no. 2005-2 (COM/ENV/TD(2004)33/FINAL). Paris: OECD; 2005.
[42] Schneider M, Holzer A, Volker H. Understanding the CDM's contribution to technology transfer. Energy Policy 2008;36:2930–8.
[43] Masinda MT. National Systems of Innovation: implications on science and technology policies in Sub-Saharan Africa. Report #98-05. Canada: CPROST (Centre for Policy Research on Science and Technology) Publications; 1998.
[44] IEA – International Energy Agency. Energy technology perspectives: scenario & strategies to 2050 – in support of the G-8 Plan of Action. Paris, France: OECD/IEA; 2006.
[45] Westling H. Status of pilot project. Documentation for the expert meeting in Helsinki; 1997.
[46] IEA – International Energy Agency. Renewables for power generation – status and prospects. Paris, France: OECD/IEA; 2003.
[47] SenterNovem. Energy investment tax relief (Netherlands). Available at: http://www.senternovem.nl/eia/English.asp; 2007.
[48] Karagiorgas M, Botzios T. GSR experience in industrial applications of solar thermal systems in Greece. Athens, Greece: CRES; 1999.
[49] Agnolucci P. Wind electricity in Denmark: a survey of policies, their effectiveness and factors motivating their introduction. Renewable and Sustainable Energy Reviews 2007;11:951–63.
[50] Grohnheit E. Denmark: long-term planning with different objectives. In: Vrolijk C, editor. Climate change and power: economic instruments for european electricity. London: Earthscan Publications Ltd.; 2002. p. 108–30.
[51] DEA – Danish Energy Agency. Wind energy in Denmark. Danish Energy Agency. Copenhagen, Denmark: OPET; 2002.
[52] Meyer NI. Renewable energy policy in Denmark. Energy for Sustainable Development 2004;8(1):25–35.
[53] Lorenzen KH. Report on fiscal incentives and subsidy schemes influencing the use of renewable energy in Denmark. Altener, Ener-IURE Project Phase II; 2001
[54] OPET – Organisations for the Promotion of Energy Technologies. Danish legislation in the field of renewable energy. Taastrup, Denmark: OPET; 2001.
[55] Jäger-Waldau A. Renewable Energy Unit, PV status, report 2008: research, solar cell production and market implementation of photovoltaics, EUR 23604 EN. Ispra, Italia: European Commission, DG Joint Research Centre, Institute for Energy, Renewable Energies Unit; 2008.
[56] Banco Central de Chile 2006b. Síntesis estadística de Chile 2001–2005. Santiago, Chile: Banco Central de Chile; 2006. p. 54.
[57] U.S. Energy Information Administration. Chile-Country analysis brief. Washington, DC: U.S. Administration; 2006. p. 11.
[58] AWEA – American Wind Energy Association. Wind energy applications guide. Washington, DC: AWEA; 2001.
[59] GEF – Global Environment Facility. Assessment of World Bank/GEF Strategy for the market development of concentrating solar thermal power. Washington, DC, USA: The World Bank/GEF; 2005.
[60] EREC – European Renewable Energy Council. Renewable energy technology roadmap: up to 2020. Available at: http://www.erec.org/documents/publications.html; 2007.
[61] Muriithi J. Developing small hydropower infrastructure in Kenya. In: 2nd small hydropower for today conference, "Policy stimulating hydropower development". International Network on Small Hydropower (IN-SHP); 2006.
[62] Bhattacharya SC, Abdul Salam P. A review of selected biomass energy technologies: gasification, combustion, carbonization and densification. Khlong Luang, Pathumthani, Thailand: Regional Energy Resources Information Center (RERIC) Publications, Asian Institute of Technology (AIT); 2006.
[63] Therdyothin A, Bhattacharya SC, Chirarattananon S. Electricity generation potential of Thai sugar mills. Energy Sources 1992;14:367–80.
[64] UNEP – United Nations Environment Programme and IEA – International Energy Agency. Analysing our energy future, some pointers for policy-makers. UNEP Publications; 2007.
[65] Commission of the European Communities. The support of electricity from renewable energy sources, COM(2005) 627 final. Brussels, Belgium: Communication from the Commission; 2005.
[66] Seres, S. Analysis of technology transfer in CDM projects. Prepared for UNFCCC Registration & Issuance Unit CDM/SDM; 2007.
[67] Adhikari S, Mithulananthan N, Dutta A, Mathias AJ. Potential of sustainable energy technologies under CDM in Thailand: opportunities and barriers. Renewable Energy 2008;33(9):2122–33.
[68] Doukas H, Karakosta C, Psarras J. RES technology transfer within the new climate regime: a "helicopter" view under the CDM. Renewable and Sustainable Energy Reviews 2009;13(5):1138–43.
[69] Hayashi D, Krey M. Assessment of clean development mechanism potential of large-scale energy efficiency measures in heavy industries. Energy 2007; 32(10):1917–31.
[70] Purohit P. Small hydro power projects under clean development mechanism in India: a preliminary assessment. Energy Policy 2008;36(6):2000–15.
[71] Purohit P, Michaelowa A. CDM potential of bagasse cogeneration in India. Energy Policy 2007;35(10):4779–98.
[72] Begg K, Parkinson S, van der Horst D, Wilkinson R, Theuri D, Gitonga S, et al. Encouraging CDM energy projects to aid poverty alleviation. Final report of project DFID-KARR, Centre for Environmental Strategy, Guildford, UK: University of Surrey; 2003.
[73] Yang Z, Nordhaus WD. Magnitude and direction of technological transfers for mitigating GHG emissions. Energy Economics 2006;28(5–6):730–41.
[74] Pueyo VA. Variables underpinning technology transfers through the CDM. Joint Implementation Quarterly 2007;13:5–6.
[75] Haites E, Duan MS, Seres S. Technology transfer by CDM projects. Climate Policy 2006;6:327–44.
[76] De Coninck H, Haake F, Van der Linden N. Technology transfer in the clean development mechanism. Climate Policy 2007;7:444–56.

[77] Olsen KH, Fenhann J. Sustainable development benefits of clean development mechanism projects: a new methodology for sustainability assessment based on text analysis of the project design documents submitted for validation. Energy Policy 2008;36(8):2819–30.
[78] Garcia-Quijano JF, Deckmyn G, Moons E, Proost S, Ceulemans R, Muys B. An integrated decision support framework for the prediction and evaluation of efficiency, environmental impact and total social cost of domestic and international forestry projects for greenhouse gas mitigation: description and case studies. Forest Ecology and Management 2005;207(1–2):245–62.
[79] Georgiou P, Tourkolias C, Diakoulaki D. A roadmap for selecting host countries of wind energy projects in the framework of the clean development mechanism. Renewable and Sustainable Energy Reviews 2008;12(3):712–31.
[80] Schroeder M. Utilizing the clean development mechanism for the deployment of renewable energies in China. Applied Energy 2009;86(2):237–42.
[81] Murdiyarso D, Van Noordwijk M, Puntodewo A, Widayati A, Lusiana B. District-scale prioritization for A/R CDM project activities in Indonesia in line with sustainable development objectives. Agriculture Ecosystems & Environment 2008;126(1–2):59–66.

Annex 40 bis

T. Stephenson et al., “Changes in extreme temperature and precipitation in the Caribbean region, 1961-2010”, *International Journal of Climatology*, pp. 2957-2971

Check for updates

INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **34**: 2957–2971 (2014)
Published online 13 January 2014 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/joc.3889

RMetS
Royal Meteorological Society

Changes in extreme temperature and precipitation in the Caribbean region, 1961–2010

Tannecia S. Stephenson,[a]* Lucie A. Vincent,[b] Theodore Allen,[c] Cedric J. Van Meerbeeck,[d] Natalie McLean,[a] Thomas C. Peterson,[e] Michael A. Taylor,[a] Arlene P. Aaron-Morrison,[f] Thomas Auguste,[g] Didier Bernard,[h] Joffrey R. I. Boekhoudt,[i] Rosalind C. Blenman,[j] George C. Braithwaite,[k] Glenroy Brown,[l] Mary Butler,[m] Catherine J. M. Cumberbatch,[n] Sheryl Etienne-Leblanc,[o] Dale E. Lake,[p] Delver E. Martin,[q] Joan L. McDonald,[r] Maria Ozoria Zaruela,[s] Avalon O. Porter,[t] Mayra Santana Ramirez,[u] Gerard A. Tamar,[v] Bridget A. Roberts,[w] Sukarni Sallons Mitro,[x] Adrian Shaw,[l] Jacqueline M. Spence,[l] Amos Winter[y] and Adrian R. Trotman[d]

[a] *Department of Physics, The University of the West Indies, Mona, Kingston, Jamaica*
[b] *Climate Research Division, Science and Technology Branch, Environment Canada, Toronto, Canada*
[c] *Division of Meteorology & Physical Oceanography, University of Miami, FL, USA*
[d] *Caribbean Institute for Meteorology and Hydrology, St James, Barbados*
[e] *NOAA/National Climatic Data Center, Asheville, NC, USA*
[f] *Trinidad & Tobago Meteorological Service, Piarco, Trinidad*
[g] *Saint Lucia Meteorological Services, Castries, Saint Lucia*
[h] *Laboratoire de Recherche en Géosciences et Énergies, Point-à-Pitre, Guadeloupe*
[i] *Meteorological Department Curaçao, Willemstad, Curaçao*
[j] *Barbados Meteorological Services, Christ Church, Barbados*
[k] *Antigua and Barbuda Meteorological Services, St John's, Antigua and Barbuda*
[l] *Meteorological Service, Jamaica, Kingston, Jamaica*
[m] *Department of Meteorology, Nassau, Bahamas*
[n] *National Meteorology Service of Belize, Belize*
[o] *Dominica Meteorological Service, Canefield, Dominica*
[p] *Virgin Islands Department of Disaster Management, Tortola, Virgin Islands*
[q] *St Kitts Meteorological Services, Bird Rock, St Kitts and Nevis*
[r] *Meteorological and Aeronautical Information Service, E. T. Joshua Airport, St George, St Vincent and the Grenadines*
[s] *Oficina Nacional de Meteorologia, Santo Domingo Este, Dominican Republic*
[t] *Cayman Islands National Weather Service, Grand Cayman, Cayman Islands*
[u] *Instituto de Meteorologia de la Republica de Cuba, Cuidad de la Habana, Cuba*
[v] *Grenada Airports Authority, St George's, Grenada*
[w] *Hydrometeorological Service Guyana, Stabroek, Guyana*
[x] *Meteorological Service Suriname, Paramaribo, Suriname*
[y] *Department of Marine Sciences, University of Puerto Rico, Mayaguez, Puerto Rico*

Reproduced with the permission of the Minister of Environment.

ABSTRACT: A workshop was held at the University of the West Indies, Jamaica, in May 2012 to build capacity in climate data rescue and to enhance knowledge about climate change in the Caribbean region. Scientists brought their daily observational surface temperature and precipitation data from weather stations for an assessment of quality and homogeneity and for the calculation of climate indices helpful for studying climate change in their region. This study presents the trends in daily and extreme temperature and precipitation indices in the Caribbean region for records spanning the 1961–2010 and 1986–2010 intervals. Overall, the results show a warming of the surface air temperature at land stations. In general, the indices based on minimum temperature show stronger warming trends than indices calculated from maximum temperature. The frequency of warm days, warm nights and extreme high temperatures has increased while fewer cool days, cool nights and extreme low temperatures were found for both periods. Changes in precipitation indices are less consistent and the trends are generally weak. Small positive trends were found in annual total precipitation, daily intensity, maximum number of consecutive dry days and heavy rainfall events particularly during the period 1986–2010. Correlations between indices and the Atlantic multidecadal oscillation (AMO) index suggest that temperature variability and, to a lesser extent, precipitation extremes are related to the AMO signal of the North Atlantic surface sea temperatures: stronger associations are found in August and September for the temperature indices and in June and October for some of the precipitation indices.

KEY WORDS Caribbean; climate change; climate extreme; daily temperature; daily precipitation; trends; Atlantic multidecadal oscillation

Received 3 May 2013; Revised 1 November 2013; Accepted 12 November 2013

* Correspondence to: T. S. Stephenson, Department of Physics, University of the West Indies, Mona, Kingston, Jamaica.
E-mail: tannecia.stephenson02@uwimona.edu.jm

© 2014 Environment Canada. *International Journal of Climatology* published by Royal Meteorological Society and John Wiley & Sons Ltd.
This is an open access article under the terms of the Creative Commons Attribution-NonCommercial-NoDerivs License, which permits use and distribution in any medium, provided the original work is properly cited, the use is non-commercial and no modifications or adaptations are made.

1. Introduction

Small island states like those in the Caribbean have long been identified as being among the most vulnerable to climate change and climate extremes (IPCC, 2007; IPCC, 2012). This is often attributed to limited natural and human resources, restricted lands, densely populated urban and coastal areas, economic dependence on international funders and heavy reliance on fragile sectors such as tourism (Sahay, 2005; Pulwarty *et al.*, 2010; Simpson *et al.*, 2010; IPCC, 2012). Caribbean islands are attempting to address their high vulnerability and low adaptive capacity at the local (parish and community) and regional levels via a number of projects financed using adaptation funds (e.g. UNDP GEF Small Grants Programme). Fundamental to the framework however is characterizing trends in climate extremes across the region in the recent past and making projections towards the middle to end of century. This article focuses on trends in climate extremes over the Caribbean for the past 50 years.

The first regional analysis of rainfall and temperature extremes for the Caribbean was undertaken in 2001 at a workshop supported by the World Meteorological Organization (WMO) and the National Oceanic and Atmospheric Administration (NOAA) (Peterson *et al.*, 2002). Some of the results (based on 30 stations across the region) suggest that over the 1958–1999 period there has been a dramatic increase in the number of very warm days and nights, a decrease in the number of very cool days and nights, a decrease in the maximum number of consecutive dry days (CDD) and an increase in the number of heavy rainfall events for a mean Caribbean. The workshop marked the first in a series of climate change workshops held globally using the WMO Commission for Climatology (CCI) and the World Climate Research Programme (WCRP) Climate Variability and Predictability (CLIVAR) Expert Team on Climate Change Detection and Indices (ETCCDI) format and modelled on the Asia Pacific Network workshops (Manton *et al.*, 2001). Similar workshops have been held for example, in countries in the western Indian Ocean (Vincent *et al.*, 2011), South America (Aguilar *et al.*, 2005; Vincent *et al.*, 2005; Haylock *et al.*, 2006; Skansi *et al.*, 2012), parts of Africa (New *et al.*, 2006; Aguilar *et al.*, 2009), the Middle East (Zhang *et al.*, 2005), Central and South Asia (Klein Tank *et al.*, 2006), Southeast Asia and South Pacific (Griffiths *et al.*, 2005; Caesar *et al.*, 2011) and the Arab region (Donat *et al.*, 2013a). An overview of the format and progress of the regional workshops are presented in Peterson and Manton (2008). These workshops provide a consistent methodology for studying extremes across the world and results may be seamlessly aggregated in global analyses as performed by Alexander *et al.* (2006) and Donat *et al.* (2013b).

Other studies on climate trends for the Caribbean indicate a modest but statistically significant drying trend for the Caribbean's summer period in recent decades (Neelin *et al.*, 2006); annual rainfall totals declining by 250 mm since 1900 (Nurse and Sem, 2001); decreasing early and late season precipitation (see Section 2) with marked negative trend commencing in 1960 (Taylor *et al.*, 2002); declining rainfall in the central Caribbean with an increasing trend in stations in Nassau and Maracaibo (Aparicio, 1993; Singh, 1997; Walsh, 1998; Martin and Weech, 2001); an increase in temperature exceeding 0.5 °C since 1900 (Nurse and Sem, 2001). Similar trend analyses have been conducted for Cuba and suggest an increase in annual mean temperatures by nearly 0.5 °C; an increase in the frequency of intense rains and local storms; increase in winter rainfall but decrease in summer; increase in frequency of droughts and diminished landfall hurricane activity in the latter half of the 20th century (Naranjo and Centella, 1998; Lapinel *et al.*, 2002; Álvarez, 2006). See reviews in Gamble and Curtis (2008) and Chen *et al.* (2008).

This article presents results from the second climate change workshop hosted in the Caribbean at the University of the West Indies on May 7–10, 2012. The workshop aimed to build capacity in historic data rescue and investigating and quantifying climate change effects and impacts. It was an important follow up to the 2001 workshop as it allowed 30 meteorologists and climate scientists from the region to explore trends in extreme precipitation and temperature with over a decade's worth more data than available in 2001. Additionally, the second workshop exploited an expanded suite of extreme indices and improved software for evaluating homogeneity and calculating indices. This article examines trends in daily and extreme temperature and precipitation over the Caribbean for two periods: 1961–2010 and 1986–2010. For each period, trends are presented spatially and temporally. The temporal representations exploit regionally averaged indices following distinct subregions identified by Jury *et al.* (2007): Section 2 provides further rationale and description of the subregions. Additionally, Caribbean-wide averaged series is presented for comparison with Peterson *et al.* (2002) results and to investigate the representativeness of region-wide indices with respect to those derived subregionally. The approach is an important one as it represents to date the most detailed spatial representation of observational climate trends for the Caribbean region and allows the investigation of subregional variations. Finally, the relationship between the indices and the Atlantic multidecadal oscillation (AMO) index is examined in order to better understand the temperature and precipitation temporal variability over the Caribbean region.

2. Caribbean's regions

The Caribbean Basin includes a diverse collection of nations that encompasses both large (Greater Antilles) and small (Lesser Antilles) islands as well as coastlines along Central and South America. The general climate of the Caribbean can be described as *dry-winter tropical* (Rudloff, 1981) with an associated bimodal seasonal rainfall pattern. This bimodality divides the rainfall pattern

© 2014 Environment Canada. *International Journal of Climatology* published by Royal Meteorological Society and John Wiley & Sons Ltd.

10970088, 2014, 9, Downloaded from https://rmets.onlinelibrary.wiley.com/doi/10.1002/joc.3889 by CochraneBarbados, Wiley Online Library on [25/01/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

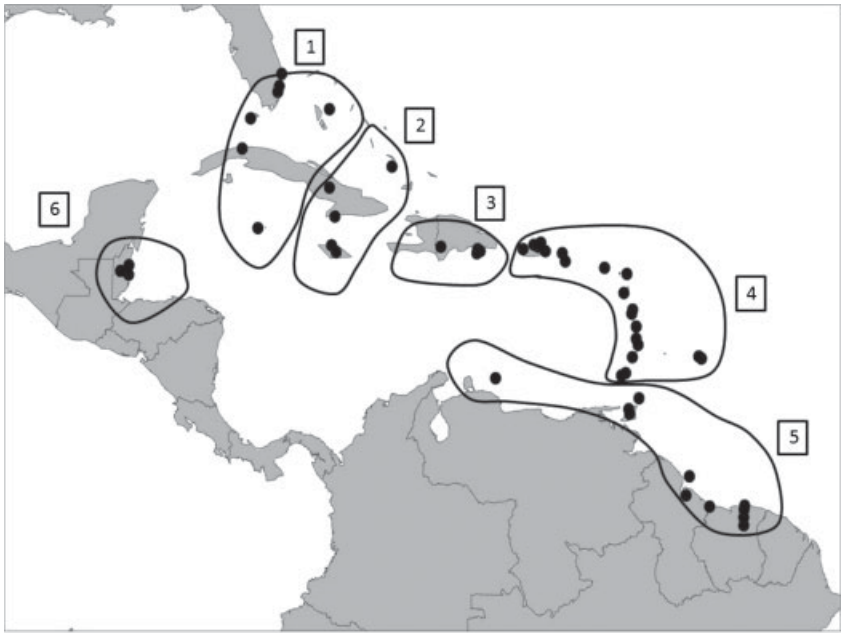


Figure 1. Location of the 51 stations divided into six regions.

into an early (April–July) and a late (August–November) rainfall season (Chen and Taylor, 2002). The relative minimum between the early and late rainfall season has many regional names such as *Petit Carême* (Trinidad and Tobago), *le carême* (Guadeloupe, Martinique), *la canicula* (Mexico) or *el veranillo* (Costa Rica), but is known in general as the mid-summer drought (MSD) throughout the Intra-American Sea (Magana *et al.*, 1999; Giannini *et al.*, 2000; Curtis, 2002; Mapes *et al.*, 2005). This seasonal tendency differs along the southernmost regions of the Caribbean where areas such as Venezuela and the Dutch Antilles experience a winter rainfall maximum (Martis *et al.*, 2002).

Despite the overall presence of an early and late rainfall season separated by the MSD, regions of distinct subbasin scale rainfall variation exist. Regional variability is present in annual totals, length of the rainy season and length and timing of the MSD. Previous research has made numerous efforts to subdivide the Caribbean Basin into regions with similar rainfall patterns using various techniques (Giannini *et al.*, 2000; Chen and Taylor, 2002; Curtis and Gamble, 2007; Gamble *et al.*, 2007). More recently, Jury *et al.* (2007) used factor analysis to create spatial clusters with orthogonal time scores. This results in a four factor solution subdividing the Caribbean Basin into four distinct zones that are distinguished from one another by their seasonal rainfall cycle and its timing.

The focus of our analysis attempts to capture the regional variability within the Caribbean Basin by treating the analysis in defined regions. By doing this, we avoid describing a generalized and potentially misleading coarse Caribbean rainfall regime, while respecting and utilizing prior successful research efforts. This attempt has been completed by Jury (2009) and Charlery *et al.* (2006) who analyse rainfall data within the Caribbean in defined regions. However for comparative purposes, the analyses presented in this study also examine results averaged across the entire Caribbean domain. Figure 1 presents the six regions: the four regions as defined by Jury *et al.* (2007) and two additional regions (regions 5 and 6) which accommodate other stations used in our study but outside of the area analysed by Jury *et al.* (2007).

3. Data and methodologies

Workshop participants brought daily maximum and minimum temperature and precipitation data for 51 stations across the Caribbean and neighbouring countries. Data records varied in length across all the locations with some stations having only precipitation or maximum and minimum temperatures. Stations used in this study are listed in Table 1. Figure 1 shows their locations. Sufficient data were compiled to undertake analyses over two periods: our primary period 1961–2010 and a secondary period 1986–2010 which allowed the inclusion of more stations. Though a great deal of the analyses was performed during the workshop, these were revisited subsequent to the workshop to ensure robustness of the results.

As the Caribbean region consists mostly of small island developing States and other developing nations, not all public weather services can maintain a climatology department. For that reason, it has frequently been a challenge to maintain consistency and continuity in time series of daily weather observations and accompanying metadata (Peterson *et al.* 2002). An additional challenge in keeping good records is the necessary conversion to digital databases for most climatological

© 2014 Environment Canada. *International Journal of Climatology* published by Royal Meteorological Society and John Wiley & Sons Ltd.

10970088, 2014, 9, Downloaded from https://rmets.onlinelibrary.wiley.com/doi/10.1002/joc.3889 by CochraneBarbados, Wiley Online Library on [25/01/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Table 1. List of stations with homogeneity results.

Country	Station name	Latitude (°N)	Longitude (°W)	Period		Zone	Detected steps[a]
				Start	End		
Antigua and Barbuda	V.C Bird International Airport	17.1	61.5	1969	2011	4	
Bahamas	Nassau	25.0	77.5	1961	2011	1	
Barbados	CIMH	13.2	59.6	1969	2010	4	
	Grantley Adams International Airport	13.1	59.5	1971	2011	4	
Belize	Belmopan	17.3	88.8	1974	2010	1	
	Central Farm	17.2	88.3	1966	2011	1	
	Philip Goldson Airport	17.5	88.3	1960	2010	1	
Cayman	Owen Robert A Georgetown	19.3	81.4	1976	2010	2	
Cuba	Cabo	19.9	77.2	1980	2012	2	
	Camagüey	21.2	77.5	1961	2012	2	↓TX 1973
	Casablanca	23.1	82.2	1961	2012	1	
	Maisi	22.3	74.2	1980	2012	2	
Curaçao	Hato	12.1	68.6	1992	2011	5	↓TX TN 2001
Dominica	Canefield Airport	15.2	61.2	1982	2010	4	↓TN 2005
	Melville Hall Airport	15.3	61.2	1975	2010	4	
Dominican Republic	Jimani	18.3	71.5	1971	2010	3	
	La Romana	18.3	69.6	1924	2012	3	
	Las Americas	18.3	69.4	1971	2011	3	
	Santo Domingo	18.3	69.5	1971	2011	3	
Grenada	Maurice Bishop International Airport	12.3	61.6	1986	2010	4	
	Point Salines	12.3	61.8	1989	2010	4	
	Point Salines	12.3	61.8	1985	2005	4	
Guadeloupe	Petit-bourg	16.2	61.7	1969	2006	4	↑TX 2001
Guyana	George Town	6.5	58.1	1962	2007[b]	5	
	Timehri	6.5	58.3	1981	2010	5	
Jamaica	Discovery Bay Maine Lab	18.5	77.4	1992	2009[c]	2	
	Worthy Park	18.2	77.2	1973	2011	2	↓TN 2003
Martinique	Lamentin	14.6	61.0	1953	2011	4	↑TX 1996
Puerto Rico	Colosso	18.5	66.5	1905	2011[d]	4	↑TN 2002
	Manati 3E	18.3	66.3	1900	2011[d]	4	↓TX 1985
	Maunabo	18.0	65.9	1960	2003[e]	4	
	Mayaguez City	18.1	67.1	1900	2011[d]	4	
	San Juan	18.5	66.1	1977	2011	4	
Saint Lucia	GFL Charles Airport	14.0	61.0	1989	2010	4	
	Hewanorra	13.7	60.9	1973	2009	4	↓TN 2004
St Kitts and Nevis	St Kitts (sugar factory)	17.3	62.7	1981	2007	4	
St Vincent and the Grenadines	E. T. Joshua Airport	13.1	61.2	1986	2012	4	
Suriname	Cultuurtuin	5.8	55.2	1971	2010	5	
	Nickerie	6.0	57.0	1971	2010	5	
	Lelydorp	5.1	55.2	1911	2010[e]	5	
	Zanderij	5.5	55.2	1971	2011	5	↓TX 1996
	Zorg en Hoop	5.8	55.2	1971	2010	5	↑TX 2007
Trinidad and Tobago	Crown Point	11.2	60.8	1967	2012	5	
	Piarco	10.6	61.3	1960	2012	5	
	St Augustine	10.6	61.4	1969	2010	5	
USA Florida	Fort Lauderdale	26.1	80.2	1948	2010	1	
	Key West WSO Airport	24.6	81.8	1948	2010	1	
	Miami WSCMO Airport	25.8	80.3	1948	2010	1	
	West Palm Beach	26.7	80.1	1948	2010	1	
Virgin Islands	Christiansted Hamilton Airport	17.7	64.8	1951	2010	4	↓TX 2000
	Charlotte Amalie Cyril E King Airport	18.3	65.0	1953	2010	4	↓TX 1996

[a]Arrow pointed up (down) indicates increasing (decreasing) step; TX (TN) indicates maximum (minimum) temperature; date of detected step. [b]For precipitation, the period is 1954-2010. [c]For precipitation, the period is 1992-2011. [d]No data for precipitation. [e]No data for temperature.

analyses. Therefore, a necessary precursor to the calculation of climate indices is thorough quality control (QC) and assessment of data homogeneity to eliminate erroneous daily rainfall (RR), minimum temperature (TN) and maximum temperature (TX) as well as to identify artificial jumps in the time series. To ensure consistency with similar regional climate extreme trends studies, we therefore used the RClimDex (version 1.0) QC and RHTests (version 3.0) data homogenization tools provided by the Expert Team on Climate Change Detection and Indices (ETCCDI). Software and documentation are available at http://etccdi.pacificclimate.org.

© 2014 Environment Canada. *International Journal of Climatology* published by Royal Meteorological Society and John Wiley & Sons Ltd.

10970088, 2014, 9, Downloaded from https://rmets.onlinelibrary.wiley.com/doi/10.1002/joc.3889 by CochraneBarbados, Wiley Online Library on [25/01/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

3.1. Data quality

With RClimDex, station records were corrected for errors in RR (negative values), and in TX and TN (TN higher or equal to TX). Erroneous RR values were always replaced with missing values. Similarly, errors pertaining to highly improbable values of either TX or TN or both were removed. However, in several instances, it was apparent that (1) TX and TN were swapped; (2) an erroneous TX value was likely the correct TN value or opposite; and (3) a digitisation error occurred, e.g. misreading of the first of two digits before the decimal point, or decimal point misplaced. In such cases, the actual erroneous value was replaced with its realistic value as identified from the climatology.

In addition, RClimDex detects outliers in RR, TX and TN based on user-defined thresholds. In this study, we defined an upper RR threshold of 300 mm which, in most of the Caribbean region, represents values that are very rare and typically only exceeded in case of direct impact by a tropical cyclone or when cool fronts meet unstable and moist trade winds. For TX and TN, a 5 standard deviation (5σ) threshold was defined. The latter is calculated for each individual day of the year based on values recorded in all years to detect outliers. Local climatological expertise was used to assess whether outliers were likely extreme values or artefacts. Outliers identified as artefacts were subsequently replaced with missing values in the observed data time series.

Finally, upon completion of the RClimDex-based QC, visual inspection of TN and TX time series was performed to identify residual artefacts, namely seemingly unrealistically low or high values that fall within 5σ. The rationale was that a given season may show substantially reduced variability compared to the same season in other years – meaning a reduced chance of 5σ outliers – though physically highly improbable values are still found, e.g. a TN of 32 °C in St Kitts in October. Such values were removed if erroneous beyond any reasonable doubt.

For this study, amongst all 51 stations and their complete period of data, less than 1% of the daily temperatures and less than 0.1% of the daily rainfall were corrected for errors and outliers.

3.2. Data homogeneity

Relocation of instruments and changes in observing procedures can sometimes introduce non-climatic shifts in climate time series and these shifts can influence the proper assessment of any climate trends (Aguilar *et al.*, 2003; Trewin, 2010; Vincent *et al.*, 2012). Homogeneity assessment can be complex since it requires long records of observations, close neighbour stations and detailed station history (metadata) in order to determine the cause of the detected shifts. Climate data homogenization in the Caribbean region is difficult because the stations are far from each other, they often belong to different climate regimes and they cover various periods and short periods of time (Figure 1 and Table 1). In addition, metadata are often sparse or non-existent for many stations in this region.

In this study, the time series of the monthly mean temperature anomalies derived from TX and TN separately were examined for temporal homogeneity using the RHTests software package (Wang and Feng, 2009). The procedure consists of detecting shifts in the difference between the time series of the monthly mean temperature anomalies of a candidate station and those of a neighbour station. The procedure was applied using four different neighbours separately. Although many shifts are identified using this procedure, only common shifts (same dates identified by at least two neighbours) were retained and further analysed.

The results are presented in Table 1. Altogether, only 14 shifts were investigated. The shifts were found in either TX or TN; only the station from Hato (Curaçao) has a decreasing step in 2001 in both TX and TN. The results also indicate that 10 shifts were decreasing steps and that 9 shifts occurred in the 2000s. No potential causes were identified in order to explain the detected shifts and it is possible that the shifts were simply due to climate variations. No adjustments were applied to the data at this time and only the longest homogeneous period was used for trend analysis. As an example, Figure 2 shows a decreasing shift in the anomalies of the monthly mean of TN in 2003 at Worthy Park (Jamaica) and in 2004 at Hewanorra (Saint Lucia). It will be possible to determine if these shifts will continue in time when additional observations become available.

Detection of inhomogeneities in precipitation time series is more difficult due to the high variability of the precipitation time and distance between neighbouring stations. Applying RHTests procedure on the log transformation of the wet months did not reveal inhomogeneities for any of the stations.

3.3. Indices

In addition to detecting outliers, RClimdex facilitates the calculation of a suite of 27 climate indices. In this study, a subset of 21 indices were investigated as they were considered relevant to the Caribbean and adjacent regions (see Table 2 for a complete description). The indices are made available to the international scientific community via the ETCCDI website (http://etccdi.pacificclimate.org/data.shtml) for climate variability and monitoring and are of lower commercial value than the raw data from which they are derived. Of the 21 indices presented in this study, 11 relate to temperature and include annual means and cool and warm extremes. Some of the extreme temperature indices are percentile based. Warm days (nights) are defined as annual or monthly count (indicated with superscript letter 'a' in Table 2) when maximum (minimum) temperature is greater than the 90th percentile; conversely, cool days (nights) are the annual count when maximum (minimum) temperature is less than the 10th percentile. The 90th and 10th percentiles are calculated

© 2014 Environment Canada. *International Journal of Climatology* published by Royal Meteorological Society and John Wiley & Sons Ltd.

10970088, 2014, 9, Downloaded from https://rmets.onlinelibrary.wiley.com/doi/10.1002/joc.3889 by CochraneBarbados, Wiley Online Library on [25/01/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

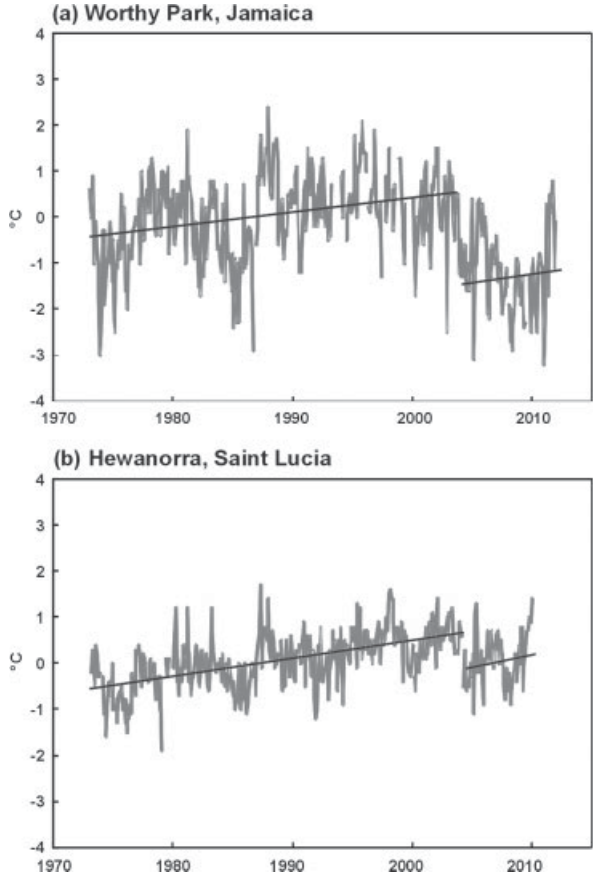


Figure 2. (a) Step identified in 2003 in the monthly mean anomalies of the daily minimum temperature of the station Worthy Park, Jamaica; (b) step identified in 2004 in the monthly mean anomalies of the daily minimum temperature of the station Hewanorra, Saint Lucia.

using a 5-day window centred on each calendar day over the reference period 1971–2000 (for the stations with shorter record, the percentiles were calculated over the period defined by the beginning year of the record to 2000). Extreme temperatures such as the highest/lowest daily values during the year or month were also investigated. In this study, 10 precipitation indices that relate to intensity, frequency and duration are analysed. They include the maximum number of CDD and consecutive wet days (CWD) (daily rainfall below and above 1 mm, respectively) observed yearly and the number of days with daily rainfall above 10, 20 and 50 mm. The annual total precipitation (PRCPTOT) was divided by the average total precipitation over 1971–2000 in order to produce a series which is not dominated by very high precipitation amounts. Similarly, the annual or monthly highest daily precipitation (RX1day), highest 5 consecutive days precipitation amount (RX5day) and heavy rainfall events (R95p) were further divided by the annual total precipitation to avoid very large values (which can influence the trend estimate) and to allow each index to be included in regional averages, with each station contributing equally to the average. Annual indices were computed if no more than 15 days were missing during the year, and percentiles were calculated if no more than 20% values were missing in the reference period.

3.4. Regional average indices

Subregional variations in precipitation and temperature over the Caribbean and neighbouring regions are represented using an average series calculated for each index over each of six regions shown in Figure 1 and indicated in Table 1. To account for the different periods covered by each station and the spatial distribution of the stations, anomalies from the 1981–2000 common reference period were first obtained at each station, and were then averaged over each of the six regions and also for the entire Caribbean area and adjacent countries. Regional average indices were calculated using stations having less than 30% of missing values in the analysed periods.

3.5. Trend estimation

Linear trends for individual stations and regional average series were fitted using the ordinary least squares regression. The trends were calculated for 1961–2010 and the shorter period 1986–2010. Although a period of 25 years is small for detecting any climate change signal, it allows for the inclusion of more stations in the analyses. The trends were computed only if more than 80% of the values were present in the time series. The statistical significance of the trends was assessed at the 5% level using the *t*-test.

4. Results

The results show consistent changes in the temperature and precipitation indices during the past 50 and 25 years in the countries and territories of the Caribbean region. However, the changes in temperature indices have a better spatial coherence than those found in the precipitation indices due to higher spatial and temporal variability in precipitation as compared to temperature. Table 3 presents the trends (index units/10 years) for the entire Caribbean region and adjacent countries for 1961–2010 and 1986–2010.

4.1. Temperature means

The analyses of the annual mean of daily maximum temperature (TXmean) suggest a general warming of the daytime temperature over the 1961–2010 period (Figure 3). TXmean Caribbean-wide regional average indicates a significant warming of 0.19 °C decade^{-1} (Table 3). The annual mean of daily minimum temperature (TNmean) suggest a significant and more pronounced warming of 0.28 °C decade^{-1} over the same period. Nighttime temperature (TNmean) trends at individual stations are generally greater than daytime temperature (TXmean) trends. This difference leads to a decrease in diurnal temperature range (DTR). Significant increasing DTR trends are evident only at Key West (Florida) and Georgetown (Guyana) over the 1961–2010 period.

© 2014 Environment Canada. *International Journal of Climatology* published by Royal Meteorological Society and John Wiley & Sons Ltd.

10970088, 2014, 9, Downloaded from https://rmets.onlinelibrary.wiley.com/doi/10.1002/joc.3889 by CochraneBarbados, Wiley Online Library on [25/01/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Table 2. Definition of the temperature and precipitation indices (computed on annual basis) used in this study. TX, TN and RR are daily maximum temperature, minimum temperature and total rainfall, respectively.

Element	Index	Descriptive name	Definition	Unit
Temperature	TXmean[a]	Annual maximum temperature	Annual mean of TX	°C
	TNmean[a]	Annual minimum temperature	Annual mean of TN	°C
	DTR[a]	Diurnal temperature range	Annual mean difference between TX and TN	°C
	TX90P[a]	Warm days	Percentage of days when TX > 90th percentile	%
	TX10P[a]	Cool days	Percentage of days when TX < 10th percentile	%
	TN90P[a]	Warm nights	Percentage of days when TN > 90th percentile	%
	TN10P[a]	Cool nights	Percentage of days when TN < 10th percentile	%
	TXx[a]	Highest TX	Annual highest value of TX	°C
	TXn[a]	Lowest TX	Annual lowest value of TX	°C
	TNx[a]	Highest TN	Annual highest value of TN	°C
	TNn[a]	Lowest TN	Annual lowest value of TN	°C
Precipitation	PRCPTOT	Annual precipitation	Annual total precipitation	mm
	SDII	Simple daily intensity index	Annual precipitation divided by number of wet days	mm/day
	CDD	Consecutive dry days	Maximum number of consecutive dry days	days
	CWD	Consecutive wet days	Maximum number of consecutive wet days	days
	R10mm	Days above 10 mm	Annual count of days when RR > 10 mm	days
	R20mm	Days above 20 mm	Annual count of days when RR > 20 mm	days
	R50mm	Days above 50 mm	Annual count of days when RR > 50 mm	days
	RX1day[a]	Max 1-day precipitation	Annual highest daily precipitation	mm
	RX5day[a]	Max 5-days precipitation	Annual highest 5 consecutive days precipitation	mm
	R95p	Very wet days	Annual total precipitation when RR > 95th percentile	mm

[a]Indices which are also calculated on a monthly basis.

Table 3. Trends for 1961–2010 and 1986–2010 (index units/10 years) for the Caribbean region and adjacent countries calculated from annual indices.

Element	Index	1961–2010	1986–2010	Unit
Temperature	TXmean	**0.19**	**0.12**	°C
	TNmean	**0.28**	**0.22**	°C
	DTR	**−0.10**	**−0.08**	°C
	TX90P	**3.31**	**6.49**	%
	TX10P	**−1.80**	−0.08	%
	TN90P	**4.07**	**5.97**	%
	TN10P	**−2.55**	−0.76	%
	TXx	**0.27**	**0.23**	°C
	TXn	**0.18**	−0.02	°C
	TNx	**0.23**	**0.31**	°C
	TNn	**0.32**	0.23	°C
Precipitation	PRCPTOT	2.32	3.46	%
	SDII	0.16	**0.59**	mm day^{-1}
	CDD	−0.81	1.25	days
	CWD	0.25	0.22	days
	R10mm	0.90	0.68	days
	R20mm	0.46	0.82	days
	R50mm	0.21	0.44	days
	RX1day	0.03	0.18	%
	RX5day	−0.03	0.18	%
	R95p	0.95	**2.05**	%

Bold values correspond to trends significant at the 5% level.

For 1986–2010, warming TXmean and TNmean trends are observed at most of the stations (Figure 3). However, a cooling of the daytime temperature is evident at several stations in Florida and Cuba (regions 1 and 2) and significant decreasing TXmean trends are found at Key West (USA) and Camagüey (Cuba). TNmean trends suggest a strong warming of the nighttime temperature. Significant decreasing trends in DTR are observed over most of the Caribbean region for 1986–2010. Increasing DTR trends are found at most Grenada and St Lucia stations and at Georgetown (Guyana) and Zorg en Hoop (Suriname). Overall, the results indicate that the Caribbean region and the adjacent countries are warming, with the signal being most robust with respect to annual mean of the daily minimum temperature.

4.2. Temperature extremes

Changes in temperature extremes are spatially consistent across the Caribbean region and the adjacent countries. Overall, the results show a statistically significant increase in the frequency of extreme warm temperatures and a significant decrease in the frequency of extreme cool temperatures at most stations (Figure 4). However, changes are not symmetrical and they are more pronounced in the extreme highs than in the extreme lows. During 1961–2010, the regional average indicates that the frequency of warm days (TX90P) and warm nights (TN90P) has increased by 3.31 and 4.07% (approximately 12 and 15 days) per decade, respectively, whereas the frequency of cool days (TX10P) and cool nights (TN10P) has decreased by only 1.80 and 2.55% per decade (Table 3). Spatially, the trends at individual stations show more warm days/nights and less cool days/nights (Figure 4). The regional average time series also indicate a very high value associated with the strong El Niño year of 1998 in TX90p and TN90p.

Over the shorter period 1986–2010, the changes in the frequency of warm days and warm nights are more pronounced than for the longer period. The regional averages show a significant increase in TX90P and TN90P of 6.49 and 5.97% per decade, respectively. The spatial pattern showing fewer warm days and more cool

© 2014 Environment Canada. *International Journal of Climatology* published by Royal Meteorological Society and John Wiley & Sons Ltd.

10970088, 2014, 9, Downloaded from https://rmets.onlinelibrary.wiley.com/doi/10.1002/joc.3889 by CochraneBarbados, Wiley Online Library on [25/01/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

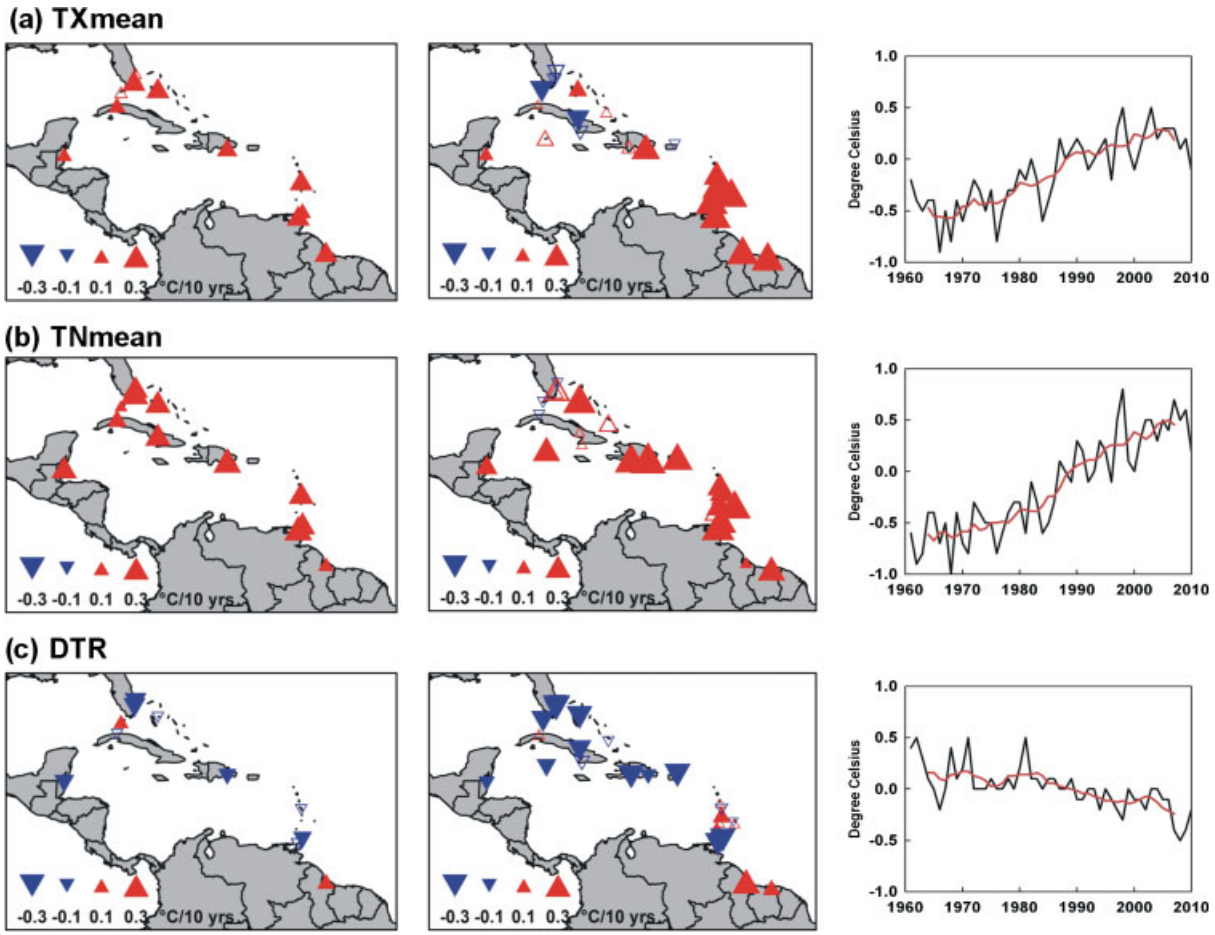


Figure 3. Trends in (a) TXmean, (b) TNmean and (c) DTR. Left panels show the trends for 1961–2010; middle panels show the trends for 1986–2010; and right panels present the time series for area averaged anomalies for 1961–2010 relative to a 1981–2000 climatology. Upward (downward) pointing triangles indicate positive (negative) trends. Solid triangles correspond to trends significant at the 5% level. The size of the triangle is proportional to the magnitude of the trend. Red colour indicates warming, blue indicates cooling trends in (a) and (b); blue colour indicates that the daily minimum is increasing more than the daily maximum in (c). The red line in the right panels is a 7-point running mean.

days in Florida and Cuba generally corresponds to the changes observed in TXmean over the past 25 years. The frequency of extreme warm nights (TN90p) has increased at all stations whereas the frequency of extreme cool nights (TN10p) has decreased at most stations during 1986–2010 (Figure 4).

The temperatures of the warmest day (TXx) and of the warmest night (TNx) of the year have increased at most stations, with the TXx and TNx regional average indicating a change of 0.27 and 0.23 °C decade^{-1}, respectively, for 1961–2010 (Table 3). Similarly, the temperatures of the coldest day (TXn) and of the coldest night (TNn) of the year show an increase of 0.18 and 0.32 °C decade^{-1}, respectively, over the same period. Spatially, the trends are positive at most of the stations: however, a few decreasing trends are also found in TXx, TXn and TNn at some of the stations in Florida and Cuba over the shorter period 1986–2010 (figure not presented).

4.3. Precipitation total, intensity and duration

For 1961–2010, the results show no statistically significant trend in the annual total precipitation (PRCPTOT) at any location at the 5% level. Similarly, a significant increase in the simple daily intensity index (SDII) was only recorded at three stations over the past 50 years (Figure 5). In congruence, small positive trends in the annual PRCPTOT and SDII regional averages were not found to be statistically significant (Table 3). Along the same line, the annual maximum numbers of CDD and CWD have not significantly changed during 1961–2010; spatially, a mixed pattern of small non-significant positive and negative trends was found over the Caribbean region.

The trends are more pronounced locally for records spanning the shorter period 1986–2010. While no significant positive trend in PRCPTOT regional average was observed, strong and significant increases are evident at Maisi (Cuba), Crown Point (Trinidad) and Georgetown (Guyana). The most significant change was found in a rise of the daily intensity rainfall at the majority of the locations, many of which are significant. The trend indicates that when precipitation occurs, it tends to be heavier. The SDII regional average indicates a significant increase of 0.59 mm day^{-1} decade^{-1} (Table 3). In addition, significant SDII increases of 0.77, 1.03 and 1.43 mm day^{-1} decade^{-1} were found in regions 1, 2 and

© 2014 Environment Canada. *International Journal of Climatology* published by Royal Meteorological Society and John Wiley & Sons Ltd.

10970088, 2014, 9, Downloaded from https://rmets.onlinelibrary.wiley.com/doi/10.1002/joc.3889 by CochraneBarbados, Wiley Online Library on [25/01/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

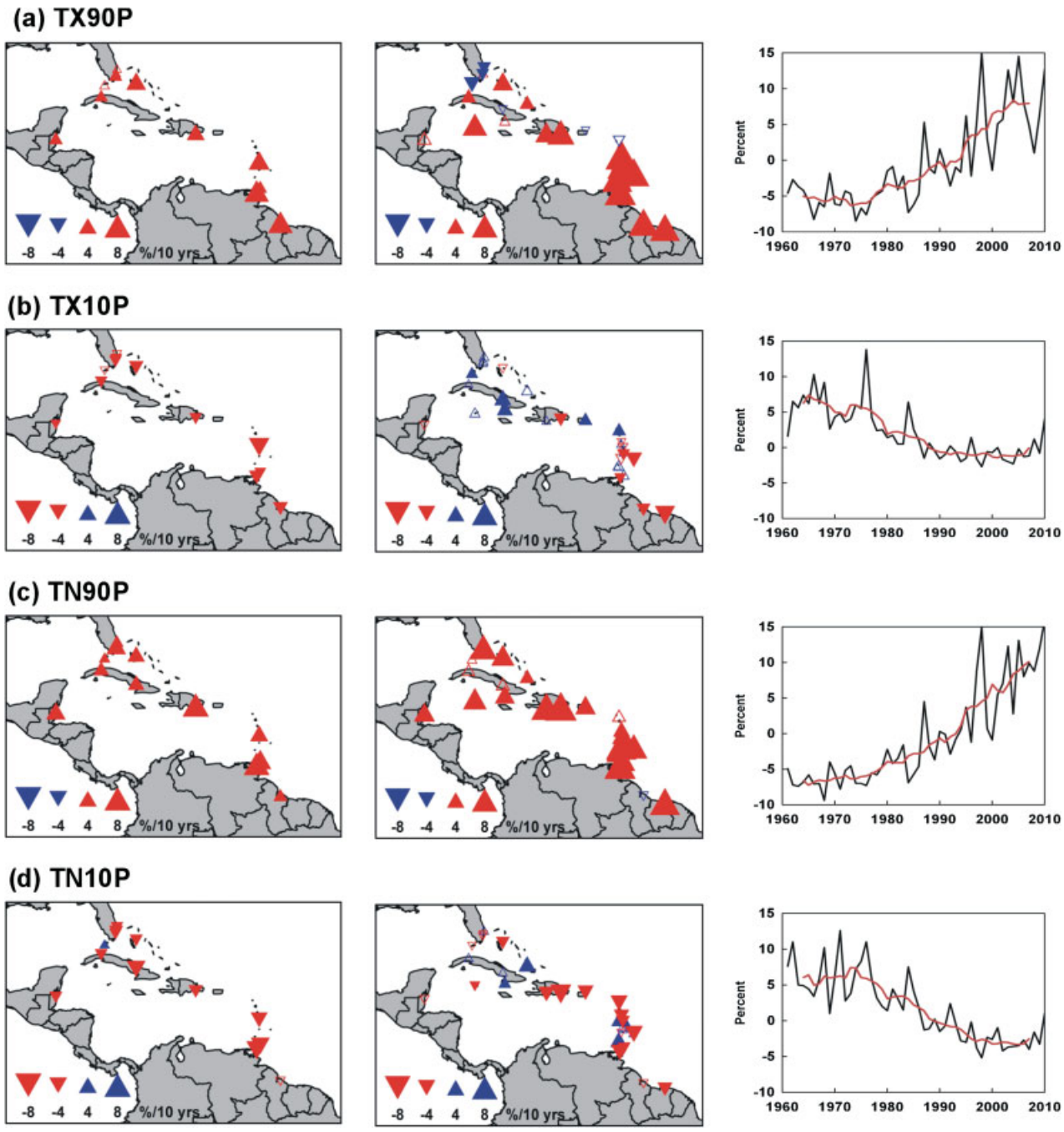


Figure 4. Same as Figure 3 but for the trends in (a) TX90p, (b) TX10p, (c) TN90p and (d) TN10p. Red colour indicates warming, blue indicates cooling trends.

3, respectively. CDD and CWD appear to have been increasing over the past 25 years, though the only CDD significant change was observed in region 1 with an increase of 2.79 days decade^{-1} over the past 25 years.

4.4. Precipitation extremes

Overall, the results do not show statistically significant change in the frequency of days with precipitation above 10 (R10mm), 20 (R20mm) and 50 (R50mm) mm for 1961–2010 (Table 3 and Figure 6). Likewise, changes in the annual highest daily precipitation (RX1day) and annual highest 5 consecutive daily precipitation (RX5day) were not significant at most stations. Furthermore, only one station, Casablanca (Cuba), noted a significant trend – a rise – in heavy rainfall events (R95p) whereas the rest of the stations suggest a mixed pattern of non-significant small positive and negative trends over the past 50 years.

Similar to the results in precipitation total and intensity, the trends in extreme precipitation are locally more pronounced over the shorter period 1986–2010. Fewer R10mm, R20mm and R50mm were found at most stations in Florida, Bahamas and Cuba whereas the stations in the remaining region indicate more R10mm,

© 2014 Environment Canada. *International Journal of Climatology* published by Royal Meteorological Society and John Wiley & Sons Ltd.

10970088, 2014, 9, Downloaded from https://rmets.onlinelibrary.wiley.com/doi/10.1002/joc.3889 by CochraneBarbados, Wiley Online Library on [25/01/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

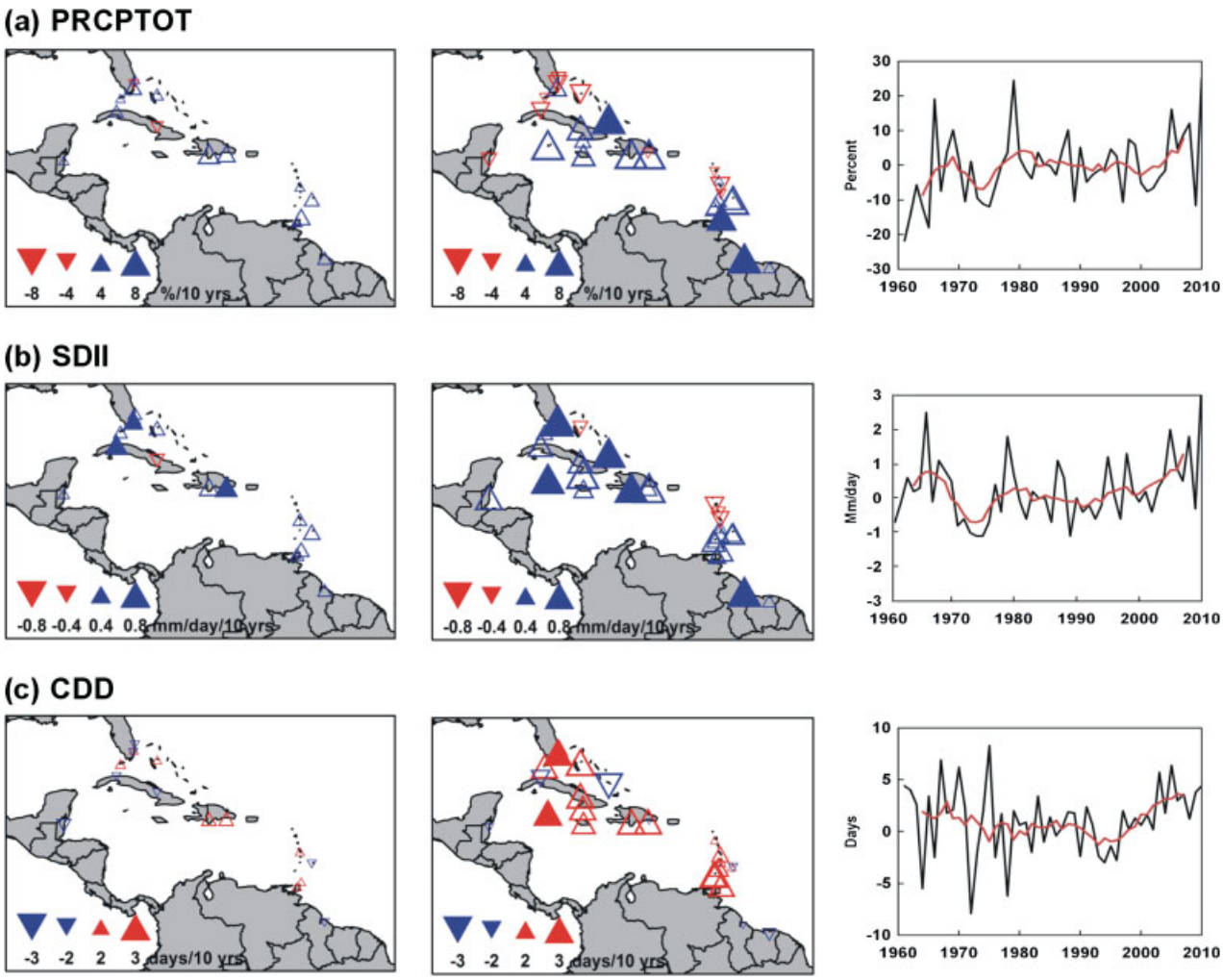


Figure 5. Same as Figure 3 but for the trends in (a) PRCPTOT, (b) SDII and (c) CDD. Blue colour indicates trends toward wetter conditions and red indicates drying trends in (a) and (b). Red colour in (c) indicates trends toward a longer drying spell.

R20mm and R50mm although the majority of the trends are non-significant (Figure 6). A mixed pattern of small positive and negative trends are observed in RX1day (not shown) and RX5day (Figure 6) over the past 25 years. The most significant change is found in the heavy rainfall events (R95p), which are generally rising. This index represents the precipitation due to events above the 95th percentile. A significant R95p increase of 2.93, 4.93 and 2.07% per decade is observed in regions 1, 2 and 5, whereas a significant increase of 2.05% per decade is found in the regional average series for the entire Caribbean region during the past 25 years (Table 3).

5. Discussion

The results presented in this study corroborate previous findings on changes in daily and extreme temperature and precipitation indices across the Caribbean, from local to regional scale. This study suggests trends towards fewer cool extremes and more warm extremes in the Caribbean region during the past 50 years. Similar results were found for neighbouring regions and comparable periods in the analyses of changes in temperature and precipitation extremes in North America (Peterson *et al.*, 2008) and in Central America and northern South America (Aguilar *et al.*, 2005; Skansi *et al.*, 2012) as well as at the country level (see for example Perez *et al.*, 2009 analyses for Cuba). Given the increase in the number of climate records and of the time span covered by them, results on temperature indices are also consistent with those obtained from the previous workshop in the Caribbean region (Peterson *et al.*, 2002) and reanalyses undertaken by Stephenson *et al.* (2008).

Regarding the precipitation indices, this study suggests that although no significant increases were found in the annual total precipitation amount, the intensity of daily rainfall and the heavy rainfall events has been significantly rising over the past 25 years. These results are in agreement with those presented in Peterson *et al.* (2008); Aguilar *et al.* (2005) and Peterson *et al.* (2002). However, it is necessary to mention that the maximum number of CDD, a measure of dry conditions, has been reported as declining in the results of the previous Caribbean workshop (Peterson *et al.*, 2002), whereas this

© 2014 Environment Canada. *International Journal of Climatology* published by Royal Meteorological Society and John Wiley & Sons Ltd.

10970088, 2014, 9, Downloaded from https://rmets.onlinelibrary.wiley.com/doi/10.1002/joc.3889 by CochraneBarbados, Wiley Online Library on [25/01/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

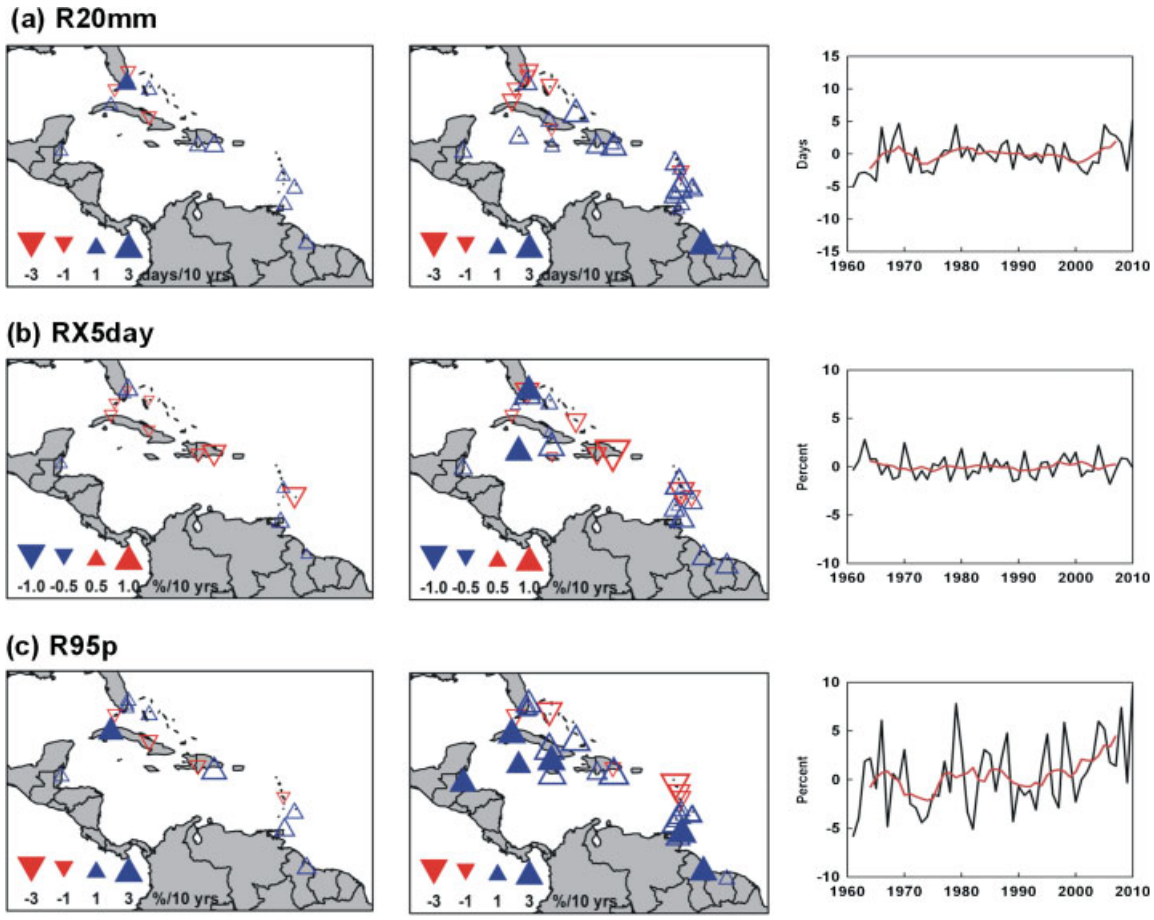


Figure 6. Same as Figure 3 but for the trends in (a) R20mm, (b) RX5day and (c) R95p. Blue colour indicates trends toward wetter conditions and red indicates drying trends.

study suggests an increase in CDD. The regional average series indeed indicates a small but steady decrease in CDD from the 1960s to the mid 1990s (Figure 5) which generally represents the period analysed by Peterson *et al.* (2002). Subsequent to the mid 1990s CDD has trended upwards through to 2010. This explains the CDD positive trends observed in this study, particularly for 1986–2010 and highlights the importance of on-going climate monitoring activities.

The results from the subregional analyses have justified the approach taken in this study – that of examining subregional manifestations of climate extremes. Among the particularly interesting results are the significant positive trends in SDII in regions 1, 2 and 3; the significant positive trend in CDD in region 1; the significant positive trends in R95p in regions 1, 2 and 5 and notably for Cuba. The suggestion for these regions is that more intense rainfall has been recorded over the last 50/25 years interrupted by longer dry spells. This may indicate an increased risk of floods though other factors such as land use and human settlement in flood plains become important as well.

In terms of attributing the observed trends in the temperature and precipitation indices, sea surface temperature (SST) is often invoked as a driving factor. Robust relationships were presented in previous literature, particularly for seasonal rainfall and SST anomalies related to the Atlantic warm pool, tropical/equatorial Atlantic, equatorial Pacific and Pacific–Atlantic gradients (Taylor *et al.*, 2002; Gimeno *et al.*, 2011). Here, a preliminary analysis is undertaken prompted by an apparent shift towards a positive trend for a number of regional average series (for example SDII, CDD and R95p) subsequent to the 1980s. This shift occurs around the same time the AMO transitions into a positive phase. The AMO is a north Atlantic SST signal that influences decadal scale variability in Caribbean precipitation (Enfield *et al.*, 2001; IPCC, 2007). In its positive (negative) phase, the AMO preconditions the Caribbean for wetter (drier) than normal conditions.

As a preliminary analysis, the time series of each index at each individual station was correlated with the AMO annual index (derived from monthly AMO values obtained from the Earth System Laboratory website at http://www.esrl.noaa.gov/psd/data/climateindices/list/). The results indicate that temperature indices are strongly correlated with the AMO index (Figure 7). The correlation for the precipitation indices is weaker but it is still significant at a number of stations. Correlation coefficients calculated between the regional average series and

© 2014 Environment Canada. *International Journal of Climatology* published by Royal Meteorological Society and John Wiley & Sons Ltd.

10970088, 2014, 9, Downloaded from https://rmets.onlinelibrary.wiley.com/doi/10.1002/joc.3889 by CochraneBarbados, Wiley Online Library on [25/01/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

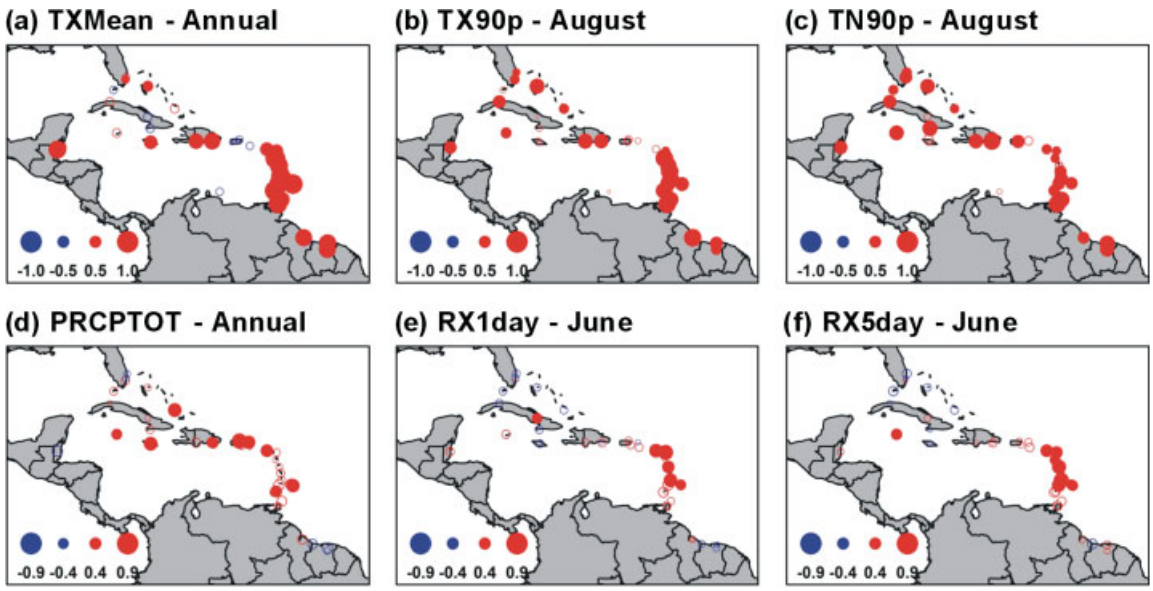


Figure 7. Correlation between the AMO annual (monthly) index and (a) annual TXmean, (b) August TX90p, (c) August TN90p, (d) annual PRCPTOT, (e) June RX1day and (f) June RX5day. Significant correlation ($p \leq 0.05$) is indicated by a full circle.

Table 4. Correlation coefficient calculated between annual temperature and precipitation indices regional series for 1961–2010 and the AMO annual index.

Element	Index	Correlation
Temperature	TXmean	**0.62**
	TNmean	**0.64**
	DTR	**−0.36**
	TX90P	**0.86**
	TX10P	**−0.50**
	TN90P	**0.80**
	TN10P	**−0.64**
	TXx	**0.73**
	TXn	0.13
	TNx	**0.70**
	TNn	**0.34**
Precipitation	PRCPTOT	**0.37**
	SDII	**0.63**
	CDD	0.19
	CWD	0.14
	R10mm	**0.28**
	R20mm	**0.32**
	R50mm	**0.41**
	RX1day	0.19
	RX5day	0.15
	R95p	**0.52**

Bold values correspond to correlation significant at the 5% level.

the AMO (presented in Table 4) reveal significant correlations for all temperature indices (with the exception of TXn) and most precipitation indices (PRCPTOT, SDII, R10mm, R20mm, R50 mm and R95p).

As all temperature indices and two precipitation indices (RX1day and RX5day) are also provided on a monthly basis (Table 2), the monthly time series at each station was correlated with the corresponding month's AMO index. The results indicate that, for the temperature indices, stations show significant correlation with the AMO monthly index and correlations are strongest in August and September (Figure 7). This suggests that the AMO signal is more pronounced on temperature during the end of the summer than for other periods of the year. For the precipitation indices RX1day and RX5day, stations display significant correlation with the AMO monthly index and correlations are strongest in June and October (corresponding to the early and late rainfall seasons). Figure 7 also shows that most of the stations with significant correlation are located in region 4. These results further suggest that there is an Atlantic SST signal in the variability of the temperature and precipitation extreme events and there is a need for further investigation and detailed attribution studies.

6. Summary and conclusion

This study presents the trends in indices of temperature and precipitation in the Caribbean region and adjacent countries for 1961–2010 and 1986–2010. Data were carefully examined for quality and homogeneity by local experts and a consistent methodology was applied for the preparation and analysis of the indices. This study presents the results of the second workshop on climate change indices which was held to further explore the trends in extreme precipitation and temperature indices with more data than available during the workshop in 2001. The resulting manuscript was designed to offer a more detailed spatial representation of the changes in extremes for the Caribbean region than presented in previous studies.

Overall, the land stations show a significant warming of the surface air temperature along with the nighttime temperature increasing more than the daytime temperature. The frequency of warm days, warm nights and extreme high temperatures has increased while fewer

© 2014 Environment Canada. *International Journal of Climatology* published by Royal Meteorological Society and John Wiley & Sons Ltd.

10970088, 2014, 9, Downloaded from https://rmets.onlinelibrary.wiley.com/doi/10.1002/joc.3889 by CochraneBarbados, Wiley Online Library on [25/01/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

cool days, cools nights and extreme low temperatures were observed. Changes in precipitation indices were less consistent. Small increasing trends were found in annual total precipitation, daily intensity, maximum number of CDD and heavy rainfall events particularly during the period 1986–2010.

Recent climate change in the Caribbean region is observed in rising temperature along with trends towards more warm extremes, less cold extremes as well as strong indications for enhanced heavy precipitation, not only region-wide, but also in different geographic sectors. The decadal variability in temperature and, to a lesser extent, rainfall extremes, is related to the AMO signal of the North Atlantic SSTs.

A next step to this study involves a detailed assessment of climate extreme indices from global and regional model scale output in order to assess model skill in representing present day extremes, and to analyze future projections for the near term and end of century (see for example Hall *et al.*, 2012). This information would be particularly useful to the Caribbean for the purposes of managing disaster risks and adaptation planning.

The issue of historic data rescue in support of climate change analyses is an important one for the Caribbean. Data collection in the Caribbean context involves data obtained from a network of meteorological stations maintained by national meteorological services, supplemented by stations either owned by other government entities, or that are privately owned particularly those on farms and estates. National weather services are often challenged with inappropriate storage and archiving of historical observational records, with some data still on deteriorating paper or as electronic data scattered across many agencies. One of the aims of the workshop was to highlight this and point to recent data rescue initiatives such as incorporated in the Caribbean Agrometeorological Initiative (CAMI) project executed by the Caribbean Institute for Meteorology and Hydrology (CIMH) or the Camaguey (Cuba) historic observations that are being hand digitized. Indeed countries welcome such initiatives and partnerships that will assist recovery of historic data, as in the case of Jamaica where archived historic microfilm weather data are yet to be digitized. The workshop facilitated the discussion of technologies that facilitate digitization and highlighted regional institutions, e.g. CIMH, or international institutions, e.g. the International Environmental Data Rescue Organization (IEDRO), that can assist such activities. The CIMH is already undertaking a larger data rescue project that incorporates all 16 member states of the Caribbean Meteorological Organization in comparison to the 10 countries covered in the CAMI project and will possibly serve as the hub for similar coordinated activities. The project is also developing a centralized database system with interactive portal to better facilitate data sharing and dissemination.

The workshop held at the University of the West Indies in Jamaica has provided a great opportunity not only to improve our understanding of changes in climate extremes but also to establish a strong scientific network for scientists working on climate change and historical data rescue in this region. This study represents an important contribution to climate change research. The indices will be made available to the international research community on the ETCCDI website at http://etccdi.pacificclimate.org/data.shtml.

Acknowledgements

The capacity building workshop on data rescue and climate change indices held in Kingston, Jamaica on May 7–10 was supported by the World Meteorological Organization, the National Oceanic and Atmospheric Administration and the Caribbean Community Climate Change Centre. The participants greatly enjoyed the hospitality provided by the Department of Physics at the University of the West Indies, Mona. Data compiled from *The Caribbean Agrometeorological Initiative* (*CAMI*) project executed by the Caribbean Institute for Meteorology and Hydrology and supported by the European Union funded African Caribbean and Pacific Group of Countries (ACP) Science and Technology Programme complemented the data provided by meteorological services across the Caribbean, Guyana and Belize. Special thanks to Shontelle Stoute and Lisa Kirton-Reed for their contribution to the CAMI Project. Other data were obtained from the National Climatic Data Centre online archive and from Météo-France. Special thanks to the directors of the National Meteorological and Hydrological Services for facilitating the participation of their staff in the workshop and for providing data.

References

Aguilar E, Auer I, Brunet M, Peterson TC and Wieringa J. 2003. Guidelines on climate metadata and homogenization. WCDMP No. 53, WMO-TD No. 1186, World Meteorological Organization. Geneva, Switzerland, 55.

Aguilar E, Peterson TC, Ramírez Obando P, Frutos R, Retana JA, Solera M, Soley J, González García I, Araujo RM, Rosa Santos A, Valle VE, Brunet M, Aguilar L, Álvarez L, Bautista M, Castañón C, Herrera L, Ruano E, Sinay JJ, Sánchez E, Hernández Oviedo GI, Obed F, Salgado JE, Vázquez JL, Baca M, Gutiérrez M, Centella C, Espinosa J, Martínez D, Olmedo B, Ojeda Espinoza CE, Núñez R, Haylock M, Benavides H, Mayorga R. 2005. Changes in precipitation and temperature extremes in Central America and Northern South America, 1961–2003. *J. Geophys. Res.* **110**: D23107, DOI: 10.1029/2005JD006119.

Aguilar E, Aziz Barry A, Brunet M, Ekang L, Fernandes A, Massoukina M, Mbah J, Mhanda A, do Nascimento DJ, Peterson TC, Thamba Umba O, Tomou M, Zhang X. 2009. Changes in temperature and precipitation extremes in western central Africa, Guinea Conakry, and Zimbabwe, 1955–2006. *J. Geophys. Res.* **114**: D02115, DOI: 10.1029/2008JD011010.

Alexander LV, Zhang X, Peterson TC, Caesar J, Gleason B, Klein Tank AMG, Haylock M, Collins D, Trewin B, Rahim F, Tagipour A, Kumar Kolli R, Revadekar JV, Griffiths G, Vincent L, Stephenson DB, Burn J, Aguilar E, Brunet M, Taylor M, New M, Zhai P, Rusticucci M, Vazquez Aguirre JL. 2006. Global observed changes in daily climate extremes of temperature and precipitation. *J. Geophys. Res.* **111**: D05109, DOI: 10.1029/2005JD006290.

Álvarez L. 2006, *Estudio de la localización espacial de las tormentas eléctricas en Cuba y su tendencia*, Tesis presentada en opción del

© 2014 Environment Canada. *International Journal of Climatology* published by Royal Meteorological Society and John Wiley & Sons Ltd.

10970088, 2014, 9, Downloaded from https://rmets.onlinelibrary.wiley.com/doi/10.1002/joc.3889 by CochraneBarbados, Wiley Online Library on [25/01/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

grado de Doctor en Ciencias Meteorológicas, UDICT, Instituto de Meteorología, 149.

Aparicio R. 1993. Meteorological and oceanographic conditions along the southern coastal boundary of the Caribbean Sea, 1951–1986. In *Climatic Change in the Intra-Americas Sea: Implications for Future Climate on the Ecosystems and Socio-Economic Structure in the Marine and Coastal Regions of the Caribbean Sea, Gulf of Mexico, Bahamas, and the Northeast Coast of South America*, Maul GA (ed). Edward Arnold: London, UK; 100–114.

Caesar J, Alexander LV, Trewin B, Tse-ring K, Sorany L, Vuniyayawa V, Keosavang N, Shimana A, Htay MM, Karmacharya J, Jayasinghearachchi DA, Sakkamart J, Soares E, Hung LT, Thuong LT, Hue CT, Dung NTT, Hung PV, Cuong HD, Cuong NM, Sirabaha S. 2011. Changes in temperature and precipitation extremes over the Indo-Pacific region from 1971 to 2005. *Int. J. Climatol.* **31**: 791–801, DOI: 10.1002/joc.2118.

Charlery J, Nurse L, Whitehall K. 2006. Exploring the relationship between the North Atlantic Oscillation and rainfall patterns in Barbados. *Int. J. Climatol.* **26**: 819–827.

Chen AA, Taylor M. 2002. Investigating the link between early season Caribbean rainfall and the El Nino + 1 year. *Int. J. Climatol.* **22**: 87–106.

Chen AA, Taylor M, Centella A, Farrell D. 2008. Climate trends and scenarios: report of working group I, climate change and biodiversity in Caribbean islands. CANARI Technical Report No. 381. CANARI: Trinidad, Trinidad and Tobago.

Curtis S. 2002. Interannual variability of the bimodal distribution of summertime rainfall over Central America and tropical storm activity in the far-eastern Pacific. *Climate Res.* **22**: 141–146.

Curtis S, Gamble DW. 2007. Regional variations of the Caribbean mid-summer drought. *Theor. Appl. Climatol.* **94**: 25–34.

Donat MG, Peterson TC, Brunet M, King AD, Almazroui M, Kolli RK, Boucherf D, Al-Mulla AY, Nour AY, Aly AA, Nada TAA, Semawi MM, Dashti HAA, Salhab TG, El Fadli KI, Muftah MK, Eida SD, Badi W, Driouech F, Rhaz KE, Abubaker MJY, Ghulam AS, Erayah AS, Mansour MB, Alabdouli WO, Dhanhani JSA, Al Shekaili MN. 2013a. Changes in extreme temperature and precipitation in the Arab region: long-term trends and variability related to ENSO and NAO. *Int. J. Climatol.*, DOI: 10.1002/joc.3707.

Donat MG, Alexander LV, Yang H, Durre I, Vose R, Dunn RJH, Willett KM, Aguilar E, Brunet M, Caesar J, Hewitson B, Jack C, Klein Tank AMG, Kruger AC, Marengo J, Peterson TC, Renom M, Oria Rojas C, Rusticucci M, Salinger J, Elrayah AS, Sekele SS, Srivastava AK, Trewin B, Villarroel C, Vincent LA, Zhai P, Zhang X, Kitching S. 2013b. Updated analyses of temperature and precipitation extreme indices since the beginning of the twentieth century: The HadEX2 dataset. *J. Geophys. Res. Atmos.* **118**: 2098–2118, DOI: 10.1002/jgrd.50150.

Enfield DB, Mestas-Nunez AM, Trimble PJ. 2001. The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental US. *Geophys. Res. Lett.* **28**: 2077–2080.

Gamble DW, Curtis S. 2008. Caribbean precipitation: review, model, and prospect. *Prog. Phys. Geogr.* **32**(3): 265–276.

Gamble D, Parnell D, Curtis S. 2007. Spatial variability of the Caribbean mid-summer drought and relation to north Atlantic high circulation. *Int. J. Climatol.* **28**: 343–350.

Giannini A, Kushnir Y, Cane MA. 2000. Interannual variability of Caribbean rainfall, ENSO, and the Atlantic Ocean. *J. Climate* **13**: 297–311.

Gimeno L, Magaña V, Enfield DB. 2011. Introduction to special section on the role of the Atlantic warm pool in the climate of the Western Hemisphere. *J. Geophys. Res.* **116**: D00Q01, DOI: 10.1029/2011JD016699.

Griffiths GM, Chambers LE, Haylock MR, Manton MJ, Nicholls N, Baek H-J, Choi Y, Della-Marta PM, Gosai A, Iga N, Lata R, Laurent V, Maitrepierre L, Nakamigawa H, Ouprasitwong N, Solofa D, Tahani L, Thuy DT, Tibig L, Trewin B, Vediapan K, Zhai P. 2005. Change in mean temperature as a predictor of extreme temperature change in the Asia-Pacific region. *Int. J. Climatol.* **25**: 1301–1330, DOI: 10.1002/joc.1194.

Hall TC, Sealy AM, Stephenson TS, Kusunoki S, Taylor MA, Chen AA, Kitoh A. 2012. Future climate of the Caribbean from a super-high-resolution atmospheric general circulation model. *Theor. Appl. Climatol.*, DOI: 10.1007/s00704-012-077907.

Haylock MR, Peterson TC, Alves LM, Ambrizzi T, Anunciacao T, Baez J, Barros VR, Berlato MA, Bidegain M, Coronel G, Corradi V, Garcia VJ, Grimm AM, Jaildo dos Anjos R, Karoly D, Marengo JA, Marino MB, Meira PR, Miranda GC, Molion L, Muncunil DF, Nechet D, Ontaneda G, Quintana J, Ramirez E, Rebello E, Rusticucci M, Santos JL, Varillas IT, Vincent L, Yumiko M. 2006. Trends in total and extreme South American rainfall 1960–2000 and links with sea surface temperature. *J. Climate* **19**: 1490–1512.

IPCC. 2007. Climate Change 2007: Synthesis Report. Working Group I, II and III contributions to the Fourth Assessment Report. http://www.ipcc.ch.

IPCC. 2012. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. http://ipcc-wg2.gov/SREX/report/full-report/.

Jury M. 2009. An intercomparison of observational, reanalysis, satellite, and coupled model data on mean rainfall in the Caribbean. *J. Hydrometeorol.* **10**: 413–430.

Jury MR, Malmgren BA, Winter A. 2007. Subregional precipitation climate of the Caribbean and relationships with ENSO and NAO. *J. Geophys. Res.* **112**: D16107, DOI: 10.1029/2006JD007541.

Klein Tank AMG, Peterson TC, Quadir DA, Dorji S, Zou X, Tang H, Santhosh K, Joshi UR, Jaswal AK, Kolli RK, Sikder AB, Deshpande NR, Revadekar JV, Yeleuova K, Vandasheva S, Faleyeva M, Gomboluudev P, Budhathoki KP, Hussain A, Afzaal M, Chandrapala L, Anvar H, Amanmurad D, Asanova VS, Jones PD, New MG, Spektorman T. 2006. Changes in daily temperature and precipitation extremes in Central and South Asia. *J. Geophys. Res.* **111**: D16105, DOI: 10.1029/2005JD006316.

Lapinel B, Pérez D, Cutié V, Fonseca C. 2002. Los eventos ENOS y su asociación con la sequía en Cuba. *Revista Cubana de Meteorología* **9**(2): 38.

Magana V, Amador JA, Medina S. 1999. The midsummer drought over Mexico and Central America. *J. Climate* **12**: 1577–1588.

Manton MJ, Della-Marta PM, Haylock MR, Hennessy KJ, Nicholls N, Chambers LE, Collins DA, Daw G, Finet A, Gunawan D, Inape K, Isobe H, Kestin TS, Lefale P, Leyu CH, Lwin T, Maitrepierre L, Ouprasitwong N, Page CM, Pahalad J, Plummer N, Salinger MJ, Suppiah R, Tran VL, Trewin B, Tibig I, Yee D. 2001. Trends in extreme daily rainfall and temperature in Southeast Asia and the South Pacific: 1961–1998. *Int. J. Climatol.* **21**: 269–284, DOI: 10.1002/joc.610.

Mapes BE, Liu P, Buenning N. 2005. Indian monsoon onset and Americas midsummer drought: out-of-equilibrium responses to smooth seasonal forcing. *J. Climate* **18**: 1109–1115.

Martin HC, Weech PS. 2001. Climate Change in the Bahamas? Evidence in the meteorological records. *Bahamas J. Sci.* **5**: 22–32.

Martis A, Van Oldenborgh GJ, Burgers G. 2002. Predicting rainfall in the Dutch Caribbean – more than El Niño? *Int. J. Climatol.* **22**: 1219–1234.

Naranjo L, Centella A. 1998. Recent trends in climate of Cuba. *Weather* **53**: 78–85, DOI: 10.1002/j.1477-8696.1998.tb03964.

Neelin JD, Munnich M, Su H, Meyerson JE, Holloway C. 2006. Tropical drying trends in global warming models and observations. *Proc. Natl. Acad. Sci. USA* **103**: 6110–6115.

New M, Hewitson B, Stephenson DB, Tsiga A, Kruger A, Manhique A, Gomez B, Coelho CAS, Masisi DN, Kululanga E, Mbambalala E, Adesina F, Saleh H, Kanyanga J, Adosi J, Bulane L, Fortunata L, Mdoka ML, Lajoie R. 2006. Evidence of trends in daily climate extremes over southern and West Africa. *J. Geophys. Res.* **111**: D14102, DOI: 10.1029/2005JD006289.

Nurse LA, Sem G. 2001. Small island states. *Climate change 2001 – the scientific basis. Contribution of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)*, Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Xiaosu D (eds). Cambridge University Press: Cambridge, UK; 843–875.

Perez SR, Fonseca C, Lapinel B, Gonzalez C, Planes E, Cutié V, Ballester M, Limia M, Vega R. 2009. Updating the knowledge of variations, climate change and trends in Cuba. Scientific Report. Instituto de Meteorologia de la Republica de Cuba: Cuba.

Peterson TC, Manton MJ. 2008. Monitoring changes in climate extremes: a tale of international collaboration. *Bull. Am. Meteorol. Soc.* **89**: 1266–1271.

Peterson TC, Taylor MA, Demeritte R, Duncombe DL, Burton S, Thompson F, Porter A, Mercedes M, Villegas E, Fils RS, Klein Tank A, Martis A, Warner R, Joyette A, Mills W, Alexander L, Gleason B. 2002. Recent changes in climate extremes in the Caribbean region. *J. Geophys. Res.* **107**(D21): 4601, DOI: 10.1029/2002JD002251.

Peterson TC, Zhang X, Brunet-India M, Vázquez-Aguire JL. 2008. Changes in North American extremes derived from daily weather data. *J. Geophys. Res.* **113**: D07113, DOI: 10.1029/2007JD009453.

© 2014 Environment Canada. *International Journal of Climatology* published by Royal Meteorological Society and John Wiley & Sons Ltd.

10970088, 2014, 9, Downloaded from https://rmets.onlinelibrary.wiley.com/doi/10.1002/joc.3889 by CochraneBarbados, Wiley Online Library on [25/01/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Pulwarty RS, Nurse LA, Trotz UO. 2010. *Caribbean Islands in a Changing Climate Environment*. http://www.environmentmagazine.org/Archives/Back%20Issues/ November-December%202010/caribbean-islands-full.html.

Rudloff W. 1981. *World-Climates, With Tables of Climatic Data and Practical Suggestions*. Wissenschaftliche Verlagsgesellschaft mbH: Stuttgart.

Sahay R. 2005. Stabilization, Debt & Fiscal Policy in the Caribbean IMF Working Paper WP/05/26. Washington, DC.

Simpson MC, Scott D, Harrison M, Silver N, O'Keeffe E, Sim R, Harrison S, Taylor M, Lizcano G, Rutty M, Stager H, Oldham J, Wilson M, New M, Clarke J, Day OJ, Fields N, Georges J, Waithe R, McSharry P. 2010. Quantification and magnitude of losses and damages resulting from the impacts of climate change: modelling the transformational impacts and costs of sea level rise in the Caribbean (Summary Document). United Nations Development Programme (UNDP). Barbados: West Indies.

Singh B. 1997. Climate changes in the greater and southern Caribbean. *Int. J. Climatol.* **17**: 1093–1114.

Skansi M, Brunet M, Sigró J, Aguilar E, Arevalo Groening J, Bentancur O, Castellon Geier Y, Correa Amaya R, Jacome H, Malheiros Ramos A, Oria Rojas C, Pasten AM, Sallons Mitro S, Villaroel Jiménez C, Martínez R, Alexander L, Jones PD. 2012. Warming and wetting signals emerging from analysis of changes in climate extreme indices over South America. *Global Planet. Change*, DOI: 10.1016/j.gloplacha.2012.11.004.

Stephenson TS, Goodess CM, Haylock MR, Chen AA, Taylor MA. 2008. Detecting inhomogeneities in Caribbean and adjacent Caribbean temperature data using sea-surface temperatures. *J. Geophys. Res.* **113**: D21116, DOI: 10.1029/2007JD009127.

Taylor MA, Enfield DB, Chen AA. 2002. The influence of the tropical Atlantic vs. the tropical Pacific on Caribbean rainfall. *J. Geophys. Res.* **107**(C9): 3127, DOI: 10.1029/2001JC001097.

Trewin BC. 2010. Exposure, instrumentation and observing practice effects on land temperature measurements. *Wiley Interdis Rev: Clim Change* **1**: 490–506.

Vincent L, Peterson T, Barros VR, Marino MB, Rusticucci M, Miranda G, Ramirez E, Alves LM, Ambrizzi T, Baez J, Barbosa de Brito JI, Berlato M, Grimm AM, Jaildo dos Anjos R, Marengo JA, Meira C, Molion L, Muncunil DF, Nechet D, Rebello E, Abreu de Sousa J, Anunciação YMT, Quintana J, Santos J, Ontaneda G, Baez J, Coronel G, Garcia VL, Varillas IT, Bidegain M, Corradi V, Haylock MR, Karoly D. 2005. Observed trends in indices of daily temperature extremes in South America 1960–2000. *J. Climate* **18**: 5011–5023.

Vincent LA, Aguilar E, Saindou M, Hassane AF, Jumaux G, Roy D, Booneeady P, Virasami R, Randriamarolaza LYA, Faniriantsoa FR, Amelie V, Seeward H, Montfraix B. 2011. Observed trends in indices of daily and extreme temperature and precipitation for the countries of the western Indian Ocean, 1961–2008. *J. Geophys. Res.* **116**: D10108, DOI: 10.1029/2010JD015303.

Vincent LA, Wang XL, Milewska EJ, Wan H, Yang F, Swail V. 2012. A second generation of homogenized Canadian monthly surface air temperature for climate trend analysis. *J. Geophys. Res.* **117**: D18110, DOI: 10.1029/2012JD017859.

Walsh RPD. 1998. Climatic changes in the eastern Caribbean over the past 150 years and some implications in planning sustainable development. In *Resource Sustainability and Caribbean Development*, McGregor DFM, Barker D, Evans SL (eds). The Press University of the West Indies: Kingston; 51–68.

Wang XL, Feng Y. 2009. RHtestsV3 User Manual. Climate Research Division, Atmospheric Science and Technology Directorate, Science and Technology Branch, Environment Canada. 26. (http://etccdi.pacificclimate.org/software.shtml)

Zhang X, Aguilar E, Sensoy S, Melknyan H, Taghiyeva U, Ahmed N, Kutaladze N, Rahimzadeh F, Taghipour A, Hantosh TH, Albert P, Semawi M, Ali MK, Halal M, Al-Shabibi A, Al-Oulan A, Zatari A, Al Dean Khalil I, Sagir R, Demircan M, Eken M, Adiguzel M, Alexander L, Peterson TC, Wallis T. 2005. Trends in Middle East climate extremes indices during 1950–2003. *J. Geophys. Res.* **110**: D22104, DOI: 10.1029/2005JD006181.

© 2014 Environment Canada. *International Journal of Climatology* published by Royal Meteorological Society and John Wiley & Sons Ltd.

10970088, 2014, 9, Downloaded from https://rmets.onlinelibrary.wiley.com/doi/10.1002/joc.3889 by CochraneBarbados, Wiley Online Library on [25/01/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Annex 41

"Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change", *Intergovernmental Panel on Climate Change*, 2014, pages 1-2, 14-20



ipcc

INTERGOVERNMENTAL PANEL ON climate change

CLIMATE CHANGE 2014

Impacts, Adaptation, and Vulnerability

Summary for Policymakers

WG II

WORKING GROUP II CONTRIBUTION TO THE
FIFTH ASSESSMENT REPORT OF THE
INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

WMO UNEP

SPM

Summary for Policymakers

Drafting Authors:
Christopher B. Field (USA), Vicente R. Barros (Argentina), Michael D. Mastrandrea (USA), Katharine J. Mach (USA), Mohamed A.-K. Abdrabo (Egypt), W. Neil Adger (UK), Yury A. Anokhin (Russian Federation), Oleg A. Anisimov (Russian Federation), Douglas J. Arent (USA), Jonathon Barnett (Australia), Virginia R. Burkett (USA), Rongshuo Cai (China), Monalisa Chatterjee (USA/India), Stewart J. Cohen (Canada), Wolfgang Cramer (Germany/France), Purnamita Dasgupta (India), Debra J. Davidson (Canada), Fatima Denton (Gambia), Petra Döll (Germany), Kirstin Dow (USA), Yasuaki Hijioka (Japan), Ove Hoegh-Guldberg (Australia), Richard G. Jones (UK), Roger N. Jones (Australia), Roger L. Kitching (Australia), R. Sari Kovats (UK), Joan Nymand Larsen (Iceland), Erda Lin (China), David B. Lobell (USA), Iñigo J. Losada (Spain), Graciela O. Magrin (Argentina), José A. Marengo (Brazil), Anil Markandya (Spain), Bruce A. McCarl (USA), Roger F. McLean (Australia), Linda O. Mearns (USA), Guy F. Midgley (South Africa), Nobuo Mimura (Japan), John F. Morton (UK), Isabelle Niang (Senegal), Ian R. Noble (Australia), Leonard A. Nurse (Barbados), Karen L. O'Brien (Norway), Taikan Oki (Japan), Lennart Olsson (Sweden), Michael Oppenheimer (USA), Jonathan T. Overpeck (USA), Joy J. Pereira (Malaysia), Elvira S. Poloczanska (Australia), John R. Porter (Denmark), Hans-O. Pörtner (Germany), Michael J. Prather (USA), Roger S. Pulwarty (USA), Andy Reisinger (New Zealand), Aromar Revi (India), Patricia Romero-Lankao (Mexico), Oliver C. Ruppel (Namibia), David E. Satterthwaite (UK), Daniela N. Schmidt (UK), Josef Settele (Germany), Kirk R. Smith (USA), Dáithí A. Stone (Canada/South Africa/USA), Avelino G. Suarez (Cuba), Petra Tschakert (USA), Riccardo Valentini (Italy), Alicia Villamizar (Venezuela), Rachel Warren (UK), Thomas J. Wilbanks (USA), Poh Poh Wong (Singapore), Alistair Woodward (New Zealand), Gary W. Yohe (USA)

This Summary for Policymakers should be cited as:
IPCC, 2014: Summary for policymakers. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1-32.

Contents

Assessing and Managing the Risks of Climate Change 3

Background Box SPM.1. Context for the Assessment 4

Background Box SPM.2. Terms Central for Understanding the Summary 5

Background Box SPM.3. Communication of the Degree of Certainty in Assessment Findings 6

A: Observed Impacts, Vulnerability, and Adaptation in a Complex and Changing World 4

A-1. Observed Impacts, Vulnerability, and Exposure 4

A-2. Adaptation Experience 8

A-3. The Decision-making Context 9

B: Future Risks and Opportunities for Adaptation 11

B-1. Key Risks across Sectors and Regions 11

Assessment Box SPM.1. Human Interference with the Climate System 12

B-2. Sectoral Risks and Potential for Adaptation 14

B-3. Regional Key Risks and Potential for Adaptation 20

Assessment Box SPM.2. Regional Key Risks 21

C: Managing Future Risks and Building Resilience 25

C-1. Principles for Effective Adaptation 25

C-2. Climate-resilient Pathways and Transformation 28

Supplementary Material 30

Increasing magnitudes of warming increase the likelihood of severe, pervasive, and irreversible impacts. Some risks of climate change are considerable at 1 or 2°C above preindustrial levels (as shown in Assessment Box SPM.1). Global climate change risks are high to very high with global mean temperature increase of 4°C or more above preindustrial levels in all reasons for concern (Assessment Box SPM.1), and include severe and widespread impacts on unique and threatened systems, substantial species extinction, large risks to global and regional food security, and the combination of high temperature and humidity compromising normal human activities, including growing food or working outdoors in some areas for parts of the year (*high confidence*). The precise levels of climate change sufficient to trigger tipping points (thresholds for abrupt and irreversible change) remain uncertain, but the risk associated with crossing multiple tipping points in the earth system or in interlinked human and natural systems increases with rising temperature (*medium confidence*).[45]

The overall risks of climate change impacts can be reduced by limiting the rate and magnitude of climate change. Risks are reduced substantially under the assessed scenario with the lowest temperature projections (RCP2.6 – low emissions) compared to the highest temperature projections (RCP8.5 – high emissions), particularly in the second half of the 21st century (*very high confidence*). Reducing climate change can also reduce the scale of adaptation that might be required. Under all assessed scenarios for adaptation and mitigation, some risk from adverse impacts remains (*very high confidence*).[46]

B-2. Sectoral Risks and Potential for Adaptation

Climate change is projected to amplify existing climate-related risks and create new risks for natural and human systems. Some of these risks will be limited to a particular sector or region, and others will have cascading effects. To a lesser extent, climate change is also projected to have some potential benefits.

Freshwater resources

Freshwater-related risks of climate change increase significantly with increasing greenhouse gas concentrations (*robust evidence*, *high agreement*). The fraction of global population experiencing water scarcity and the fraction affected by major river floods increase with the level of warming in the 21st century.[47]

Climate change over the 21st century is projected to reduce renewable surface water and groundwater resources significantly in most dry subtropical regions (*robust evidence*, *high agreement*), intensifying competition for water among sectors (*limited evidence*, *medium agreement*). In presently dry regions, drought frequency will *likely* increase by the end of the 21st century under RCP8.5 (*medium confidence*). In contrast, water resources are projected to increase at high latitudes (*robust evidence*, *high agreement*). Climate change is projected to reduce raw water quality and pose risks to drinking water quality even with conventional treatment, due to interacting factors: increased temperature; increased sediment, nutrient, and pollutant loadings from heavy rainfall; increased concentration of pollutants during droughts; and disruption of treatment facilities during floods (*medium evidence*, *high agreement*). Adaptive water management techniques, including scenario planning, learning-based approaches, and flexible and low-regret solutions, can help create resilience to uncertain hydrological changes and impacts due to climate change (*limited evidence*, *high agreement*).[48]

Terrestrial and freshwater ecosystems

A large fraction of both terrestrial and freshwater species faces increased extinction risk under projected climate change during and beyond the 21st century, especially as climate change interacts with other stressors, such as habitat modification, over-

[45] 4.2-3, 11.8, 19.5, 19.7, 26.5, Box CC-HS
[46] 3.4-5, 16.6, 17.2, 19.7, 20.3, 25.10, Tables 3-2, 8-3, and 8-6, Boxes 16-3 and 25-1
[47] 3.4-5, 26.3, Table 3-2, Box 25-8

exploitation, pollution, and invasive species (*high confidence*). Extinction risk is increased under all RCP scenarios, with risk increasing with both magnitude and rate of climate change. Many species will be unable to track suitable climates under mid- and high-range rates of climate change (i.e., RCP4.5, 6.0, and 8.5) during the 21st century (*medium confidence*). Lower rates of change (i.e., RCP2.6) will pose fewer problems. See Figure SPM.5. Some species will adapt to new climates. Those that cannot adapt sufficiently fast will decrease in abundance or go extinct in part or all of their ranges. Management actions, such as maintenance of genetic diversity, assisted species migration and dispersal, manipulation of disturbance regimes (e.g., fires, floods), and reduction of other stressors, can reduce, but not eliminate, risks of impacts to terrestrial and freshwater ecosystems due to climate change, as well as increase the inherent capacity of ecosystems and their species to adapt to a changing climate (*high confidence*).[49]

Within this century, magnitudes and rates of climate change associated with medium- to high-emission scenarios (RCP4.5, 6.0, and 8.5) pose high risk of abrupt and irreversible regional-scale change in the composition, structure, and function of terrestrial and freshwater ecosystems, including wetlands (*medium confidence*). Examples that could lead to substantial impact on climate are the boreal-tundra Arctic system (*medium confidence*) and the Amazon forest (*low confidence*). Carbon stored in the terrestrial biosphere (e.g., in peatlands, permafrost, and forests) is susceptible to loss to the atmosphere as a result of climate change, deforestation, and ecosystem degradation (*high confidence*). Increased tree mortality and associated forest dieback is projected to occur in many regions over the 21st century, due to increased temperatures and drought (*medium confidence*). Forest dieback poses risks for carbon storage, biodiversity, wood production, water quality, amenity, and economic activity.[50]

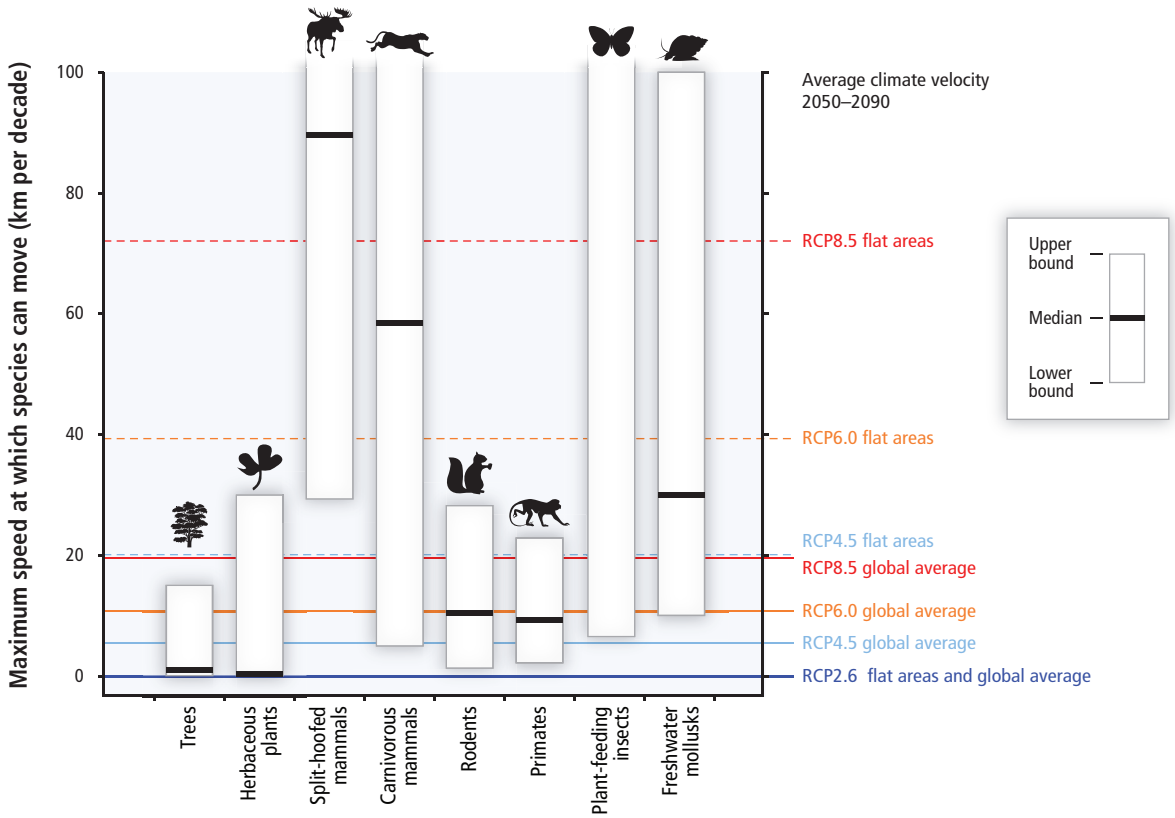


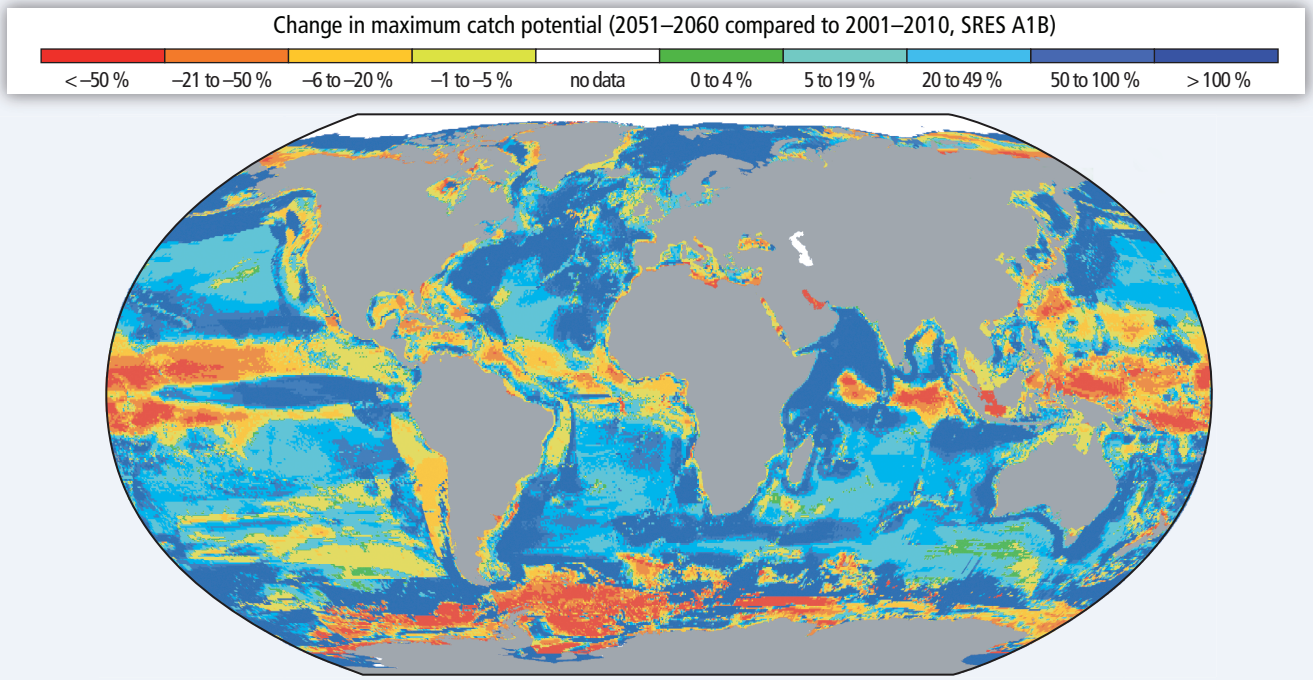
Figure SPM.5 | Maximum speeds at which species can move across landscapes (based on observations and models; vertical axis on left), compared with speeds at which temperatures are projected to move across landscapes (climate velocities for temperature; vertical axis on right). Human interventions, such as transport or habitat fragmentation, can greatly increase or decrease speeds of movement. White boxes with black bars indicate ranges and medians of maximum movement speeds for trees, plants, mammals, plant-feeding insects (median not estimated), and freshwater mollusks. For RCP2.6, 4.5, 6.0, and 8.5 for 2050–2090, horizontal lines show climate velocity for the global-land-area average and for large flat regions. Species with maximum speeds below each line are expected to be unable to track warming in the absence of human intervention. [Figure 4-5]

[48] 3.2, 3.4-6, 22.3, 23.9, 25.5, 26.3, Table 3-2, Table 23-3, Boxes 25-2, CC-RF, and CC-WE; WGI AR5 12.4

[49] 4.3-4, 25.6, 26.4, Box CC-RF

[50] 4.2-3, Figure 4-8, Boxes 4-2, 4-3, and 4-4

(A)


Change in maximum catch potential (2051–2060 compared to 2001–2010, SRES A1B)
< –50 %
–21 to –50 %
–6 to –20 %
–1 to –5 %
no data
0 to 4 %
5 to 19 %
20 to 49 %
50 to 100 %
> 100 %

(B)

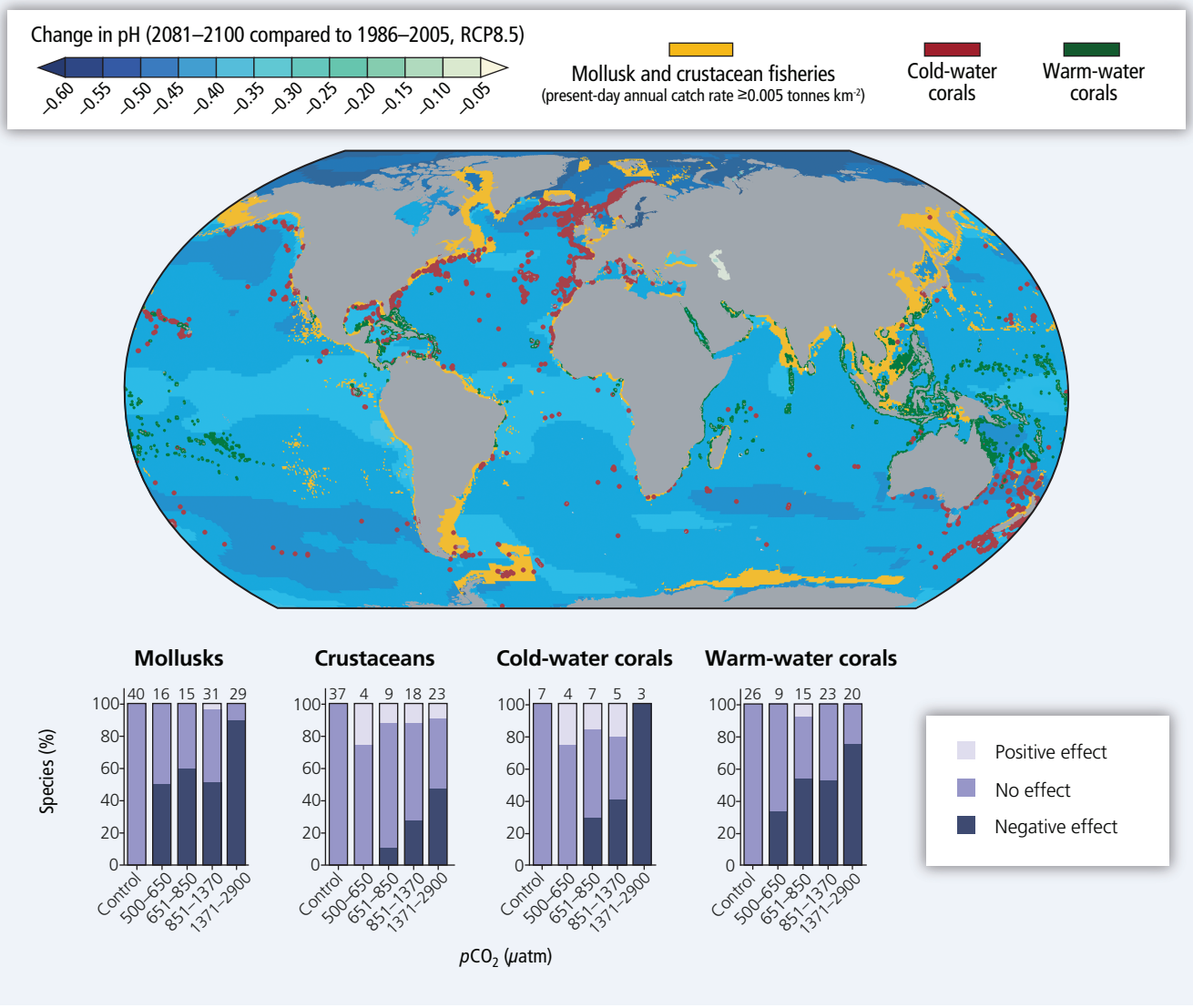

Change in pH (2081–2100 compared to 1986–2005, RCP8.5)
–0.60
–0.55
–0.50
–0.45
–0.40
–0.35
–0.30
–0.25
–0.20
–0.15
–0.10
–0.05
Mollusk and crustacean fisheries
(present-day annual catch rate ≥0.005 tonnes km-2)
Cold-water corals
Warm-water corals
Mollusks
Crustaceans
Cold-water corals
Warm-water corals
Species (%)
40 16 15 31 29
37 4 9 18 23
7 4 7 5 3
26 9 15 23 20
Control
500–650
651–850
851–1370
1371–2900
pCO2 (µatm)
Positive effect
No effect
Negative effect

Figure SPM.6 | Climate change risks for fisheries. (A) Projected global redistribution of maximum catch potential of ~1000 exploited fish and invertebrate species. Projections compare the 10-year averages 2001–2010 and 2051–2060 using SRES A1B, without analysis of potential impacts of overfishing or ocean acidification. (B) Marine mollusk and crustacean fisheries (present-day estimated annual catch rates ≥0.005 tonnes km^{-2}) and known locations of cold- and warm-water corals, depicted on a global map showing the projected distribution of ocean acidification under RCP8.5 (pH change from 1986–2005 to 2081–2100). [WGI AR5 Figure SPM.8] The bottom panel compares sensitivity to ocean acidification across mollusks, crustaceans, and corals, vulnerable animal phyla with socioeconomic relevance (e.g., for coastal protection and fisheries). The number of species analyzed across studies is given for each category of elevated CO_2. For 2100, RCP scenarios falling within each CO_2 partial pressure (pCO_2) category are as follows: RCP4.5 for 500–650 μatm (approximately equivalent to ppm in the atmosphere), RCP6.0 for 651–850 μatm, and RCP8.5 for 851–1370 μatm. By 2150, RCP8.5 falls within the 1371–2900 μatm category. The control category corresponds to 380 μatm. [6.1, 6.3, 30.5, Figures 6-10 and 6-14; WGI AR5 Box SPM.1]

Coastal systems and low-lying areas

Due to sea level rise projected throughout the 21st century and beyond, coastal systems and low-lying areas will increasingly experience adverse impacts such as submergence, coastal flooding, and coastal erosion (*very high confidence*). The population and assets projected to be exposed to coastal risks as well as human pressures on coastal ecosystems will increase significantly in the coming decades due to population growth, economic development, and urbanization (*high confidence*). The relative costs of coastal adaptation vary strongly among and within regions and countries for the 21st century. Some low-lying developing countries and small island states are expected to face very high impacts that, in some cases, could have associated damage and adaptation costs of several percentage points of GDP.[51]

Marine systems

Due to projected climate change by the mid 21st century and beyond, global marine-species redistribution and marine-biodiversity reduction in sensitive regions will challenge the sustained provision of fisheries productivity and other ecosystem services (*high confidence*). Spatial shifts of marine species due to projected warming will cause high-latitude invasions and high local-extinction rates in the tropics and semi-enclosed seas (*medium confidence*). Species richness and fisheries catch potential are projected to increase, on average, at mid and high latitudes (*high confidence*) and decrease at tropical latitudes (*medium confidence*). See Figure SPM.6A. The progressive expansion of oxygen minimum zones and anoxic "dead zones" is projected to further constrain fish habitat. Open-ocean net primary production is projected to redistribute and, by 2100, fall globally under all RCP scenarios. Climate change adds to the threats of over-fishing and other non-climatic stressors, thus complicating marine management regimes (*high confidence*).[52]

For medium- to high-emission scenarios (RCP4.5, 6.0, and 8.5), ocean acidification poses substantial risks to marine ecosystems, especially polar ecosystems and coral reefs, associated with impacts on the physiology, behavior, and population dynamics of individual species from phytoplankton to animals (*medium* to *high confidence*). Highly calcified mollusks, echinoderms, and reef-building corals are more sensitive than crustaceans (*high confidence*) and fishes (*low confidence*), with potentially detrimental consequences for fisheries and livelihoods. See Figure SPM.6B. Ocean acidification acts together with other global changes (e.g., warming, decreasing oxygen levels) and with local changes (e.g., pollution, eutrophication) (*high confidence*). Simultaneous drivers, such as warming and ocean acidification, can lead to interactive, complex, and amplified impacts for species and ecosystems.[53]

Food security and food production systems

For the major crops (wheat, rice, and maize) in tropical and temperate regions, climate change without adaptation is projected to negatively impact production for local temperature increases of 2°C or more above late-20th-century levels, although individual locations may benefit (*medium confidence*). Projected impacts vary across crops and regions and adaptation scenarios, with about 10% of projections for the period 2030–2049 showing yield gains of more than 10%, and about 10% of projections showing yield losses of more than

[51] 5.3-5, 8.2, 22.3, 24.4, 25.6, 26.3, 26.8, Table 26-1, Box 25-1
[52] 6.3-5, 7.4, 25.6, 28.3, 30.6-7, Boxes CC-MB and CC-PP
[53] 5.4, 6.3-5, 22.3, 25.6, 28.3, 30.5, Boxes CC-CR, CC-OA, and TS.7

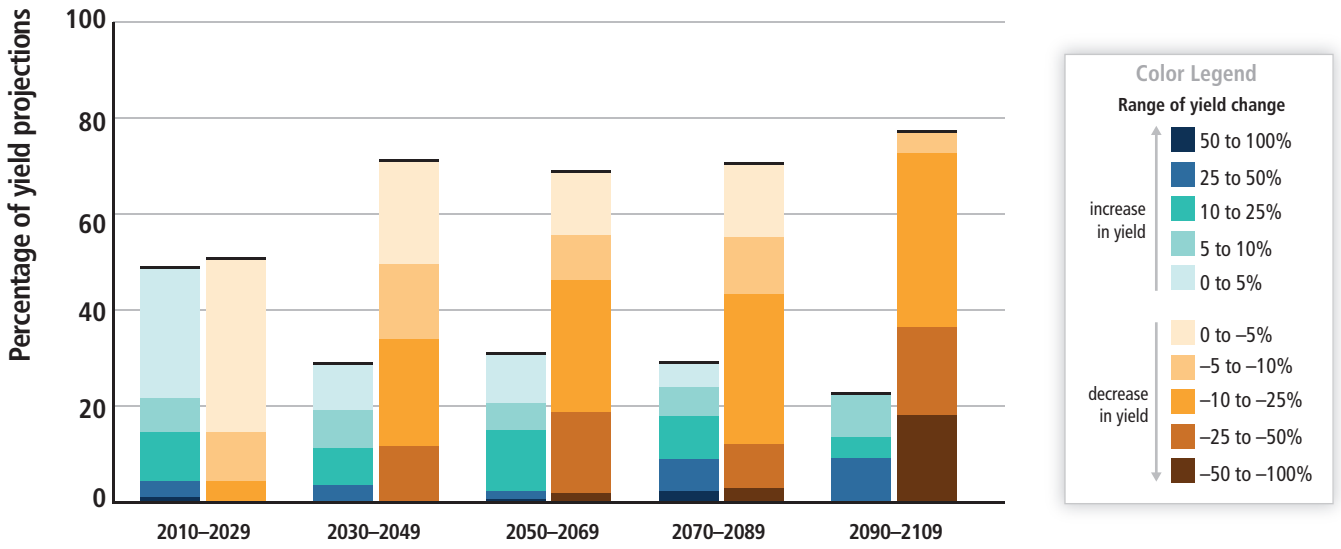


Figure SPM.7 | Summary of projected changes in crop yields, due to climate change over the 21st century. The figure includes projections for different emission scenarios, for tropical and temperate regions, and for adaptation and no-adaptation cases combined. Relatively few studies have considered impacts on cropping systems for scenarios where global mean temperatures increase by 4°C or more. For five timeframes in the near term and long term, data (n=1090) are plotted in the 20-year period on the horizontal axis that includes the midpoint of each future projection period. Changes in crop yields are relative to late-20th-century levels. Data for each timeframe sum to 100%. [Figure 7-5]

25%, compared to the late 20th century. After 2050 the risk of more severe yield impacts increases and depends on the level of warming. See Figure SPM.7. Climate change is projected to progressively increase inter-annual variability of crop yields in many regions. These projected impacts will occur in the context of rapidly rising crop demand.[54]

All aspects of food security are potentially affected by climate change, including food access, utilization, and price stability (*high confidence*). Redistribution of marine fisheries catch potential towards higher latitudes poses risk of reduced supplies, income, and employment in tropical countries, with potential implications for food security (*medium confidence*). Global temperature increases of ~4°C or more above late-20th-century levels, combined with increasing food demand, would pose large risks to food security globally and regionally (*high confidence*). Risks to food security are generally greater in low-latitude areas.[55]

Urban areas

Many global risks of climate change are concentrated in urban areas (*medium confidence*). Steps that build resilience and enable sustainable development can accelerate successful climate-change adaptation globally. Heat stress, extreme precipitation, inland and coastal flooding, landslides, air pollution, drought, and water scarcity pose risks in urban areas for people, assets, economies, and ecosystems (*very high confidence*). Risks are amplified for those lacking essential infrastructure and services or living in poor-quality housing and exposed areas. Reducing basic service deficits, improving housing, and building resilient infrastructure systems could significantly reduce vulnerability and exposure in urban areas. Urban adaptation benefits from effective multi-level urban risk governance, alignment of policies and incentives, strengthened local government and community adaptation capacity, synergies with the private sector, and appropriate financing and institutional development (*medium confidence*). Increased capacity, voice, and influence of low-income groups and vulnerable communities and their partnerships with local governments also benefit adaptation.[56]

[54] 7.4-5, 22.3, 24.4, 25.7, 26.5, Table 7-2, Figures 7-4, 7-5, 7-6, 7-7, and 7-8
[55] 6.3-5, 7.4-5, 9.3, 22.3, 24.4, 25.7, 26.5, Table 7-3, Figures 7-1, 7-4, and 7-7, Box 7-1
[56] 3.5, 8.2-4, 22.3, 24.4-5, 26.8, Table 8-2, Boxes 25-9 and CC-HS

Rural areas

Major future rural impacts are expected in the near term and beyond through impacts on water availability and supply, food security, and agricultural incomes, including shifts in production areas of food and non-food crops across the world (*high confidence*). These impacts are expected to disproportionately affect the welfare of the poor in rural areas, such as female-headed households and those with limited access to land, modern agricultural inputs, infrastructure, and education. Further adaptations for agriculture, water, forestry, and biodiversity can occur through policies taking account of rural decision-making contexts. Trade reform and investment can improve market access for small-scale farms (*medium confidence*).[57]

Key economic sectors and services

For most economic sectors, the impacts of drivers such as changes in population, age structure, income, technology, relative prices, lifestyle, regulation, and governance are projected to be large relative to the impacts of climate change (*medium evidence*, *high agreement*). Climate change is projected to reduce energy demand for heating and increase energy demand for cooling in the residential and commercial sectors (*robust evidence*, *high agreement*). Climate change is projected to affect energy sources and technologies differently, depending on resources (e.g., water flow, wind, insolation), technological processes (e.g., cooling), or locations (e.g., coastal regions, floodplains) involved. More severe and/or frequent extreme weather events and/or hazard types are projected to increase losses and loss variability in various regions and challenge insurance systems to offer affordable coverage while raising more risk-based capital, particularly in developing countries. Large-scale public-private risk reduction initiatives and economic diversification are examples of adaptation actions.[58]

Global economic impacts from climate change are difficult to estimate. Economic impact estimates completed over the past 20 years vary in their coverage of subsets of economic sectors and depend on a large number of assumptions, many of which are disputable, and many estimates do not account for catastrophic changes, tipping points, and many other factors.[59] With these recognized limitations, the incomplete estimates of global annual economic losses for additional temperature increases of ~2°C are between 0.2 and 2.0% of income (±1 standard deviation around the mean) (*medium evidence*, *medium agreement*). Losses are *more likely than not* to be greater, rather than smaller, than this range (*limited evidence*, *high agreement*). Additionally, there are large differences between and within countries. Losses accelerate with greater warming (*limited evidence*, *high agreement*), but few quantitative estimates have been completed for additional warming around 3°C or above. Estimates of the incremental economic impact of emitting carbon dioxide lie between a few dollars and several hundreds of dollars per tonne of carbon[60] (*robust evidence*, *medium agreement*). Estimates vary strongly with the assumed damage function and discount rate.[61]

Human health

Until mid-century, projected climate change will impact human health mainly by exacerbating health problems that already exist (*very high confidence*). Throughout the 21st century, climate change is expected to lead to increases in ill-health in many regions and especially in developing countries with low income, as compared to a baseline without climate change (*high confidence*). Examples include greater likelihood of injury, disease, and death due to more intense heat waves and fires (*very high confidence*); increased likelihood of under-nutrition resulting from diminished food production in poor regions (*high confidence*); risks from lost work capacity and reduced labor productivity in vulnerable populations; and increased risks from food- and water-borne diseases (*very high confidence*) and

[57] 9.3, 25.9, 26.8, 28.2, 28.4, Box 25-5

[58] 3.5, 10.2, 10.7, 10.10, 17.4-5, 25.7, 26.7-9, Box 25-7

[59] Disaster loss estimates are lower-bound estimates because many impacts, such as loss of human lives, cultural heritage, and ecosystem services, are difficult to value and monetize, and thus they are poorly reflected in estimates of losses. Impacts on the informal or undocumented economy as well as indirect economic effects can be very important in some areas and sectors, but are generally not counted in reported estimates of losses. [SREX 4.5]

[60] 1 tonne of carbon = 3.667 tonne of CO_2

[61] 10.9

vector-borne diseases (*medium confidence*). Positive effects are expected to include modest reductions in cold-related mortality and morbidity in some areas due to fewer cold extremes (*low confidence*), geographical shifts in food production (*medium confidence*), and reduced capacity of vectors to transmit some diseases. But globally over the 21st century, the magnitude and severity of negative impacts are projected to increasingly outweigh positive impacts (*high confidence*). The most effective vulnerability reduction measures for health in the near term are programs that implement and improve basic public health measures such as provision of clean water and sanitation, secure essential health care including vaccination and child health services, increase capacity for disaster preparedness and response, and alleviate poverty (*very high confidence*). By 2100 for the high-emission scenario RCP8.5, the combination of high temperature and humidity in some areas for parts of the year is projected to compromise normal human activities, including growing food or working outdoors (*high confidence*).[62]

Human security

Climate change over the 21st century is projected to increase displacement of people (*medium evidence*, *high agreement*). Displacement risk increases when populations that lack the resources for planned migration experience higher exposure to extreme weather events, in both rural and urban areas, particularly in developing countries with low income. Expanding opportunities for mobility can reduce vulnerability for such populations. Changes in migration patterns can be responses to both extreme weather events and longer-term climate variability and change, and migration can also be an effective adaptation strategy. There is *low confidence* in quantitative projections of changes in mobility, due to its complex, multi-causal nature.[63]

Climate change can indirectly increase risks of violent conflicts in the form of civil war and inter-group violence by amplifying well-documented drivers of these conflicts such as poverty and economic shocks (*medium confidence*). Multiple lines of evidence relate climate variability to these forms of conflict.[64]

The impacts of climate change on the critical infrastructure and territorial integrity of many states are expected to influence national security policies (*medium evidence*, *medium agreement*). For example, land inundation due to sea level rise poses risks to the territorial integrity of small island states and states with extensive coastlines. Some transboundary impacts of climate change, such as changes in sea ice, shared water resources, and pelagic fish stocks, have the potential to increase rivalry among states, but robust national and intergovernmental institutions can enhance cooperation and manage many of these rivalries.[65]

Livelihoods and poverty

Throughout the 21st century, climate-change impacts are projected to slow down economic growth, make poverty reduction more difficult, further erode food security, and prolong existing and create new poverty traps, the latter particularly in urban areas and emerging hotspots of hunger (*medium confidence*). Climate-change impacts are expected to exacerbate poverty in most developing countries and create new poverty pockets in countries with increasing inequality, in both developed and developing countries. In urban and rural areas, wage-labor-dependent poor households that are net buyers of food are expected to be particularly affected due to food price increases, including in regions with high food insecurity and high inequality (particularly in Africa), although the agricultural self-employed could benefit. Insurance programs, social protection measures, and disaster risk management may enhance long-term livelihood resilience among poor and marginalized people, if policies address poverty and multidimensional inequalities.[66]

B-3. Regional Key Risks and Potential for Adaptation

Risks will vary through time across regions and populations, dependent on myriad factors including the extent of adaptation and mitigation. A selection of key regional risks identified with *medium* to *high confidence* is presented in Assessment Box SPM.2. For extended summary of regional risks and potential benefits, see Technical Summary Section B-3 and WGII AR5 Part B: Regional Aspects.

Annex 41 bis

Simpson et al., "CARIBSAVE Climate Change Risk Atlas (CCCRA) – Barbados", 2012, DFID, AusAID and The CARIBSAVE Partnership, Barbados, West Indies, pages 76-80

Caribbean Regional Headquarters
Hastings House
Balmoral Gap
Christ Church
Barbados
West Indies
Tel: +1 246 426 2042

UK Office
Almond House
Betteshanger Business Park
Deal
Kent CT14 0LX
United Kingdom
Tel: +44 (0) 1304 619 929

admin@caribsave.org ~ www.caribsave.org

Protecting and enhancing the livelihoods, environments and economies of the Caribbean Basin

THE CARIBSAVE CLIMATE CHANGE RISK ATLAS (CCCRA)

Climate Change Risk Profile for Barbados



Prepared by The CARIBSAVE Partnership with funding from UKaid from the Department for International Development (DFID) and the Australian Agency for International Development (AusAID)

March 2012

4.6.2. Vulnerability of Infrastructure and Settlements to Climate Change

There is overwhelming scientific evidence that SLR associated with climate change is projected to occur in the 21st Century and beyond, representing a chronic threat to the coastal zones in Barbados. The sea level has risen in the Caribbean at about 3.1 mm/year from 1950 to 2000 (Church *et al.*, 2004). Global SLR is anticipated to increase as much as 1.5 m to 2 m above present levels in the 21st century (Rahmstorf, 2007; Vermeer and Rahmstorf, 2009; Grinsted *et al.*, 2009; Jevrejeva *et al*., n.d.; Horton *et al*., 2008). It is also important to note that recent studies of the relative magnitude of regional SLR also suggest that because of the Caribbean's proximity to the equator, SLR will be more pronounced than in some other regions (Bamber *et al.,* 2009; Hu *et al.,* 2009).

Consistent with other assessments of the potential impacts of sea-level rise (e.g. Dasgupta *et al.,* 2007 for the World Bank), sea-level rise scenarios of 1.0 m and 2.0 m and beach erosion scenarios of 50 m and 100 m were calculated to assess the potential vulnerability of major tourism resources across Barbados.

To examine the SLR exposure risk of Barbados, research grade Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) data sets that were recently publically released by the National Aeronautics and Space Administration (NASA) and the Japanese Ministry of Economy, Trade and Industry, were integrated into a Geographic Information System (GIS). The ASTER GDEM was downloaded from Japan's Earth Remote Sensing Data Analysis Centre using a rough outline of the Caribbean to select the needed tiles, which were then loaded into an ArcMap document. The next step was to mosaic the tiles into a larger analysis area, followed by the creation of the SLR scenarios as binary raster layers to analyse whether an area is affected by SLR through the reclassification of the GDEM mosaics (see Simpson *et al*., 2010 for a more detailed discussion on the methodology). These assessments were used to calculate the impacts of sea level rise on the whole island.

To examine SLR-induced coastal erosion, a simplified approximation of the Bruun Rule (shore recession = sea-level rise X 100) that has been used in other studies on the implications of sea-level rise for coastal erosion was adopted for this analysis. The prediction of how sea-level rise will reshape coastlines is influenced by a range of coastal morphological factors (coastal geology, bathymetry, waves, tidal currents, human interventions). The most widely used method of quantifying the response of sandy coastlines to rising sea levels is the Bruun Rule, which is appropriate for assessing shoreline retreat caused by the reestablishment of equilibrium beach profile inland by the erosion of beach material from the higher part of the beach and deposition it in the lower beach zone (Zhang *et al.,* 2004).

Table 4.6.1: Impacts associated with 1m and 2 m SLR and 50 m and 100 m beach erosion in Barbados

		Tourism Attractions		Transportation Infrastructure		
		Major Tourism Resorts	Sea Turtle Nesting Sites	Airport Land	Road Networks	Port Lands
SLR	1.0 m	8%	3%	0%	0%	100%
	2.0 m	32%	8%	0%	0%	100%
Erosion	50 m	56%	63%	-	-	-
	100 m	67%	100%	-	-	-

A summary of results for SLR and erosion impacts in Barbados at the national level are noted in Table 4.6.1. These results highlight that some tourism infrastructure is more vulnerable than others. A 1 m SLR places

8% of the major tourism properties at risk, with an additional 32% at risk with a 2 m SLR. It is important to note that the critical beach assets would be affected much earlier than the SLR induced erosion damages to tourism infrastructure.

Indeed if erosion is damaging tourism infrastructure, it means the beach will have essentially disappeared. With projected 100 m erosion, more than half of the resorts in Barbados would be at risk. Such impacts would transform coastal tourism in Barbados, with implications for property values, insurance costs, destination competitiveness, marketing and wider issues of local employment and economic well-being of thousands of employees. Sea turtle nesting sites, a tourist attraction, are also at risk to SLR and erosion, with 63% affected by 50 m erosion scenario and all at risk with 100 m of beach erosion. Transportation infrastructure, also of key importance to tourism, is also at risk. Though roads and airports are not at risk with a 2 m SLR scenario, ports are threatened, with 100% of port lands in the country projected to be inundated with a 1 m SLR.

Given Barbados' tourism dependent economy, the country will be particularly affected with annual costs as a direct result of SLR. For example, the tourism sector in Barbados will incur annual losses between US $283 million in 2050 to over US $850 million in 2080 (based on a mid range scenario). Capital costs are also high, with rebuild costs for tourist resorts damaged and inundated by SLR amounting to over US $400 million in 2050 up to US $946 million in 2080. Infrastructure critical to the tourism sector will also be heavily impacted by SLR resulting in capital cost to rebuild ports estimated to be between US $16 million by 2050 to US $ 40 million by 2080 (Simpson, *et al.,* 2010).

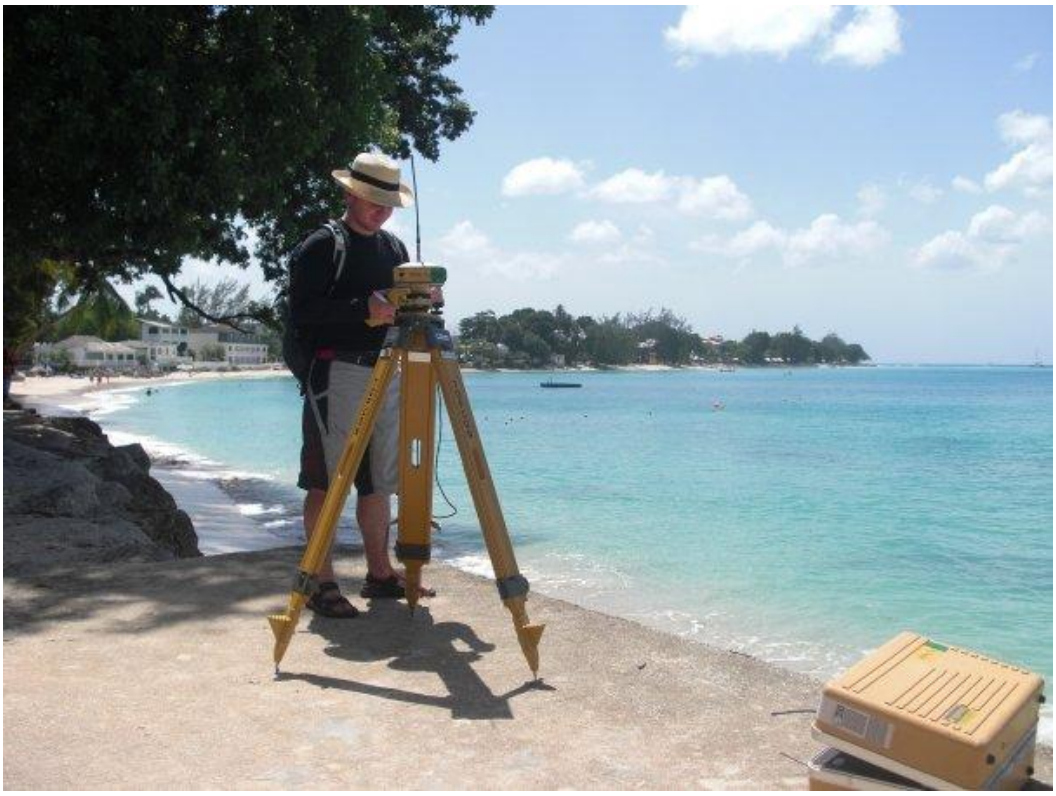


Figure 4.6.1: High Resolution Coastal Profile Surveying with GPS, Holetown, Barbados.

In addition to the national assessment, the CARIBSAVE partnership coordinated a field research team with members from the University of Waterloo (Canada), Oxford University (UK) and the Barbados Coastal Zone Management Unit (CZMU), to complete detailed coastal profile surveying (Figure 4.6.1).

The sites were surveyed using a TOPCON Real Time Kinetic (RTK) GPS system including a base station, 15 km radius antenna, surveying stick and a hand held data logger. Distance between points along transects were measured using a Lecia Disto laser distancing meter. Transects were spaced at approximately 30-50 m intervals depending on the length of the beach of interest and variability in topography along the beach. The water's edge was fixed to a datum point of 0 for the field measurements, but later adjusted according to tide charts. Generally, satellite connections were very good, receiving up to 10 satellites, resulting in 10 cm accuracy. The mean vertical accuracy for all points was approximately 0.20 cm while the horizontal accuracy had a mean average of 0.10 cm accuracy. An average of 6 measurements was taken for each point along transect lines. At each point, the nature of the ground cover (e.g. sand, vegetation, concrete) was logged to aid in the post-processing analysis. Ground control points were taken to anchor the GPS positions to locations that are identifiable from aerial photographs to improve horizontal accuracy. These were taken where suitable landmarks at each transect location and throughout the island. GCP points were measured over 60 readings at 1 second intervals. At each GCP, the physical characteristics of the site were logged to enable the point to be identified from aerial images. Photographs were taken from north, south, east and west perspectives to aid this process. The GCP points were also collected as a means of geo-referencing digital satellite imagery for the study sites.

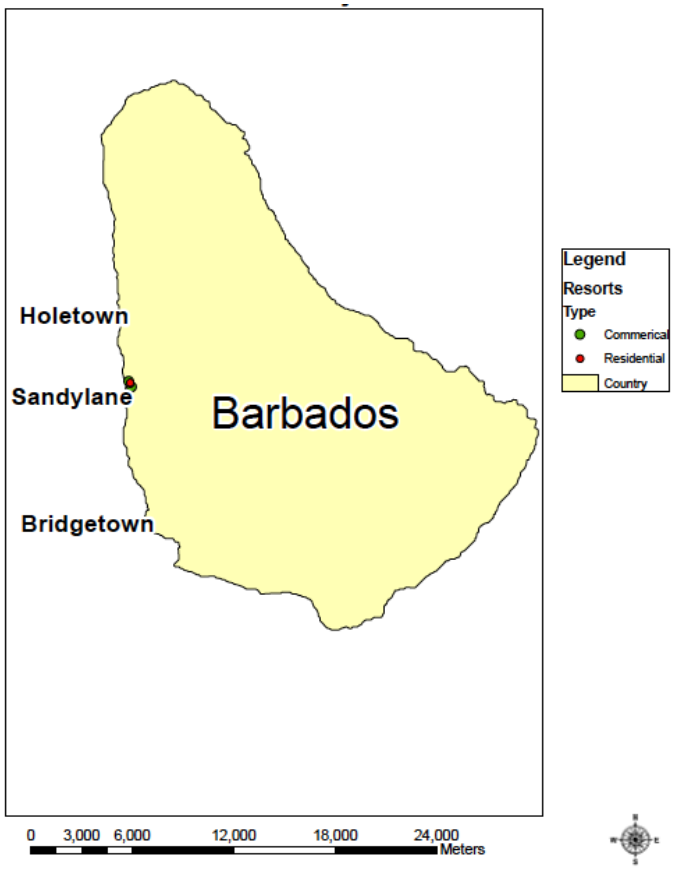


Figure 4.6.2: SLR Study Areas in Barbados

Following the field collection, all of the GPS points were downloaded on to a Windows PC, and converted into several GIS formats. Most notably, the GPS points were converted into ESRI Shapefile format to be used with ESRI ArcGIS suite. Aerial Imagery was obtained from Google Earth, and was geo-referenced using the 22 GCPs collected. The data was then inspected for errors and incorporated with other GIS data collected while in the field. Absolute mean sea level was determined by comparing the first GPS point (water's edge) to tide tables to determine the high tide mark. Three dimensional topographic models of

each of the 15 study sites were then produced from a raster topographic surface using the GPS elevation points as base height information. A Triangular Irregular Network (TIN) model was created to represent the beach profiles in three dimensions. Contour lines were delineated from both the TIN and raster topographic surface model. For the purpose of this study, contour lines were represented for every metre of elevation change above sea level. Using the topographic elevation data, flood lines were delineated in one metre intervals. In an effort to share the data with a wider audience, all GIS data will be compatible with several software applications, including Google Earth.

A particularly vulnerable coastline in Barbados is Sandy Lane and Holetown area (Figure 4.6.3). The field team conducted survey transects (perpendicular to the shoreline) at 5 locations around these two study sites where tourism infrastructure was located. Four SLR scenarios (0.5 m, 1.0 m, 2.0 m, 3.0 m) were then applied with the results mapped in Figure 4.6.3 and Figure 4.6.4.

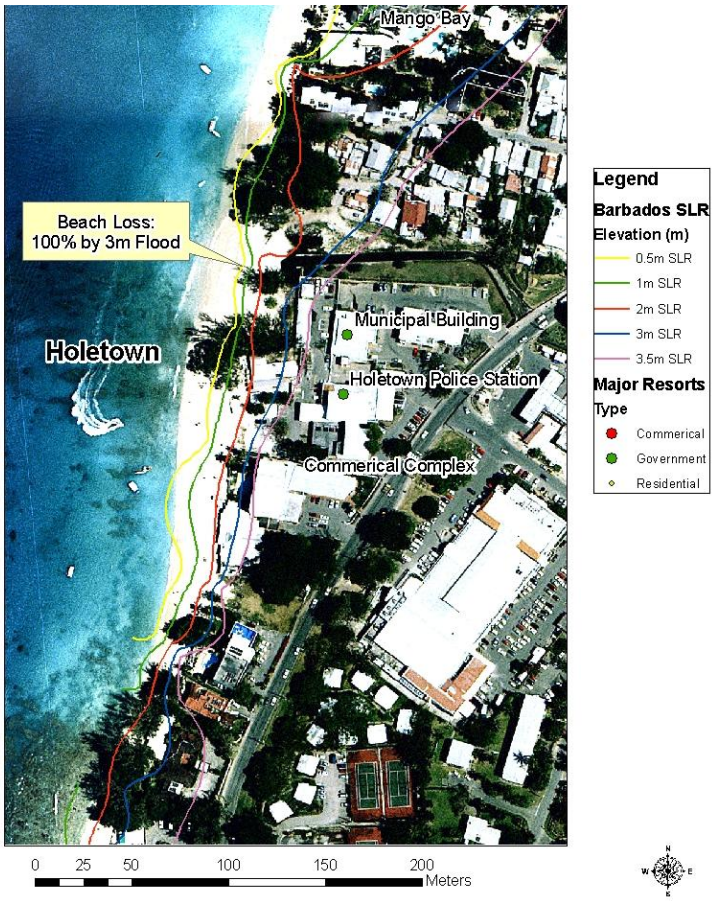


Figure 4.6.3: Land Lost from SLR in Holetown, Barbados

Even under the smallest SLR scenario (0.5 m, yellow contour), 37% to 72% of the highly valued beach resources in Sandy Lane and in Holetown would be lost (Table 4.6.2). With a 2 m SLR (red contour), 65% of Sandy Lane and 97% of Holetown's beach would become inundated. With a 3 m SLR impacts would be further exacerbated and Holetown beach would be lost; and Sandy Lane's beach would be lost at a 3.5 m SLR.

Table 4.6.2: Beach area lost in two sea-level rise scenarios across study sites in Barbados

	Sandy Lane		Holetown	
SLR Scenario	Beach Area Lost To SLR (m^2)	Beach Area Lost (%)	Beach Area Lost To SLR (m^2)	Beach Area Lost (%)
0.5 m	6772.67	36.78%	18696.53	72.92%
1.0 m	155278	46.31%	21855.94	85.25%
2.0 m	12113.94	65.79%	25015.34	97.57%
3.0 m	16989.18	92.27%	25638.19	100.00%
3.5 m	18411.38	100.00%	-	-

A map of the severe risk that Sandy Lane, one of Barbados' largest and most widely used beaches would face under a 3 m SLR is illustrated in Figure 4.6.4. The response of tourists to such a diminished beach area remains an important question for future research; Sandy Lane Hotel is a key tourist destination in Barbados and is projected to lose its entire beach with a 3.5 m SLR scenario.

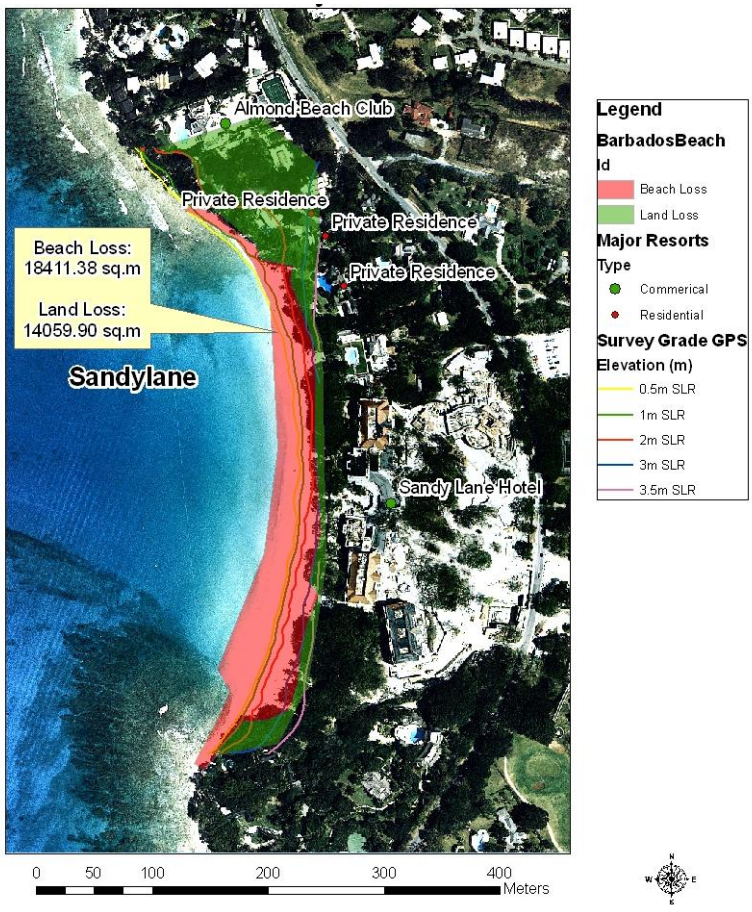


Figure 4.6.4: Land Lost from SLR at Sandy Lane, Barbados in a 3 metre flooding scenario.

Annex 42

"Annex I: Glossary. Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty", Cambridge University Press, *Intergovernmental Panel on Climate Change,* 2018, pages 541-542

Annexes

AI

Annex I: Glossary

Coordinating Editor:
J.B. Robin Matthews (France/UK)

Editorial Team:
Mustafa Babiker (Sudan), Heleen de Coninck (Netherlands/EU), Sarah Connors (France/UK), Renée van Diemen (UK/Netherlands), Riyanti Djalante (Japan/Indonesia), Kristie L. Ebi (USA), Neville Ellis (Australia), Andreas Fischlin (Switzerland), Tania Guillén Bolaños (Germany/Nicaragua), Kiane de Kleijne (Netherlands/EU), Valérie Masson-Delmotte (France), Richard Millar (UK), Elvira S. Poloczanska (Germany/UK), Hans-Otto Pörtner (Germany), Andy Reisinger (New Zealand), Joeri Rogelj (Austria/Belgium), Sonia I. Seneviratne (Switzerland), Chandni Singh (India), Petra Tschakert (Australia/Austria), Nora M. Weyer (Germany)

Notes:
Note that subterms are in italics beneath main terms.

This glossary defines some specific terms as the Lead Authors intend them to be interpreted in the context of this report. Blue, italicized words indicate that the term is defined in the Glossary.

This annex should be cited as:
IPCC, 2018: Annex I: Glossary [Matthews, J.B.R. (ed.)]. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 541-562. https://doi.org/10.1017/9781009157940.008.

1.5°C pathway See *Pathways*.

1.5°C warmer worlds *Projected* worlds in which *global warming* has reached and, unless otherwise indicated, been limited to 1.5°C above *pre-industrial* levels. There is no single 1.5°C warmer world, and *projections* of 1.5°C warmer worlds look different depending on whether it is considered on a near-term transient trajectory or at climate equilibrium after several millennia, and, in both cases, if it occurs with or without *overshoot*. Within the 21st century, several aspects play a role for the assessment of risk and potential *impacts* in 1.5°C warmer worlds: the possible occurrence, magnitude and duration of an overshoot; the way in which emissions reductions are achieved; the ways in which policies might be able to influence the *resilience* of human and natural systems; and the nature of the regional and sub-regional risks. Beyond the 21st century, several elements of the *climate system* would continue to change even if the global mean temperatures remain stable, including further increases of sea level.

2030 Agenda for Sustainable Development A UN resolution in September 2015 adopting a plan of action for people, planet and prosperity in a new global development framework anchored in 17 *Sustainable Development Goals* (UN, 2015). See also *Sustainable Development Goals (SDGs)*.

Acceptability of policy or system change The extent to which a policy or system change is evaluated unfavourably or favourably, or rejected or supported, by members of the general public (public acceptability) or politicians or governments (political acceptability). Acceptability may vary from totally unacceptable/fully rejected to totally acceptable/fully supported; individuals may differ in how acceptable policies or system changes are believed to be.

Adaptability See *Adaptive capacity*.

Adaptation In *human systems*, the process of adjustment to actual or expected *climate* and its effects, in order to moderate harm or exploit beneficial opportunities. In natural systems, the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate and its effects.

Incremental adaptation
Adaptation that maintains the essence and integrity of a system or process at a given scale. In some cases, incremental adaptation can accrue to result in *transformational adaptation* (Termeer et al., 2017; Tàbara et al., 2018).

Transformational adaptation
Adaptation that changes the fundamental attributes of a *socio-ecological system* in anticipation of *climate change* and its *impacts*.

Adaptation limits
The point at which an actor's objectives (or system needs) cannot be secured from intolerable risks through adaptive actions.
- Hard adaptation limit: No adaptive actions are possible to avoid intolerable risks.
- Soft adaptation limit: Options are currently not available to avoid intolerable risks through adaptive action.

See also *Adaptation options*, *Adaptive capacity* and *Maladaptive actions (Maladaptation)*.

Adaptation behaviour See *Human behaviour*.

Adaptation limits See *Adaptation*.

Adaptation options The array of strategies and measures that are available and appropriate for addressing *adaptation*. They include a wide range of actions that can be categorized as structural, institutional, ecological or behavioural. See also *Adaptation*, *Adaptive capacity* and *Maladaptive actions (Maladaptation).*

Adaptation pathways See *Pathways*.

Adaptive capacity The ability of systems, *institutions*, humans and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences. This glossary entry builds from definitions used in previous IPCC reports and the Millennium Ecosystem Assessment (MEA, 2005). See also *Adaptation*, *Adaptation options and Maladaptive actions (Maladaptation)*.

Adaptive governance See *Governance*.

Aerosol A suspension of airborne solid or liquid particles, with a typical size between a few nanometres and 10 µm that reside in the *atmosphere* for at least several hours. The term aerosol, which includes both the particles and the suspending gas, is often used in this report in its plural form to mean aerosol particles. Aerosols may be of either natural or *anthropogenic* origin. Aerosols may influence *climate* in several ways: through both interactions that scatter and/or absorb radiation and through interactions with cloud microphysics and other cloud properties, or upon deposition on snow- or ice-covered surfaces thereby altering their *albedo* and contributing to *climate feedback*. Atmospheric aerosols, whether natural or anthropogenic, originate from two different pathways: emissions of primary particulate matter (PM), and formation of secondary PM from gaseous *precursors*. The bulk of aerosols are of natural origin. Some scientists use group labels that refer to the chemical composition, namely: sea salt, organic carbon, *black carbon (BC)*, mineral species (mainly desert dust), sulphate, nitrate, and ammonium. These labels are, however, imperfect as aerosols combine particles to create complex mixtures. See also *Short-lived climate forcers (SLCF)* and *Black carbon (BC)*.

Afforestation Planting of new *forests* on lands that historically have not contained forests. For a discussion of the term forest and related terms such as afforestation, *reforestation* and *deforestation*, see the IPCC Special Report on Land Use, Land-Use Change, and Forestry (IPCC, 2000), information provided by the United Nations Framework Convention on Climate Change (UNFCCC, 2013) and the report on Definitions and Methodological Options to Inventory Emissions from Direct Human-induced Degradation of Forests and Devegetation of Other Vegetation Types (IPCC, 2003). See also *Reforestation*, *Deforestation*, and *Reducing Emissions from Deforestation and Forest Degradation (REDD+)*.

Agreement In this report, the degree of agreement within the scientific body of knowledge on a particular finding is assessed based on multiple lines of *evidence* (e.g., mechanistic understanding, theory, data, models, expert judgement) and expressed qualitatively (Mastrandrea et al., 2010). See also *Evidence*, *Confidence*, *Likelihood* and *Uncertainty*.

Air pollution Degradation of air quality with negative effects on human health or the natural or built environment due to the introduction, by natural processes or human activity, into the *atmosphere* of substances (gases, *aerosols*) which have a direct (primary pollutants) or indirect (secondary pollutants) harmful effect. See also *Aerosol* and *Short-lived climate forcers (SLCF)*.

Albedo The fraction of solar radiation reflected by a surface or object, often expressed as a percentage. Snow-covered surfaces have a high albedo, the surface albedo of soils ranges from high to low, and vegetation-covered surfaces and the oceans have a low albedo. The Earth's planetary albedo changes mainly through varying cloudiness and changes in snow, ice, leaf area and land cover.

Ambient persuasive technology Technological systems and environments that are designed to change human cognitive processing,

Annex 42 bis

L. Nurse, "The implication of global climate change for fisheries management in the Caribbean", *Climate and Development*, 2011, pp. 228-241, pages 228, 231-233

review article

climate and development

The implications of global climate change for fisheries management in the Caribbean

LEONARD A. NURSE*

Centre for Resource Management and Environmental Studies, University of the West Indies, Cave Hill Campus, BB11000 Barbados, West Indies

Downloaded by [Leonard A. Nurse] at 10:18 12 October 2011

Concerns about the socio-economic impacts of observed and projected climate change have been high on the research agendas of scientists for the last several decades. According to the Intergovernmental Panel on Climate Change, the recent observed warming is largely human induced, and the trend will continue well into the next century owing to 'thermal inertia', related to the concentration of greenhouse gases already emitted to the atmosphere. While there is a dearth of research on the effects of climate change on commercial and artisanal fisheries in the Caribbean, valuable insights can be gleaned from observations in other jurisdictions. This paper concludes that the consequences of climate change on Caribbean fisheries are likely to be mostly negative. Adverse impacts are expected to manifest themselves through habitat alteration and loss, reduced abundance and diversity, and shifts in distribution induced by changes in ocean currents. Stakeholders in the regional fishing industry might therefore wish to give greater credence to the challenges posed by climate change and climate variability than currently appears to be the case. Appropriate response strategies may not require radical changes in current approaches to management, but rather more effective implementation of existing and proposed arrangements.

Keywords: adaptation; Caribbean; climate change; fisheries; vulnerability

1. The global context

Global mean air temperatures have increased by approximately 0.7°C during the 100-year period 1906–2005. For the next two decades, a warming of about 0.2°C per decade is projected for a range of greenhouse gas (GHG) emission scenarios (IPCC, 2007). In addition, during the 20th century, global sea levels rose at a rate approximately 10 times faster than the average rate for the previous 3,000 years (IPCC, 2007). Outputs from a suite of climate models indicate that human-induced warming (approx. 0.1°C per decade) and incremental sea-level rise would continue for centuries due to inertia in the climate system, even if GHG concentrations were to be stabilized at year 2000 levels (IPCC, 2007).

Stakeholders in the fisheries sector should equally be concerned about the post-1900 increases in frequency, intensity and persistence of warm (El Niño) phases of the El Niño Southern Oscillation (ENSO), as well as an observed trend of increasing sea-surface temperatures. Before the end of the current century, mean global sea-surface temperatures are expected to be approximately 1.0–2.0°C higher than the 1990 mean (IPCC, 2001). In the specific case of the tropical oceans, temperatures are projected to be 2°C by the 2050s and 3°C higher by the 2080s, relative to the same 1990 baseline (Lal et al., 2002). The link between ocean warming, El Niño occurrences and coral bleaching is now well established, and there is considerable observational evidence to show that the most intense bleaching events since 1900 have all occurred in those years

■ *E-mail: leonard.nurse@cavehill.uwi.edu

CLIMATE AND DEVELOPMENT 3 (2011) 228–241 doi:10.1080/17565529.2011.603195

© 2011 Taylor & Francis ISSN: 1756-5529 (print), 1756-5537 (online) www.tandfonline.com/tcld

Routledge Taylor & Francis Group

Downloaded by [Leonard A. Nurse] at 10:18 12 October 2011

many fish species may be impacted more by changes in ocean chemistry (linked to climate change) than by elevated sea-surface temperatures per se. Moreover, these climate-induced changes are likely to be exacerbated by other well-documented anthropogenic stresses, including overfishing (IPCC, 2007; Harley et al., 2008).

3. What are the key climate change projections of relevance to the Caribbean fisheries sector?

Apart from the obvious implications of the global observations highlighted above, there are additional avenues via which climate change will impact on the Caribbean fisheries sector, directly and indirectly. The discussion that follows is not intended to be exhaustive; it merely seeks to highlight issues of relevance to the region's fisheries sector for which sound, scientific consensus is emerging. It is also anticipated that the analysis will contribute to the development of a clearer understanding of the range of climate-related risks to which the sector will be exposed.

Of critical significance is the fact that the pattern of observed temperature changes in the region is generally consistent with the global trend (IPCC, 2007; Hayes and Goreau, 2008; Jury and Winter, 2010). Regional temperatures increased in the 20th century with the 1990s being the warmest decade since 1900. Outputs from a suite of global climate models (GCMs) suggest that surface air temperatures in the Caribbean will continue to increase in the present century by between 0.5° and 1°C during the period 2010–2039, 0.8° and 2.5°C in the decades 2040–2069, and 0.94° and 4.8°C between 2070 and 2099. Recent climate model runs for the Eastern and Southern Caribbean show that a similar trend in sea-surface temperatures can also be expected.[1] This is shown in Figure 1, which is derived from the HADCM 3 and ECHAM4 GCM, downscaled to 25 km resolution using the PRECIS model. These results clearly suggest that sea-surface temperatures will not only increase during the summer (JJA), but also during the traditional 'cool' season (DJF). Of equal interest is the indication that both the diurnal and seasonal temperature ranges will also decrease. This has particularly severe implications for Caribbean corals which would, under such circumstances, be consistently exposed to even higher minimum and maximum temperatures than at present.

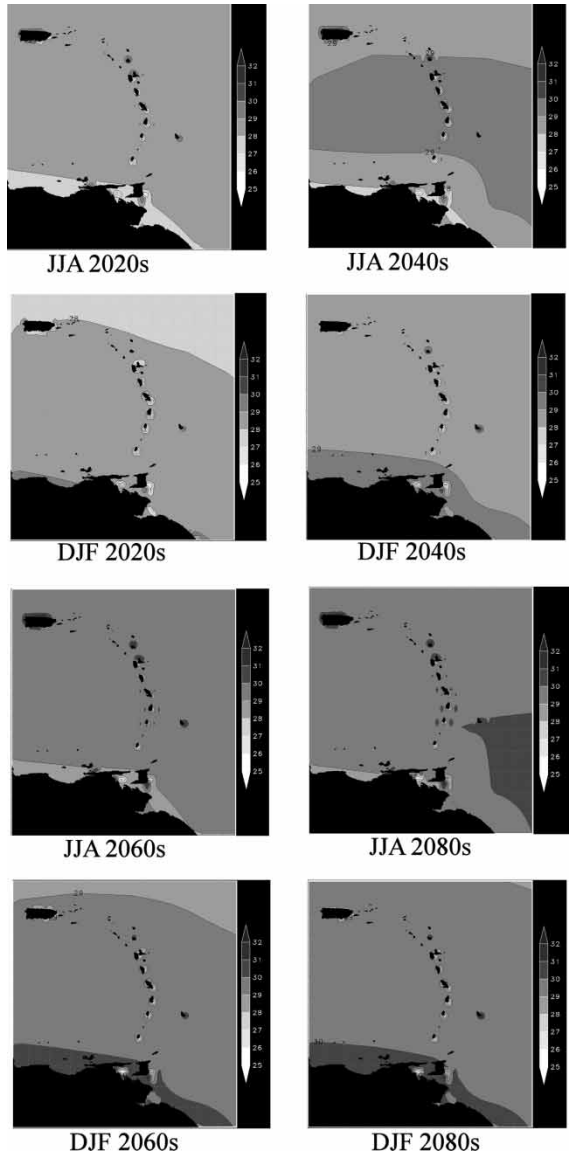


FIGURE 1 Projected decadal winter (DJF) and summer (JJA) sea surface temperatures for the Eastern Caribbean.

Downloaded by [Leonard A. Nurse] at 10:18 12 October 2011

There is strong support from the observational records that elevated sea-surface temperatures are a primary cause of coral bleaching. The most severe episodes in the past have coincided with years when the El Niño signal was strongest, for instance in 1983, 1985, 1997/98, 2005/2006 (Glynn, 1984; Hoegh-Guldberg, 1999; Goreau et al., 2000; Alvarez-Filip et al., 2009). In the 1997/98 event, more than 95 per cent of Pacific corals were bleached, and approximately 25–30 per cent in the Caribbean. The most recent intense bleaching episode in the Caribbean occurred during the summer of 2005, when bleaching occurred in an area extending from Mexico in the north, to Tobago in the south. A detailed case study of the event at Barbados revealed that throughout the summer, sea-surface temperatures were consistently between 1° and 2°C above seasonal maxima, and all nearshore and offshore habitats were affected (Oxenford et al., 2008). The situation in Barbados was not unique to the Eastern Caribbean, since many other islands also reported significant bleaching. Certainly, fishers will find no comfort in these events, particularly since they are projected to become more frequent in the future.

Another emerging issue that could be potentially worrisome for fisheries stakeholders is the observed and projected change in the level of acidity of the world's oceans, associated with increasing anthropogenic emissions of CO_2. Research has shown that the world's oceans have become approximately 30 per cent more acidic (i.e. a reduction in pH from 8.2 to 8.1 units) since 1750 – the start of the Industrial Revolution (IPCC, 1990, 2001, 2007). Although the effects on marine organisms are not yet fully understood, ocean acidification is expected to be a limiting factor in the development of corals and other organisms, which use carbonate ions in sea water to build calcium carbonate shells and exoskeletons. With rising CO_2 emissions, more CO_2 is absorbed by the oceans, sea water becomes more acidic by stripping out carbonate ions, thus making it more difficult for organisms to form shells (Kleypas et al., 2006; Fabry et al., 2008; Talmage and Gobler, 2010). With global CO_2 emissions continuing to increase at a rapid rate, the threat to reef habitats and associated fauna, including fish assemblages, will become more pronounced (Cooley and Doney, 2009; Silverman et al., 2009). Since the reef fishery constitutes a vital component of small-scale activity, this sector of the industry is likely to be most affected. Notwithstanding the findings reported above, further research is needed to fully explore the relationship between ocean acidification and marine organisms including fish, as a few controlled laboratory studies (see, for instance, Iglesias-Rodriguez et al., 2008) appear to suggest that not all marine species may experience reduced rates of calcification.

While there is, as yet, no clear indication that tropical cyclones (hurricane) frequency will change, modelled data indicate that peak wind intensities are expected to increase by approximately 5–10 per cent by the 2050s (Emanuel, 2006; IPCC, 2007). Moreover, of those systems that reach hurricane status, a greater proportion appears to be attaining a status of category 3 and above than in prior decades. For instance, in the first seven years of the decade 2001–2010 eight category 5 hurricanes developed, compared with a total of 23 recorded between 1928 and 2000[2] (Table 1). Although it is still too early to suggest that this represents a trend, recent experience has shown that a number of these systems may be reaching high intensity over a

TABLE 1 Category 5 Atlantic Hurricanes, 2001–2007

Hurricane	Year	Maximum winds, km/hour (mph)
Isabel	2003	266 (165)
Ivan	2004	266 (165)
Emily	2005	290 (180)
Katrina	2005	282 (175)
Rita	2005	290 (180)
Wilma	2005	298 (185)
Dean	2007	266 (165)
Felix	2007	266 (165)

Source: NOAA hurricane database.

Downloaded by [Leonard A. Nurse] at 10:18 12 October 2011

shorter duration than previously observed. This is exemplified by hurricanes Wilma (2005) and Gustav (2008), which moved from tropical depression status to category 5 and 4 hurricanes in less than 24 hours. However, if this becomes a trend, fishers will be faced with the prospect of having greatly reduced time frames for securing boats, gear and other equipment. Similarly, the expected increase in maximum wind speeds, combined with currently projected increments of sea-level rise for the region, would amplify storm surge effects, and accelerate coastal erosion and loss. This enhanced exposure would not only cause damage to equipment and gear, but would also place critical infrastructure such as wharves jetties and other fish landing at very high risk under this likely scenario. Thus, apart from having to adapt to altered conditions such as changes in fish stock distribution and abundance, stakeholders will also be confronted by the possibility of increased storminess at sea and on land, and higher risk to the safety of fishers as well as vessels. The resulting disruption to both sea- and shore-based operations would evidently have a negative impact on the livelihood of fishers themselves and other dependent stakeholders (Brander, 2007; Allison et al., 2009; Daw et al., 2009; McConney et al., 2009). For these reasons the call echoed by researchers including Mahon (2002), Garcia and Cochrane (2005), and more recently by Badjeck et al. (2010) for action to improve vessel quality and seaworthiness, safety equipment and the routine enforcement of safety protocols is not only timely but urgent.

4. Vulnerability of Caribbean small-scale fisheries to climate change

As elsewhere, the threat posed by climate change to the fishing industry in the Caribbean assumes an important economic and social dimension as well. Globally, the sector is critical to livelihoods in many ways, including its contribution to revenue earnings, nutrition and food security, employment generation and poverty reduction (Andrew et al., 2007; Conservation International, 2008; Badjeck et al., 2010; FAO, 2010; Garcia and Rosenberg, 2010; Rice and Garcia, 2011). Within the CARICOM region, the sector employs just under 200,000 persons, earns between US$5,000 million and US$6,000 million in foreign exchange, and accounts for approximately 10 per cent of the region's protein intake (Caribbean News Now, 2011). It has been estimated that for the year 2000, the annual net benefits to the Caribbean provided by coral reefs through fisheries amounted to some US$300 million (Burke and Maidens, 2004). For the Montego Bay Marine Park, Jamaica, the net present value of the reefs associated with fishing was calculated to vary between US$1.7 million to US$7.5 million as far back as 1995 (Gustavson, 1998). In the both the Cayman Islands and the Turks and Caicos, revenues from fisheries earned around US$3.7 million (Carleton and Lawrence, 2005). For the Caribbean as a whole, it is estimated that dive tourism based on coral reefs earned around US$2.1 billion in 2000 (Burke and Maidens, 2004). Coral reefs are also estimated to have contributed US$43.5 million to Tobago's economy in 2006, or 15 per cent of GDP (Burke et al., 2008).

There is universal agreement that the vulnerability of any sector to climate change is a function of (a) the degree of exposure to the threat; (b) the sector's sensitivity to the risk; and (c) the capacity of the sector to cope with or adapt to the threat (IPCC, 2001, 2007; FAO, 2005). Any objective assessment of small-scale fisheries in the Caribbean's would conclude that exposure and sensitivity to the climate change threat are *high*, while adaptive capacity is *low* (see e.g. FAO, 2005; IPCC, 2007; Salas et al., 2007). Most of the region's fishing facilities tend to congregate in low-lying vulnerable coastal areas. These serve not only as the residential locations of the fishing communities, but also as the 'haul up' sites for vessels, gear and other equipments. These sites are also frequently used for boat building and repair. The *exposure* of the sector to the adverse consequences of climate change would therefore be heightened by factors including sea-level rise and an increase

Annex 43

"Framing and Context. Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty", Cambridge University Press, *Intergovernmental Panel on Climate Change,* 2018, pages 49-50, 81

1 Framing and Context

Coordinating Lead Authors:
Myles R. Allen (UK), Opha Pauline Dube (Botswana), William Solecki (USA)

Lead Authors:
Fernando Aragón-Durand (Mexico), Wolfgang Cramer (France/Germany), Stephen Humphreys (UK/Ireland), Mikiko Kainuma (Japan), Jatin Kala (Australia), Natalie Mahowald (USA), Yacob Mulugetta (UK/Ethiopia), Rosa Perez (Philippines), Morgan Wairiu (Solomon Islands), Kirsten Zickfeld (Canada/Germany)

Contributing Authors:
Purnamita Dasgupta (India), Haile Eakin (USA), Bronwyn Hayward (New Zealand), Diana Liverman (USA), Richard Millar (UK), Graciela Raga (Mexico/Argentina), Aurélien Ribes (France), Mark Richardson (USA/UK), Maisa Rojas (Chile), Roland Séférian (France), Sonia I. Seneviratne (Switzerland), Christopher Smith (UK), Will Steffen (Australia), Peter Thorne (Ireland/UK)

Chapter Scientist:
Richard Millar (UK)

Review Editors:
Ismail Elgizouli Idris (Sudan), Andreas Fischlin (Switzerland), Xuejie Gao (China)

This chapter should be cited as:
Allen, M.R., O.P. Dube, W. Solecki, F. Aragón-Durand, W. Cramer, S. Humphreys, M. Kainuma, J. Kala, N. Mahowald, Y. Mulugetta, R. Perez, M. Wairiu, and K. Zickfeld, 2018: Framing and Context. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 49-92. https://doi.org/10.1017/9781009157940.003.

1

Table of Contents

Executive Summary 51

1.1 Assessing the Knowledge Base for a 1.5°C Warmer World 53

Box 1.1: The Anthropocene: Strengthening the Global Response to 1.5°C Global Warming 54

1.1.1 Equity and a 1.5°C Warmer World 54

1.1.2 Eradication of Poverty 55

1.1.3 Sustainable Development and a 1.5°C Warmer World 55

1.2 Understanding 1.5°C: Reference Levels, Probability, Transience, Overshoot, and Stabilization 56

1.2.1 Working Definitions of 1.5°C and 2°C Warming Relative to Pre-Industrial Levels 56

1.2.2 Global versus Regional and Seasonal Warming 59

1.2.3 Definition of 1.5°C Pathways: Probability, Transience, Stabilization and Overshoot 59

Cross-Chapter Box 1: Scenarios and Pathways 62

1.2.4 Geophysical Warming Commitment 64

Cross-Chapter Box 2: Measuring Progress to Net Zero Emissions Combining Long-Lived and Short-Lived Climate Forcers 66

1.3 Impacts at 1.5°C and Beyond 68

1.3.1 Definitions 68

1.3.2 Drivers of Impacts 69

1.3.3 Uncertainty and Non-Linearity of Impacts 69

1.4 Strengthening the Global Response 70

1.4.1 Classifying Response Options 70

1.4.2 Governance, Implementation and Policies 71

Cross-Chapter Box 3: Framing Feasibility: Key Concepts and Conditions for Limiting Global Temperature Increases to 1.5°C 71

1.4.3 Transformation, Transformation Pathways, and Transition: Evaluating Trade-Offs and Synergies Between Mitigation, Adaptation and Sustainable Development Goals 73

Cross-Chapter Box 4: Sustainable Development and the Sustainable Development Goals 73

1.5 Assessment Frameworks and Emerging Methodologies that Integrate Climate Change Mitigation and Adaptation with Sustainable Development 75

1.5.1 Knowledge Sources and Evidence Used in the Report 75

1.5.2 Assessment Frameworks and Methodologies 76

1.6 Confidence, Uncertainty and Risk 77

1.7 Storyline of the Report 77

Frequently Asked Questions

FAQ 1.1: Why are we Talking about 1.5°C? 79

FAQ 1.2: How Close are we to 1.5°C? 81

References 83

Frequently Asked Questions

FAQ 1.2 | How Close are we to 1.5°C?

Summary: *Human-induced warming has already reached about 1°C above pre-industrial levels at the time of writing of this Special Report. By the decade 2006–2015, human activity had warmed the world by 0.87°C (±0.12°C) compared to pre-industrial times (1850–1900). If the current warming rate continues, the world would reach human-induced global warming of 1.5°C around 2040.*

Under the 2015 Paris Agreement, countries agreed to cut greenhouse gas emissions with a view to 'holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels'. While the overall intention of strengthening the global response to climate change is clear, the Paris Agreement does not specify precisely what is meant by 'global average temperature', or what period in history should be considered 'pre-industrial'. To answer the question of how close are we to 1.5°C of warming, we need to first be clear about how both terms are defined in this Special Report.

The choice of pre-industrial reference period, along with the method used to calculate global average temperature, can alter scientists' estimates of historical warming by a couple of tenths of a degree Celsius. Such differences become important in the context of a global temperature limit just half a degree above where we are now. But provided consistent definitions are used, they do not affect our understanding of how human activity is influencing the climate.

In principle, 'pre-industrial levels' could refer to any period of time before the start of the industrial revolution. But the number of direct temperature measurements decreases as we go back in time. Defining a 'pre-industrial' reference period is, therefore, a compromise between the reliability of the temperature information and how representative it is of truly pre-industrial conditions. Some pre-industrial periods are cooler than others for purely natural reasons. This could be because of spontaneous climate variability or the response of the climate to natural perturbations, such as volcanic eruptions and variations in the sun's activity. This IPCC Special Report on Global Warming of 1.5°C uses the reference period 1850–1900 to represent pre-industrial temperature. This is the earliest period with near-global observations and is the reference period used as an approximation of pre-industrial temperatures in the IPCC Fifth Assessment Report.

Once scientists have defined 'pre-industrial', the next step is to calculate the amount of warming at any given time relative to that reference period. In this report, warming is defined as the increase in the 30-year global average of combined air temperature over land and water temperature at the ocean surface. The 30-year timespan accounts for the effect of natural variability, which can cause global temperatures to fluctuate from one year to the next. For example, 2015 and 2016 were both affected by a strong El Niño event, which amplified the underlying human-caused warming.

In the decade 2006–2015, warming reached 0.87°C (±0.12°C) relative to 1850–1900, predominantly due to human activity increasing the amount of greenhouse gases in the atmosphere. Given that global temperature is currently rising by 0.2°C (±0.1°C) per decade, human-induced warming reached 1°C above pre-industrial levels around 2017 and, if this pace of warming continues, would reach 1.5°C around 2040.

While the change in global average temperature tells researchers about how the planet as a whole is changing, looking more closely at specific regions, countries and seasons reveals important details. Since the 1970s, most land regions have been warming faster than the global average, for example. This means that warming in many regions has already exceeded 1.5°C above pre-industrial levels. Over a fifth of the global population live in regions that have already experienced warming in at least one season that is greater than 1.5°C above pre-industrial levels.

(continued on next page)

Annex 44

George Agbugba et al., *The decoupling of economic growth from carbon emissions: UK evidence,* UK Office for National Statistics, 2019, pages 1-9

Office for National Statistics

Compendium

The decoupling of economic growth from carbon emissions: UK evidence

How the UK's economy has developed over time and the efforts it has made to reduce its carbon dioxide (CO2) emissions.

Contact:
Dr Amina Syed
economic.advice@ons.gov.uk
+44 (0)1633 455315

Release date:
21 October 2019

Next release:
To be announced

Correction

23 October 2019 12:42

Earlier figures were based on OECD data but Figure 12 uses data from Eora.

Notice

23 October 2019

Main points, 4th bullet: Earlier version mentioned emissions, however, these figures refer to carbon dioxide emission intensity.

Table of contents

1. Main points

2. Introduction

3. Background information

4. The relationship between environment and the economy

5. UK’s structural change

6. Technical progress and improvements in energy efficiency

7. International trade of carbon emissions

8. Conclusion

9. Authors

10. References

11. Appendix A: Total UK greenhouse gas (GHG) emissions

12. Appendix B: Regression analysis

13. Appendix C: Turning point calculation

1 . Main points

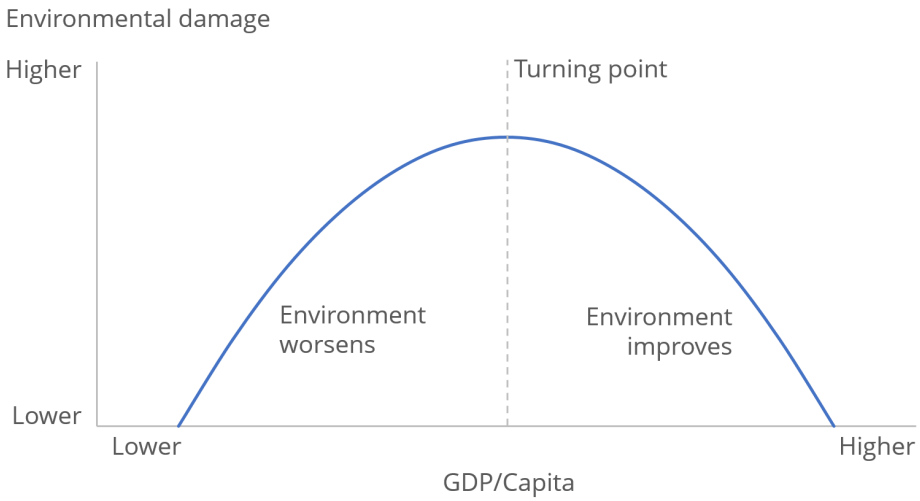
- While UK carbon dioxide (CO2) emissions peaked in 1972, once we consider imported emissions – such as when the UK imports products that are manufactured abroad – UK emissions peaked in 2007.
- The biggest source of these “imported” emissions is China, followed by the EU.
- Emissions produced directly by the UK declined as the result of a combination of environmental policies and a shift of the UK economy from more carbon-intensive manufacturing to less carbon-intensive service-based industries.
- When looking at the UK’s carbon dioxide emission intensity, which continues to fall, the energy generation (negative 67%), manufacturing (negative 43%), water supply (negative 38%), and transport (negative 33%) sectors saw the biggest falls between 1990 and 2017.
- The change from coal to renewable energy has resulted in UK CO2 emissions continuing to fall.

2 . Introduction

The relationship between economic growth and the environment has become increasingly scrutinised in the last 100 years. The unprecedented growth of the world economy has resulted in an increasing concern that its development is a contributing factor to the greenhouse effect[1]. This topic has drawn upon various theoretical models, one of which is presented by the Environmental Kuznets Curve (EKC). The EKC was first recognised in 1992 as the relationship between concentrations of sulphur dioxide and per head gross domestic product (GDP) in 47 cities distributed over 31 countries (Yandle and others, 2004).

Figure 1: Initial increases in GDP per head result in increased greenhouse gas emissions but, as an economy transitions from industrial production to service-based industries the environmental damage gradually falls

Environmental Kuznet Curve



Source: Environmental Kuznets Curve

The EKC depicted in Figure 1 highlights the scale effect, which is the initial transition of the economy from agricultural production in rural areas to industrial production in urban areas. As industrial production intensifies, more energy is used, resulting in increased greenhouse gas (GHG) emissions through combustion. However, as the economy develops, there will be a structural change from manufacturing and industrial production to service-based industries. Higher economic development leads to better technology, environmental awareness and enforcement of environmental regulations resulting in the gradual decline of environmental degradation.

To inform the debate surrounding the UK's decoupling[2], we use data from the Office for National Statistics, the Bank of England, the Department for Business, Energy and Industrial Strategy (BEIS), the World Resources Institute (WRI) and Eora to explore the evolution of the EKC concept and its driving factors. Specifically, we focus on carbon dioxide (CO2) effects, as these account for around 84% of all UK GHG emissions from human activities (please refer to Appendix A, for a breakdown of all UK GHG emissions).

The UK has shown evidence of absolute decoupling between 1985 and 2016, as gross domestic product (GDP) per head grew by 70.7%, while CO2 emissions fell by 34.2%. This decoupling relationship is largely a result of the economic structural change, technological advancement and enforcement of environmental regulations such as the Climate Change Act in 2008. Under this Act, the UK is legally required to achieve the 2050 commitment to reduce GHG emissions by at least 80% compared with 1990 levels.

In May 2019, these targets were reassessed by the Committee on Climate Change (CCC). Their Net Zero Technical Report advises the UK to reduce GHG emissions by 100% from 1990 levels by 2050. The CCC also revised Scotland's targets to meet net-zero by 2045, and for Wales to reduce GHG emissions by 95% by 2050. These recommendations will deliver the commitment the UK made in the 2015 Paris agreement.

The evident economic structural change saw the services sector contribute to around 80% of total GDP in 2017, in comparison with 51% in 1948. As the UK's economy also witnessed technological development, the substitution of fossil fuels with renewable energy quickened substantially. For example, between 1990 and 2017, energy from renewable sources increased by 1,267%, while fossil fuel energy consumption declined by 22%, further diminishing its effect on pollution levels.

However, one of the criticisms of the EKC theory is that service-focused countries tend to create indirect emission by outsourcing the manufacturing of consumer items to countries with lower labour costs such as China. An increasing proportion of the UK's economy is devoted to the higher-value services sector, which consumes less energy. This raises emissions through international trade flows, exaggerating any apparent decline in territorial-based emissions. A global approach is needed to analyse the relationship between GDP and emissions. This article will contribute to the existing literature on the EKC theory by analysing the evolution of the EKC concept and the possible causes of an EKC-pattern in the UK.

Notes for: Introduction

1. Greenhouse effect – heat being trapped in the atmosphere resulting in temperature warming.

2. Decoupling occurs when the growth rate of an environmental pressure (for example, CO2 emissions) is less than that of its economic driving force (for example, GDP per head) over a given period. Decoupling can be either absolute or relative. Absolute decoupling is said to occur when CO2 emissions is stable or decreasing while the GDP per head growth is growing. While, relative decoupling is when the growth rate of the CO2 emissions is positive, but less than the growth rate of the GDP per head (Ruffing, 2007).

3 . Background information

The relationship between gross domestic product (GDP) and the environment has become more important, because the rapid economic growth of developing countries has contributed to environmental degradation. The Environmental Kuznets Curve (EKC) theory suggests that economic growth will eventually reduce the environmental degradation created in the early period of development. Therefore, an economy should focus on economic growth in the short-term and any environmental effects will be counteracted in the long-term.

The observed evidence of the EKC theory is mixed, although most studies find evidence of an inverted-U shape relationship between real GDP per head and measures of environmental degradation such as sulphur dioxide and /or carbon dioxide emissions. De Bruyn and others (1998) argue that even though economic growth leads to an increase in emissions in the early stages of economic development, emissions may fall over time if there are technological and structural changes to the economy. More recent literature by Giovanis (2013), Mohapatra and others (2016), Mikayilov and others (2018), and Luzzati and others (2018) found that relative decoupling was more evident in developed countries. For example, Mikayilov and others (2018) used a panel data of European countries and found countries that showed evidence of decoupling followed stricter carbon mitigation policies. Therefore, it is necessary for the government to implement environmental policies such as carbon taxation, carbon pricing, cap and trade, and so on to ensure economies grow sustainably.

Everett and others (2010) and Luzzati and others (2018) agree with the conclusions of these studies to an extent. The results of Luzzati and others (2018) only showed weak evidence of EKC for the period 1971 to 2001 and found that this evidence does not hold up for the rest of their time frame because of the new wave of globalisation. The globalised nature of the world economy implies that this relationship needs to be analysed at an international level, rather than by individual countries because environmental damage cannot simply be reduced by moving production processes from advanced to developing countries (Everett and others, 2010).

4 . The relationship between environment and the economy

The UK Industrial Revolution of the 18th and 19th centuries resulted in the transition of the UK economy from a reliance on agriculture to manufacturing, starting a period of unprecedented economic growth. The carbon-intensive nature of the manufacturing sector meant that growth in the economy was accompanied by previously unseen levels of emissions.

Figure 2: Reduction in coal consumption and carbon dioxide emissions follow introduction of environmental regulations

GDP per head, territorial CO2 Emissions and coal consumption

Data download

Note:

1. Annual UK territorial CO2 emissions and coal consumption values were obtained from Carbon Brief, 2017; which used data sources via Department for Business, Energy & Industrial Strategy, 2019 and World Resources Institute, 2017. Real GDP per head values are sourced via Bank of England, 2019.

As observed in Figure 2, between 1850 and 1985, the UK's gross domestic product (GDP) per head and carbon dioxide (CO2) emissions exhibited a strong coupling, increasing by 516% and 354% respectively. The only exceptions were 1921, 1926 and 1984 where the miners' strikes led to a fall in coal production and caused a sharp dip in CO2 levels as observed previously (Church and others, 1990).

Most of this emission originated from the combustion of fossil fuels used to heat homes, such as coal , combined with emissions produced by factories during the Industrial Revolution. UK coal consumption increased from around 29 million tonnes a year in 1850 to 206 million tonnes in 1950.

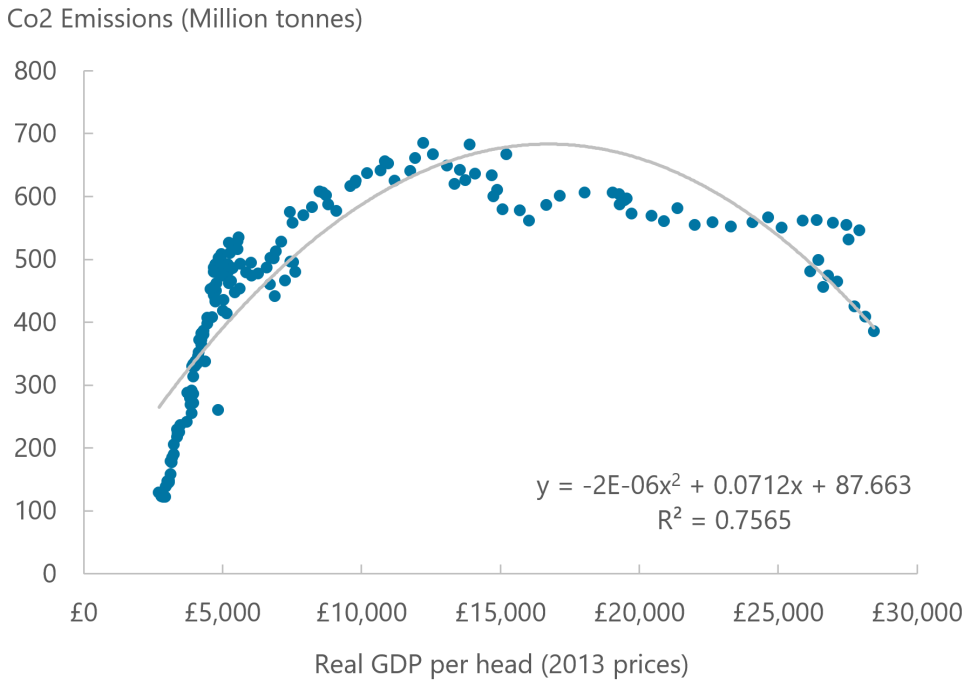
In 1952, smoke generated from the excess burning of coal combined with fog eventually led to a thick layer of smog in major cities such as London, Glasgow, Leeds and Manchester. The smog blocked out the sun, blackened buildings, increased the seriousness of fog, and damaged people's health (Brimblecombe, 2006).

According to the Environmental Kuznets Curve (EKC) theory, the decoupling of economic growth from environmental degradation eventually occurs after a certain GDP per head level. This is because higher economic development leads to environmental awareness, enforcement of environmental regulations and better technology, resulting in the gradual decline of environmental degradation. In a UK context, environmental awareness and a political appetite for enforcement of environmental regulations may have been a precedent for the eventual reduction in CO2 emissions.

The London smog prompted creation of the Clean Air Acts of 1956 and 1968, which prohibited discharges of dark smoke and declared that the inhabitants of urban regions and administrators of processing plants must switch over to smokeless fuels. By shifting domestic sources of heat towards cleaner coal, electricity and gas, it reduced the amount of smoke pollution and carbon dioxide from household fires and contributed to the eventual decline of coal (Brimblecombe, 2006). The level of coal consumption is shown in Figure 2 to decline after 1956.

Figure 3: The approximate turning point for decoupling of GDP per head and carbon dioxide emissions seems to have been around 1985

Correlation between real GDP per head and CO2 Emissions (Tonnes), 1850 to 2016



Source: Bank of England, 2019, World Resources Institute, 2017 and Business Energy Industrial Strategy, 2019

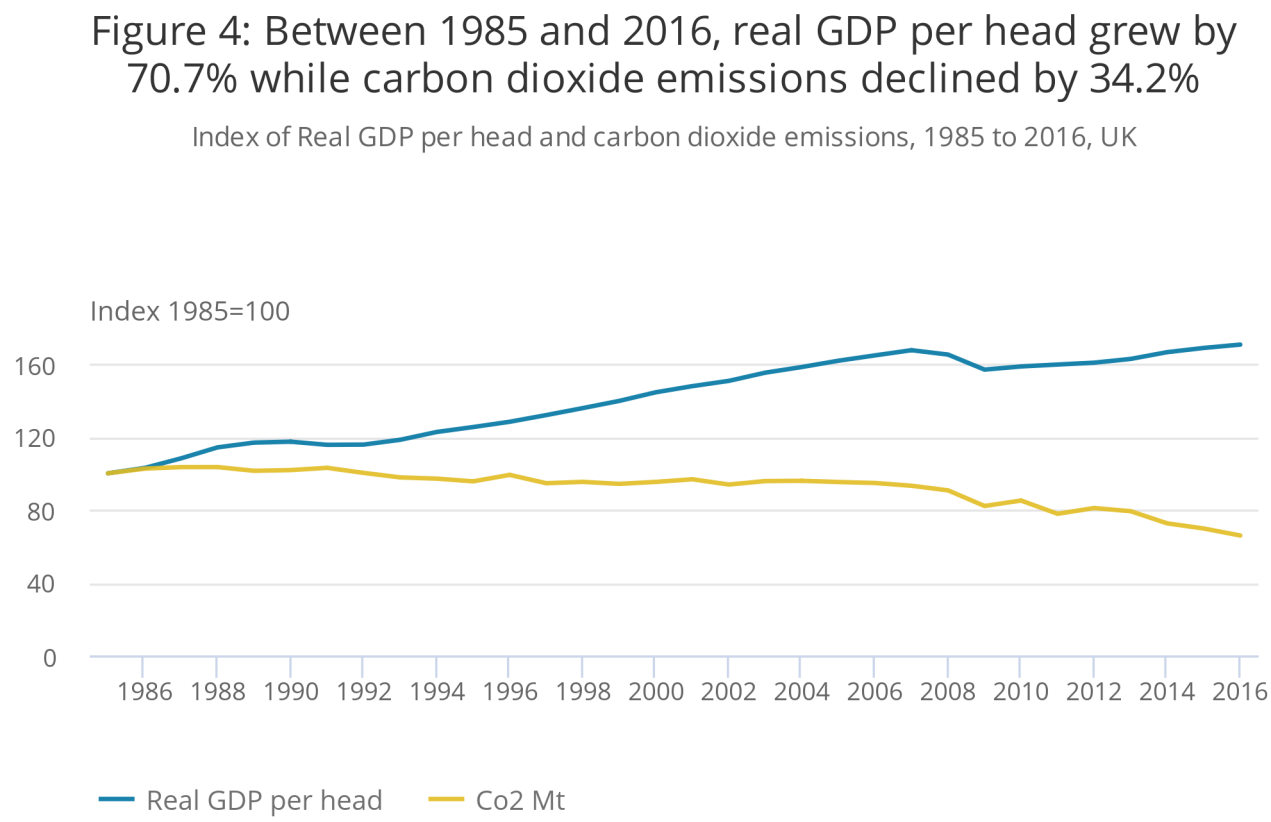
Notes:

1. Annual UK CO2 emissions were obtained from Carbon Brief, 2017; which used data sources via Business, Energy and Industrial Strategy , 2019 and World Resource Institute, 2017. Real GDP per head values are sourced via Bank of England, 2019.

For the UK, the approximate turning point at which the decoupling of GDP per head and carbon dioxide emissions seemed to have happened was in 1985, with a GDP per head of £16,667 and corresponding CO2 emissions of around 586 million tonnes, as shown in Figure 3. For a more in-depth analysis of the turning point calculation, please refer to Appendix C.

Figure 4: Between 1985 and 2016, real GDP per head grew by 70.7% while carbon dioxide emissions declined by 34.2%

Index of Real GDP per head and carbon dioxide emissions, 1985 to 2016, UK



Source: Bank of England, 2019, World Resources Institute, 2017 and Business Energy Industrial Strategy, 2019

Notes:

1. Annual UK CO2 emissions were obtained from Carbon Brief, 2017; which used data sources via Business, Energy and Industrial Strategy , 2019 and World Resource Institute, 2017. Real GDP per head values are sourced via Bank of England, 2019.

Figure 4 shows absolute decoupling of real GDP per head and carbon dioxide emissions, with 1985 as the base year to reflect changes following the decoupling. Real GDP per head grew by 70.7% between 1985 and 2016 while carbon dioxide emissions declined by 34.2% during the same period.

The Climate Change Act of 2008 (PDF, 440KB) was a further effort by the government to reduce the UK's impact on the environment. The Act formalised the UK's approach to tackling climate change and required preparation for climate change risks, as well as the reduction of the net UK carbon account of at least 80% by 2050, compared with 1990 levels.

The rate of decline in carbon dioxide (CO2) emissions quickened from 2008 as shown in Figure 4. The global economic slowdown during this period is likely to have contributed to the initial decline in emissions because of a reduction in global demand, therefore the exact impact of the Act on CO2 emissions is uncertain. However, the continued decline in emissions following the economic recovery is evidence of environmental improvement. In 2016, CO2 emissions were 35% below 1990 levels while GDP per head grew by 45% over the same period.

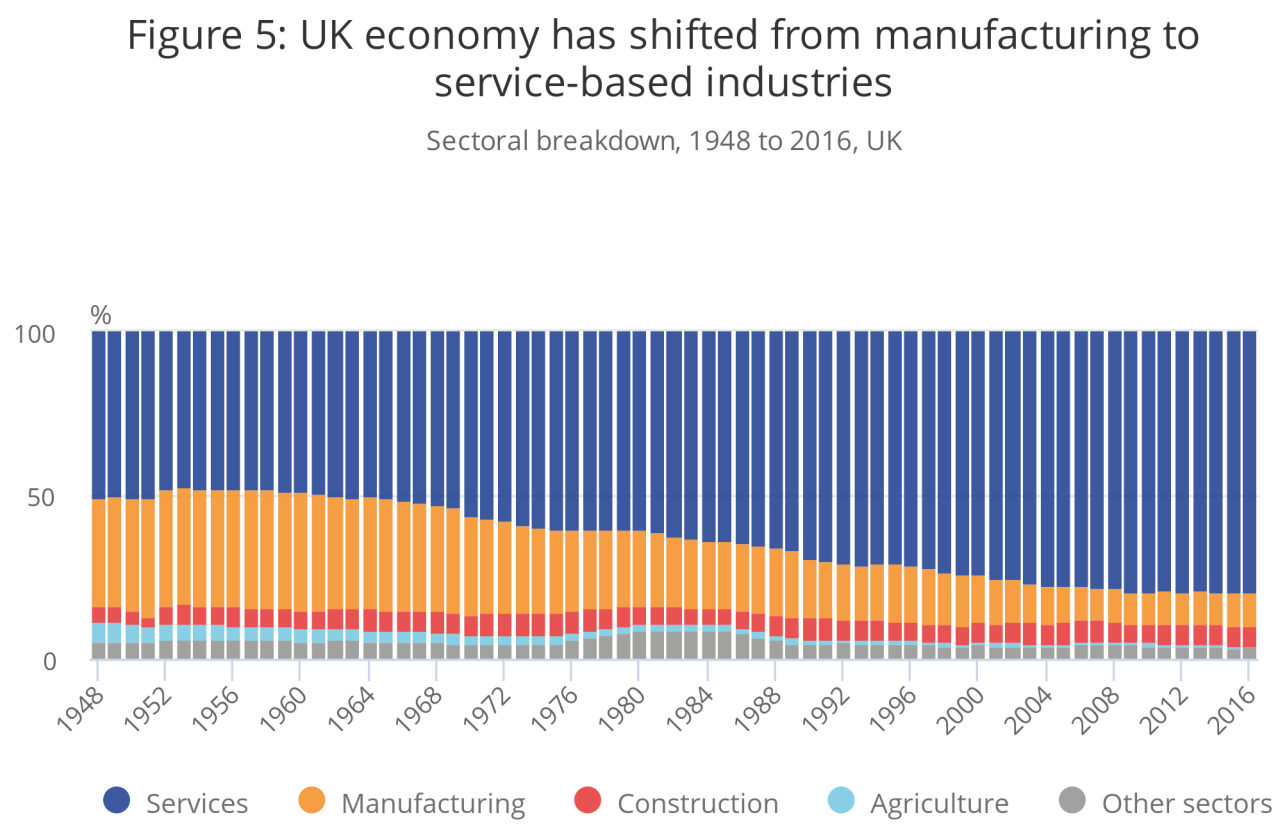
The Climate Change Act was amended in 2019 following the recommendations of the Committee on Climate Change to introduce the target of at least a 100% reduction of the net UK carbon account by 2050 compared with 1990 levels. The policies described previously highlight the importance of environmental policy for reducing the UK's environmental impact while maintaining economic growth. However, there could be several other reasons for decoupling of GDP per head from CO2 emissions, such as the structural change in the UK economy and technological advancement.

5 . UK's structural change

The structural transformation of the economy is relevant to the Environmental Kuznets Curve (EKC) concept. The theory suggests that economic development results in a structural change that transfers the economic production system from low-polluting agricultural industries to pollution-intensive manufacturing sectors and shifts again to less carbon-intensive service sectors.

Figure 5: UK economy has shifted from manufacturing to service-based industries

Sectoral breakdown, 1948 to 2016, UK



Source: Bank of England, 2019

Consistent with the EKC theory, Figure 5 shows that the UK economy is now devoted towards the services sector. In particular the knowledge-intensive services such as finance, professional services, and information and communication technology (Department for Business, Innovation and Skills, 2012).

Annex 44 bis

The Climate Studies Group Mona, The University of the West Indies, "The State of the Caribbean Climate", 2020, pages 1-6, 39-53, 86-108

THE UNIVERSITY OF THE WEST INDIES
MONA CAMPUS
JAMAICA, WEST INDIES

NDRM
Natural Disaster Risk Management in the CARIFORUM

An initiative of the African, Caribbean and Pacific Group, funded by the European Union, and implemented by:

CDEMA
CARIBBEAN DISASTER EMERGENCY MANAGEMENT AGENCY
Resilient States - Safer Lives

REPÚBLICA DOMINICANA
MINISTERIO DE LA PRESIDENCIA

THE STATE OF THE CARIBBEAN CLIMATE



Prepared by
The Climate Studies Group Mona
The University of the West Indies

For
The Caribbean Development Bank

April 2020



THE STATE OF THE CARIBBEAN CLIMATE

This publication is to be cited as follows:

Climate Studies Group Mona (Eds.). 2020. "The State of the Caribbean Climate". Produced for the Caribbean Development Bank.

REPORT AUTHORS:

Climate Studies Group Mona[1] (Chapters 1-5, 7 and 9):

Michael. A. Taylor
Tannecia S. Stephenson
Leonardo Clarke
Candice S. Charlton
Kimberly A. Stephenson
Pietra Brown
Dale Rankine
Jayaka D. Campbell
Roxann Stennett-Brown
Felicia Whyte
Alrick A. Brown
Deron Maitland
Christina Douglas
Delando Grant
Sarah Buckland
Rochelle N. Walters
Alton Daley

Caribbean Institute for Meteorology and Hydrology (Chapters 6 and 8):

Chapter 6
Cedric J. Van Meerbeeck[2]
Wazita Scott[2]
Teddy Allen[2]
Cherise Brathwaite[2]
Hannah Nissan[3]
Roché Mahon[2]
Adrian Trotman[2]

Chapter 8
Adrian Trotman[2]
Roché Mahon[2]
Glenroy Brown[4]
Kenneth Kerr[5]
Cedric Van Meerbeeck[2]

Instituto de Meteorología de la Republica de Cuba[6] (Chapter 5):

Abel Centella-Artola
Arnoldo Bezanilla-Morlot

This publication or parts of it may be reproduced for educational or non-profit purposes without special permission, provided acknowledgement of the source is made. (See citation above).

The views expressed in this publication are those of the authors and do not necessarily represent those of the Caribbean Development Bank

ACKNOWLEDGEMENTS:

» The State of the Caribbean Climate Report was financed through a technical assistance provided by the Caribbean Development Bank from resources allocated under the African, Caribbean, Pacific, European Union-CDB Natural Disaster Risk Management (ACP-EU-CDB NDRM) in CARIFORUM Countries Programme. The UWI/CSGM acknowledges support for project implementation from CDB, led by Dr. Yves Robert Personna, Project Manager, ACP-EU-CDB NDRM, Environmental Sustainability Unit.

1 The Climate Studies Group, Department of Physics, University of the West Indies, Mona, Kingston 7, Jamaica.
2 The Caribbean Institute for Meteorology and Hydrology, Husbands, St. James, Barbados.
3 International Research Institute for Climate and Society, Earth Institute, Columbia University, Lamont Campus, NY, USA.
4 Meteorological Service of Jamaica, 65 Half Way Tree Road, Kingston, Jamaica.
5 Trinidad & Tobago Meteorological Service, Rawinsonde Building, Piarco International Airport, Golden Grove Rd, Trinidad & Tobago.
6 Instituto de Meteorología de la Republica de Cuba, La Habana, Cuba.

EXECUTIVE SUMMARY

In the Caribbean, weather and climate events recurrently impact economic performance, productivity, livelihoods and quality of life. The record-breaking 2017 hurricane season stands as one of several recent examples that strongly underscore the economic, physical and social vulnerability of Caribbean nations to climate-related phenomena. Evidence-based and proactive decision-making will be fundamental to the transformation process from vulnerable to resilient Caribbean societies.

This State of the Caribbean Climate (SOCC) Report was prepared to strengthen the strategic planning and decision-making processes that will be required to accelerate resilience-building efforts in the Caribbean, specifically within the 19 Borrowing Member Countries (BMCs) of the Caribbean Development Bank (CDB). By providing significant climate data, information, analysis and references, distributed across 10 chapters, the SOCC Report is expected to become the premise for actionable recommendations that will support climate proofing at national and regional levels.

The structure and content of this report facilitate provision and analysis of climate data and information in a manner that takes cognizance of the similarities and differences among Caribbean nations. Chapters 1 and 2 provide the introductory background and methods and sources of data collection, respectively. Chapters 3 to 6 describe historical and future climate by focusing on key variables, e.g., temperature and rainfall, as well as extreme climate phenomena such as droughts, floods, sea level rise and hurricanes. The impacts of these climate variables and extremes on key sectors have been summarized in Chapter 7. Chapter 8 details the Caribbean approach and experience in developing climate services for improving national and regional response mechanisms. An overview of the key report findings and recommendations for the way forward are set forth in Chapter 9, and a list of all the references (by chapter) used in the preparation of this document is presented in Chapter 10.

While this report provides a significant repository of climate data and information (some of which have been summarized in the table below), there are a number of critical data-related gaps and challenges that need to be addressed as the region seeks to employ evidence-based approaches to decision-making. These data challenges are linked to inadequate coverage of weather and climatological stations that will (i) facilitate analysis at sectoral, national and regional scales (ii) enable automatic reporting, and (iii) improve continuous monitoring and analysis of key variables for sufficiently long timescales (greater than 30 years). Also to be addressed in support of better decision-making are (i) inadequate data collection and monitoring systems at the sectoral level that limit the understanding of climate-sectoral linkages (ii) the need for higher resolution modelling outputs as well as more impacts-based modelling, and (iii) coordination and capacity challenges that have reduced the effectiveness of climate action in the region.

Table ES 1: Summary of Climate Trends and Projections for the Caribbean

HISTORICAL TREND[2]	PROJECTION[3]
RAINFALL	
» Caribbean region has a defined dry (December to April) and wet (May to November) season. » Caribbean countries can be divided into six rainfall zones, based on the pattern of rainfall received. » Central Caribbean (Zones 3 and 4) receives smaller rainfall amounts (2-17 mm/month) while the far western and southern Caribbean (Zones 1 and 6) receive rainfall amounts ranging from 2 to 27 mm/month. » More than 70% of the rainfall occurs in the wet season for each zone. » In the long-term historical record (1900-2014), the Caribbean has not gotten wetter or drier (no significant observed linear trend). » Decadal variations account for 7% of the observed variability in Caribbean rainfall. Year-to-year (interannual) variations account for up to 91%. » The number of consecutive dry days is increasing, as well as the amount of rainfall during rainfall events.	» The Caribbean as a whole will gradually dry through to the end of the century. Drying is expected to be less in the far north Caribbean and more in the south and southeast. » Global Climate Models (GCMs) suggest for the central and southern Caribbean basin, drying up to 20 per cent for annual rainfall, while Regional Climate Model (RCM) based projections suggest up to 25 and 35 per cent less rainfall by the end of the century » GCMs suggest that mid-2020s will see up to 2% less rainfall in the annual mean. By the 2050s, the region is in the mean up to 6% drier, and by the end of century, the region may be up to 17% drier. » The Caribbean drying trend is likely driven by drying in the late wet season (September-November). » Dry season rainfall generally shows small increases or no change. » RCMs suggest sub-regional variation in projections with some parts of the region being more significantly impacted by drier conditions than others. A general pattern is for Belize in the far west Caribbean (Zone 1) and the Lesser Antilles and southern Caribbean (Zones 5 and 6) to be the most severely impacted once drying has begun, as well as the central Caribbean (Zone 4) to a lesser extent. » Changes to mean annual rainfall in the far north and north Caribbean (Zones 2 and 3) may suggest slightly wetter conditions through to mid-century, which change to drier conditions by the end of century. It is important to note however, that even for the far north Caribbean, the rainy seasons are projected to dry from as early as the 2020s. » Small to large increases in consecutive dry days are projected across the region.
AIR TEMPERATURES	
» Most of the variability observed (~65%) in temperature in the Caribbean is due to a significant upward (linear) trend. » Increase in temperature in Caribbean is consistent with global warming trend. » There is an increasing trend in very warm days and nights for the Caribbean as a whole.	» The Caribbean as a whole will gradually warm through to the end of the century. » Minimum, maximum and mean temperatures increase irrespective of scenario through the end of the century. » The mean temperature increase (in °C) from GCMs will be 0.48-0.56°C by the 2020s; 0.65-0.84°C by the 2030s, 0.86°-1.50°C by the 2050s, and 0.83-3.05°C by the end of the century with respect to a 1986-2005 baseline over all four RCPs. » RCMs suggest higher magnitude increases for the downscaled grid boxes - up to 4°C by end of century. » Temperature increases across all seasons of the year. » There are regional variations in warming evident in the RCM results. The far western Caribbean (Zone 1) and the southern Caribbean (Zone 6) show slightly higher warming than the rest of the region. » Projections based on statistical downscaling show an increase for both warm days and warm nights by the end of the century - warm days ranged between 51 and 251 days, and warm nights between 24 and 360 days for RCP 8.5. » The trend is for a decrease in both cool days and nights. The range for cool days was between 1 and 41 days, and between 1 and 32 days for cool nights for the end of century under RCP 8.5.

2 Historical trends are based on observations made over 1900-2014.

3 GCM-generated projections are relative to a 1986-2005 baseline, RCM-generated projections are relative to a 1961-1990 baseline.

HISTORICAL TREND[2]	PROJECTION[3]
SEA SURFACE TEMPERATURES	
» Range from 25°C to 30°C over the period of the year and follows a normal distribution pattern, with the lower temperatures in December/January and the highest temperatures in July.	» Recent warming trend in SSTs will continue in the future. » Under a business-as-usual scenario, SSTs increase by 1.76 ± 0.39°C per century in the wider Caribbean. » The mean annual SST range (~ 3.3°C) currently observed in the Caribbean Sea is projected to contract to 2.9°C in the 2030s, and to 2.3°C in the 2090s. By the end of the century, years of coolest projected SSTs fall within the range of the warmest years in the present.
SEA LEVELS	
» There is a general increasing trend in the sea level of the Caribbean region: » A regional rate of increase of 1.8 ± 0.1 mm/year between 1950 and 2009. » Higher rate of increase in later years: 1.7 ± 1.3 mm/year between 1993 and 2010. » Caribbean Sea level changes are near the global mean. » Larger sea level increases observed for post 2000 period during which hurricane intensity and sea level interannual variability have both increased.	» For the Caribbean, the combined range for projected SLR spans 0.26-0.82 m by 2100 relative to 1986-2005 levels. The range is 0.17-0.38 for 2046 – 2065. Other recent studies suggest an upper limit for the Caribbean of up to 1.5 m under RCP8.5. » Regional variation in SLR is small with the north Caribbean tending to have slighter higher projected values than the southern Caribbean. By the end of the century, sea level rise is projected to reach or exceed 1m across the Caribbean.
HURRICANES	
» Significant increase in frequency and duration of Atlantic hurricanes since 1995. » Increase in category 4 and 5 hurricanes; rainfall intensity, ass°Ciated peak wind intensities, mean rainfall for same period.	» No change or slight decrease in frequency of hurricanes. » Shift toward stronger storms by the end of the century as measured by maximum wind speed increases of +2 to +11%. » +20% to +30% increase in rainfall rates for the model hurricane's inner core. Smaller increase (~10%) at radii of 200 km or larger. » An 80% increase in the frequency of Saffir-Simpson category 4 and 5 Atlantic hurricanes over the next 80 years using the A1B scenario.

As the region considers how to respond in light of the implications of the key findings of this report and the uncertainty of future climate threats, there are three simple key messages or guiding principles that should undergird decision-making.

KEY MESSAGE 1: PLAN FOR THE CURRENT CLIMATE – BUT BE GUIDED BY LESSONS OF THE PAST.

It is important that the Caribbean region learns the lessons of the past and use them to guide current and future decision-making processes. Chapters 3 and 4 present the historical (long-term) characterization of Caribbean climate, by focusing on variables such as rainfall and temperature (sea surface and air) and climate extremes such as droughts, floods, sea level rise and hurricanes. The region has struggled with addressing these climate-related threats in an anticipatory manner, and this has increased individual and collective vulnerability. One key example of this is the frequently reactive manner in which slow-onset events such as droughts are addressed. Despite significant efforts such as work led by the Caribbean Institute for Meteorology and Hydrology (CIMH) to improve early warning for drought (see Chapter 8), there has been limited implementation of major long-term policy and other adaptation initiatives by decisionmakers to reduce drought's damaging impacts. The lessons of the past dictate that we can no longer afford to wait until an event happens, or is about to happen, before action is taken to deal with climate hazards. It is important that planning and decision-making efforts are (i) proactive, (ii) not curtailed or stalled once the threat is deemed to be past, and (iii) guided by past lessons and available expertise.

KEY MESSAGE 2: PLAN FOR THE FUTURE CLIMATE – BUT DO IT COLLABORATIVELY.

Prioritized collective action, coordinated across sectoral, national and regional levels, will be critical for successful decision-making. The projections for the Caribbean (presented in Chapter 5) are for rising sea levels, hotter temperatures, more variable rainfall with increased drying, increased sea surface temperatures, and more intense hurricanes. These projections, especially in light of the recent extremes discussed in Chapter 6 and the climate impacts in Chapter 7, call for urgent and coordinated action even while the region tries to grapple with existing threats. The climate-related phenomena that so drastically affect Caribbean countries are not locally derived, and as such, our response mechanisms must also be regionally driven and locally applied. The small size of Caribbean islands is one factor pointing to the need to work together to strengthen regional response mechanisms. In identifying those prioritized actions that the Caribbean should take, consideration should be given to (i) the social and economic costs of inaction or delayed action against the value to be derived from resilience efforts, (ii) the levels of resilience that can sustainably be targeted, and (iii) the systems that will need to be in place to support the transition to a more resilient Caribbean.

KEY MESSAGE 3: PRIORITIZE HARNESSING AND ENHANCING REGIONAL STRENGTHS AND EXPERTISE IN SUPPORT OF IMPROVED DECISION-MAKING

Chapter 8 presents an overview of climate services in the region, as well as national and regional mechanisms for supporting same. These efforts, which stand as key examples of regional strengths, have been led by the CIMH in collaboration with a consortium of regional partners. There is significant scope for bolstering these and similar services as well as the implementing institutions so that critical data, information, products and tools to improve decision-making are readily available to end users. As the region tackles climate change, identification and exploitation of regional strengths and opportunities, such as those for integrated, interdisciplinary and targeted research and development programmes as well as climate products and services, must play a substantial role in decision-making.

1. INTRODUCTION

1.1. CONTEXT

The very climate that has for decades underpinned the economies of many Caribbean territories is now proving to be their greatest area of vulnerability. This is in large part due to significant economic dependence upon climate sensitive sectors, like tourism and agriculture, in the face of a changing climate regime. There are, however, several other factors that further contribute to regional climate sensitivity and a heightened vulnerability to climate variations and change. These include limited coastal plains for siting major towns, cities and zones of economic activities (due to the small sizes and/or complex terrain of most Caribbean territories); a strong dependence on rainfall for water; and limited capabilities for hazard forecasting. For much of the Caribbean, there has been an expectation that the climate must follow anticipated and accustomed patterns, and as a result, planning related to both quality of life and economic development is strongly premised on these 'normal' patterns of climate. This is true even when the region experiences 'anomalous' climate phenomena, i.e., even variations from the 'normal' are expected to occur within bounds of familiarity.

Recent years, however, have seemingly brought the emergence of climatic conditions that are not only unfamiliar, but also unprecedented. This has been seen in such phenomena as rising sea levels, more prolonged region-wide droughts, increased heavy rainfall and flooding events, and greater numbers of very hot days and nights in a year. It is not just the magnitude of the change that has proven challenging (e.g., the intensity of the rainfall events leading to flooding, or the length of the droughts), but also the frequency of extreme event occurrence. Such is the case when the region is impacted by a climate extreme even before it has managed to recover from another. Projections of future Caribbean climates indicate that changes already seen are likely to continue and further intensify, exposing the region to an increasing number of extreme climatic events. The Caribbean is, therefore, projected to keep facing the challenges that accompany the adjustment to climate change, for example, from more frequent and/or intense tropical storms and hurricanes.

The 2017 hurricane season provided valuable insight into what the Caribbean might face in the future under climate change. Far surpassing any upper limits of devastation in prior experience, the 2017 hurricane season was among the deadliest on record, and the costliest to date - estimated at over US$350 billion globally (Seria 2018). According to the Caribbean Development Bank (CDB), several of its Borrowing Member Countries (BMCs)[4], shown in Figure 1.1, were affected by the hurricanes of September 2017. Hurricanes Irma and Maria, in particular, challenged prior concepts of familiarity and preparedness, both in terms of the record-breaking speed with which they attained category 5 status, and their relentless onslaught upon the region. The damage caused by these hurricanes led to substantial loss of life, widespread infrastructural damage, destruction of crops and livestock, diminished standards of living, and loss of livelihoods. Recovery from that most devastating of seasons is still proving to be a challenge for the scope of regional experience, and perhaps regional economic power as well. (It is noted that the challenge posed to the region by recurrent hazards of unprecedented nature was being played out even as this document was being finalized. The 2019 hurricane season proved to also be record breaking with Hurricane Dorian (category 5) causing significant devastation in the Bahamas (ECLAC 2019).

4 CDB BMCs: Anguilla, Antigua and Barbuda, Bahamas, Barbados, Belize, British Virgin Islands, Cayman Islands, Dominica, Grenada, Guyana, Haiti, Jamaica, Montserrat, St Kitts and Nevis, St Lucia, St Vincent and the Grenadines, Suriname, Trinidad and Tobago, and Turks and Caicos Islands

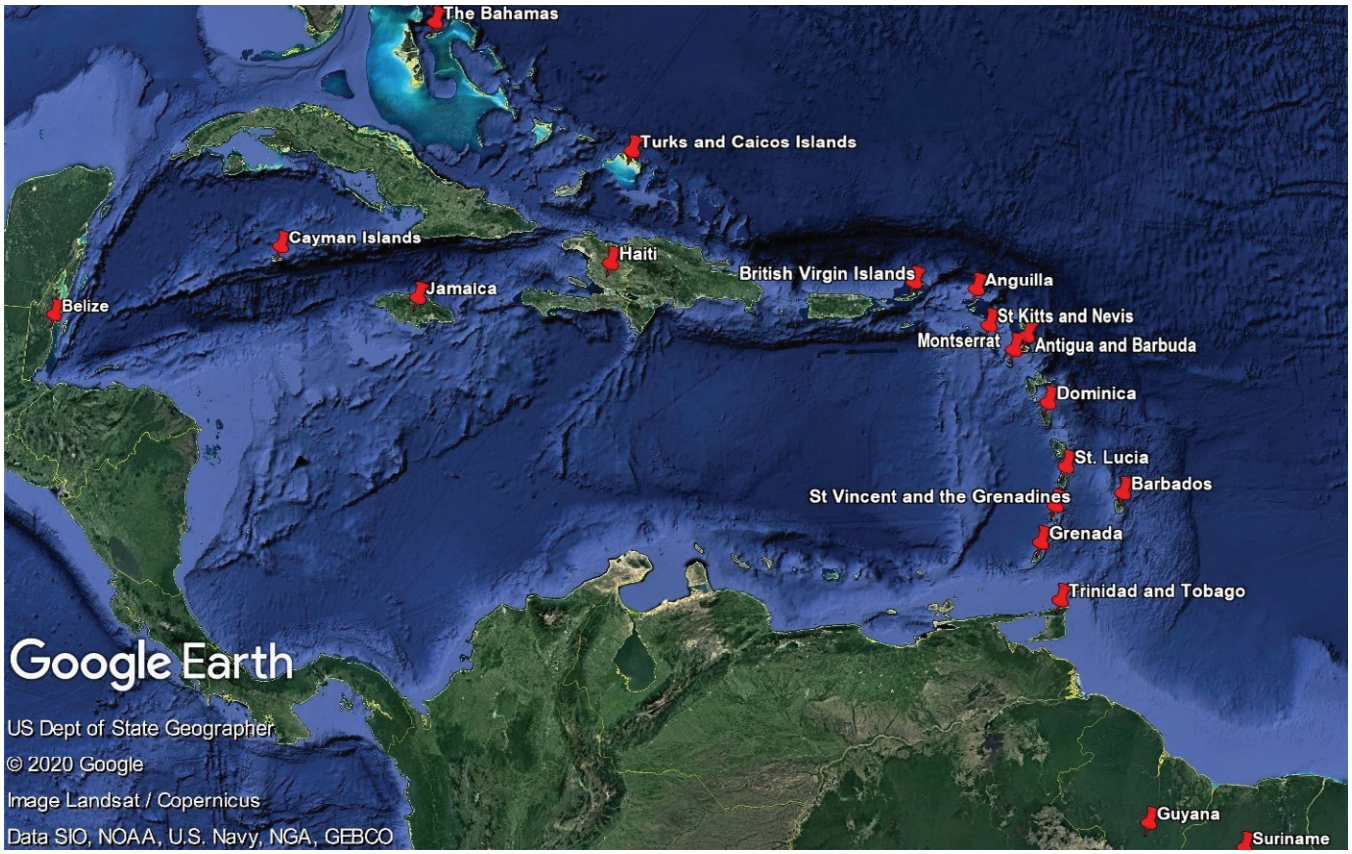


Figure 1.1: Map of the Caribbean showing CDB BMCs (Source: Google Earth 2020)

Given recent experiences and future projections, it seems clear that the Caribbean can no longer afford the cost of the catastrophic consequences of climate change, nor can it afford not to respond to climate change. Therefore, regional efforts aimed at augmenting climate resilience are necessary given that the Caribbean's vulnerability to climate variability and change is projected to only increase. Such resilience will require a multi-faceted, strategic, and sustainable approach which will only be possible with the support of decision-makers in government and industry.

This document serves as a contribution to the regional resilience building effort through the provision of historical and future climate information for use by regional decision-makers. In order to mainstream climate variability and change into regional planning and decision-making, it is necessary to have an understanding of: (i) the baseline or mean climate of the region, (ii) how that climate has changed in the recent past and how it is projected to change in the future, (iii) how those changes are expected to have an impact at local levels, and (iv) potential measures that have already been implemented or will be required to reduce vulnerability to climate change. This document, compiled under the auspices of the State of the Caribbean Climate (SOCC) Project, provides the climate-related information decisionmakers will need as they seek to proactively plan and effectively respond to a changing climate.

1.2. THE STATE OF THE CARIBBEAN CLIMATE PROJECT

The CDB has long been cognizant of the need for increased knowledge about climate change and its effects. In 2017, the organisation provided a grant of 445,056 euros to The University of the West Indies (UWI), Mona through financing from the European Union (EU), to implement the Project "State of the Caribbean Climate Report: Information for Resilience Building". Funding for the project came as a result of a 2014 agreement with the EU for the CDB to execute projects within the African Caribbean Pacific (ACP)[5]-EU Natural Disaster Risk Management

5 The African, Caribbean and Pacific Group of States is now called The Organisation of African, Caribbean and Pacific States (OACPs).

(NDRM) Programme in the CARIFORUM states[6]. The main objective of the five-year NDRM Programme is "to contribute to reducing the vulnerability to long term impacts of natural hazards, including the potential impacts of climate change, thereby achieving regional and national sustainable development and poverty reduction goals in the CARIFORUM States." (Jambou 2015).

The State of the Caribbean Climate Project contributes to the goals of the NDRM Programme by seeking to increase awareness about, and use of, updated and reliable climate data in CDB BMCs. The Climate Studies Group, Mona (CSGM), within the Department of Physics at The UWI, is directly responsible for technical implementation of the project across its three main components listed below:



Preparation of the "State of the Caribbean Climate Report". This is intended to be a comprehensive 'first-stop' reference report that details the state of knowledge of climate variability and change at the time of its compilation. This report is expected to become the premise for actionable recommendations to improve the region's resilience across all levels and sectors. Two validation workshops for targeted end-users, one in Jamaica and one in St. Lucia, formed part of the report finalization process. Section 1.3 presents further details on the report.



Conducting interactive "Climate SMART Series" workshops. These were targeted at key governmental representatives within BMCs of the CDB as well as relevant regional organisations. The workshops focussed on: (a) building knowledge and awareness of climate change and its impacts on climate-sensitive sectors, and (b) guiding the BMCs to effectively use the data in the State of the Caribbean Climate Report to assess the effects of climate variability and change on specific sectors, and integrate climate data into development planning and strategies.



Development of an online platform. This will permanently host content relating to the State of the Caribbean Climate Report. The platform will also host workshop materials, and other relevant climate resources, thereby increasing the reach and capacity-building potential of the Project.

In the delivery of the State of the Caribbean Climate Report the CSGM partnered with the Caribbean Institute for Meteorology and Hydrology (CIMH) to produce two chapters (see the author listing in the front material). This report has also significantly benefitted from collaborative dynamical downscaling modelling work done with the Cuban Instituto de Meteorología (INSMET) under the auspices of the Caribbean Climate Modellers Consortium.

6 Caribbean Forum of African, Caribbean and Pacific States.



1.3. ABOUT THIS DOCUMENT

The State of the Caribbean Climate Report (hereafter SOCC Report) contains updated and reliable climate data for the Caribbean region, including observed climate variability and trends, recent extreme climatic events and impacts, a compilation of potential impacts of climate change for climate sensitive sectors, and an examination of the value of climate information. The report is geared towards increasing decision-makers' basic understanding of climate variability and change, facilitating evidence-based planning and policy, and implementing prioritised actions tailored to respond to climatic threats as well as sector-specific sensitivity contexts. Ultimately, this SOCC Report is expected to be used to support disaster risk reduction, facilitate the formation of climate change adaptation strategic plans, and aid work programme development, all of which will contribute to the increased resilience of vulnerable Caribbean countries and communities.

Although general assessment reports for the Caribbean do exist, there are often limitations to their access and use, particularly in the following ways: (a) many exist in peer-reviewed literature and are not readily accessible by decision-makers, (b) they are unsuited for policy-makers due to their technical scope, (c) the projections used tend to rely on general circulation models that do not provide sufficiently detailed data and information at spatial scales required by small Caribbean islands, (d) climate variability is not taken into account, and (e) existing climate change projections at the regional level are not based on the most recent science. The SOCC Report seeks to address these limitations.

Despite the fact that there have been significant improvements in the collection and availability of climate data over the last ten years, the data do not often play a critical role in planning and decision-making processes. In some cases, this is due to limitations in (i) understanding and awareness of climate variability and change as it relates to the Caribbean region, and (ii) knowledge of how and where to access climate information and data for the Caribbean. Furthermore, while many Caribbean policymakers have a strong interest in climate change issues, the perception is that such matters are often presented in an overly academic and technical manner, which discourages attempts at both understanding and using the information. The SOCC Project is an attempt to provide tools for bridging these gaps. One goal of the project is to increase basic knowledge and understanding of recent and future climate variability and change in the Caribbean region, in the hope that doing so will yield evidence-based policy and investment actions. In particular, the SOCC Report attempts to do this by amalgamating all current Caribbean region-specific climate-related information for a non-scientific audience. Table 1.1 outlines the structure of the report.

Table 1.1: Structure of the State of the Caribbean Climate Report

CHAPTER	TITLE	SUMMARY
CHAPTER 1	INTRODUCTION	Caribbean context and State of the Caribbean Climate Project.
CHAPTER 2	DATA AND METHODOLOGIES	Methods and sources of data collection.
CHAPTER 3	RAINFALL AND TEMPERATURE	Defining climatology, extremes, and trends.
CHAPTER 4	SEA LEVEL RISE, DROUGHTS & FLOODS, HURRICANES	Historical variability or long-term trends.
CHAPTER 5	CLIMATE SCENARIOS AND PROJECTIONS	Caribbean climate in the future using regional climate models and statistical downscaling.
CHAPTER 6	CLIMATE EXTREMES AND EARLY WARNING	A description of extreme climatic events and the current regional early warning information for improved preparedness to such events.
CHAPTER 7	IMPACTS OF CLIMATE CHANGE ON THE CARIBBEAN	A compilation of potential impacts of climate change for relevant sectors in the Caribbean with references.
CHAPTER 8	ADDING VALUE TO CLIMATE INFORMATION THROUGH SERVICES	Caribbean approach to climate services at national and regional levels.
CHAPTER 9	CONCLUSIONS AND RECOMMENDATIONS	Summary of key report findings and recommendations for the way forward.
CHAPTER 10	REFERENCES	A list of all the references (by chapter) used in the preparation of this document.
APPENDIX 1	CLIMATE RESOURCES	A comprehensive review of credible climate tools, reports, and articles on Caribbean climate.


1010
L
H
1029
1020
L
1004
1012
1004


DO NOT
ENTER

4. SEA LEVEL RISE, DROUGHTS & FLOODS, HURRICANES

4.1. INTRODUCTION

In this chapter, historical trends in sea level, as well as trends in the occurrence of floods, droughts and hurricanes are examined. In general, the climatology of each variable is examined first, followed by a summary of what is known about historical trends. For floods, use is made of the EM-DAT database (The Emergency Events Database) (Guha-Sapir et al. 2015). As opposed to examinations of trends and variability in Caribbean temperature and rainfall records, there is far less research done on sea level rise, droughts, floods and hurricanes for the Caribbean region as a whole.

4.2. SEA LEVEL RISE

4.2.1. HISTORICAL TRENDS

Globally, sea levels rose at a rate of 1.7 ± 0.2 mm/year through the 20th century according to tide gauge records (IPCC 2013). This rate of increase for the 20th century was the fastest increase in sea level for the previous 28 centuries (Robert E. Kopp et al. 2016). Table 4.1, however, shows that this sea level rise is modest in comparison to the 3.2 ± 0.4mm/year which was recorded by satellite altimeters during the end of the 20th century and the early 21st century. This suggests an acceleration in global sea level rise, which is projected to continue with increased global warming (Church & White 2006). More recently, Yi et al. (2015) have observed that this rate has increased to 4.5 ± 0.4 mm/year for regions during the period 2010-2014.

Table 4.1: Mean rate of global averaged sea level rise

PERIOD	RATE (MM/YEAR)		INFORMATION SOURCE
1901 AND 2010	1.7 ± 0.2	Tide gauge	IPCC (2013)
1993 AND 2010	3.2 ± 0.4	Satellite Altimeter	IPCC (2013)

Studies on historical Caribbean sea level trends are limited in comparison to similar studies showing trends in atmospheric variables. This is due in part to the absence of very long records. The existing studies however suggest that, in the mean, Caribbean sea level trends are very similar to the global trends.

Table 4.2 shows mean Caribbean sea level trends estimated from tide gauge records and satellite altimetry. Palanisamy et al. (2012) calculates the mean Caribbean sea level rise rate to be 1.8 ± 0.1 mm/year for the period 1950 – 2009. Torres and Tsimplis (2013) determine the rate to be 1.7 ± 1.3 mm/year over the period 1993-2010. These rates are similar to the global rate of 1.7 ± 0.2 mm/year which was shown in Table 4.1. When the mean Caribbean sea level trend measured by satellite altimetry is corrected for Global Isostatic Adjustment, it is estimated to be approximately 2.5 ± 0.4 mm/year (Torres and Tsimplis 2013).



Table 4.2: Mean rate of sea level rise averaged over the Caribbean basin.

PERIOD	RATE (MM/YEAR)	INFORMATION SOURCE
1950 - 2009	1.8 ± 0.1	Palanisamy et al. (2012)
1993 - 2010	1.7 ± 1.3	Torres and Tsimplis (2013)
1993 - 2010	2.5± 1.3	Torres and Tsimplis (2013), after correction for Global Isostatic Adjustment (GIA)

The examined historical records also indicate that there is regional variation in the rate of sea level rise i.e. it is not uniform across the Caribbean. Figure 4.1 and Table 4.3 illustrate this. Figure 4.3 shows sea level trends for different tide gauge stations around the Caribbean region. The inconsistencies in record lengths across the region are noted. Table 4.3 gives the calculated trend for each station. Both the figure and the table are adapted from Torres and Tsimplis (2013).

Notwithstanding the station examined, there is a general increasing trend in the sea level of the Caribbean region i.e. there are no negative trends. The sea level rise varies from 0.26 mm/year off the coast of Venezuela, to as high as 10.76 mm/year for the Port-au-Prince, Haiti station. Figure 4.2 shows a map of how these rates differ across the region. The map is constructed using the Mean Reconstruction sea level (MRESL) dataset. Tide gauge records are a major data component used to develop the MRESL. However other components such as post glacial rebound and tectonics are also taken into account. The variation in sea level rise rates across the region is evident in the plot with largest increasing trends found in the southern Caribbean close to the South American continent.

The mean sea level of the Caribbean region also varies on decadal and interannual time scales. The interannual variations are evident in the time series plots of Figure 4.1. Caribbean sea level is highly correlated with El Niño-Southern Oscillation (ENSO) especially since the mid-1980s, with larger increases in sea levels occurring during stronger El Niño events (Palanisamy et. al. 2012; Torres et al. 2013; Torres and Tsimplis 2014; Blunden et al. 2016). This may have led to sea levels reaching as high as 11.3 cm above mean sea level during the 2015 El Niño event. Recent studies also show a significant correlation between the interannual variability in sea level and hurricane activity (Torres and Tsimplis 2014). This is especially true for the post 2000 period, during which hurricane intensity and sea level interannual variability have both increased.



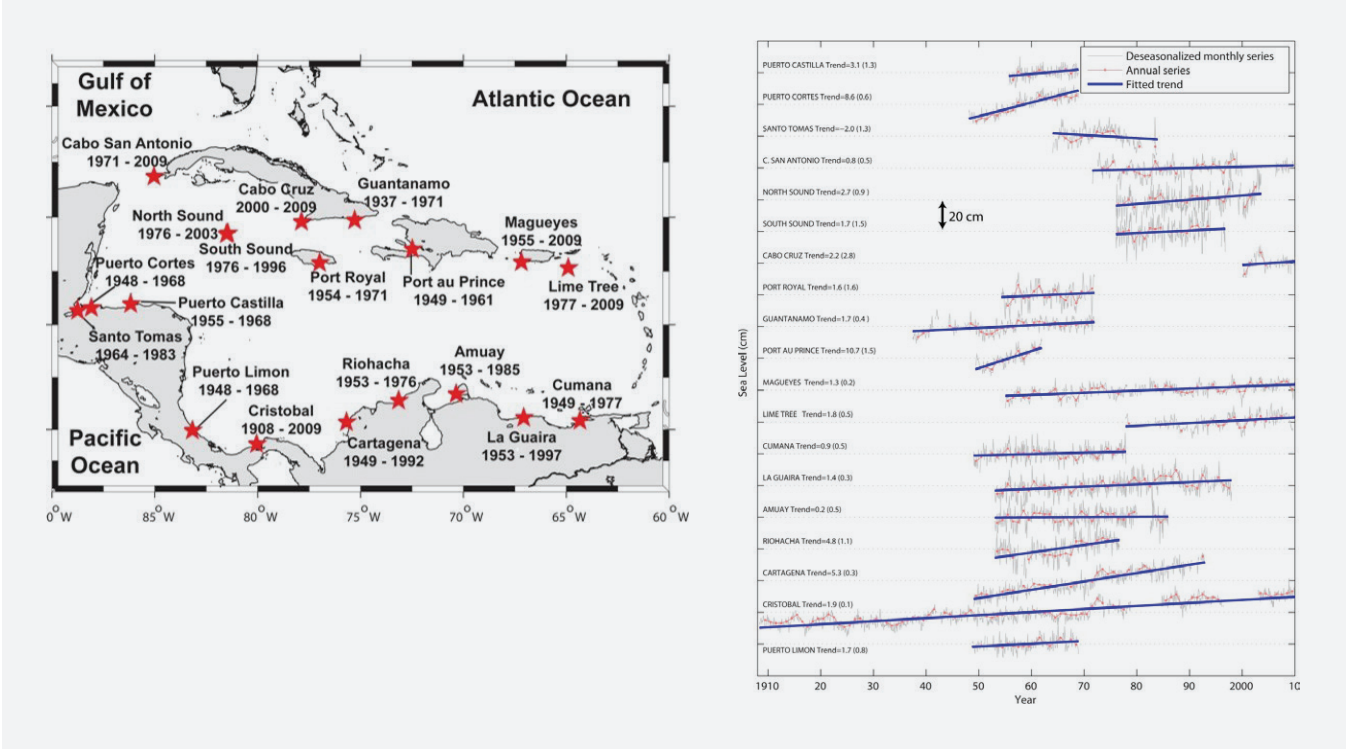


Figure 4.1: a) Location of tide gauge stations and time series start and end year. b) Tide gauge observed sea-level trends computed from all available data. Monthly time series after the removal of the seasonal cycle (gray), the linear trend (blue), and the annual series (red) are also shown. The trends (and 95% error) in mm/yr. From Torres and Tsimplis (2013).

Table 4.3: Tide gauge observed sea-level trends for Caribbean stations shown in Figure 4.1. Table adapted from Torres & Tsimplis (2013)

	Country	Lat (N)	Lon (W)	Span years	% of data	Trend (mm/ year)	Months	Gauge corrected
P. LIMON	Costa Rica	10	83	20.3	95.1	1.76±0.8	216	2.16±0.9
CRISTOBAL	Panama	9.35	79.9	101.7	86.9	1.96±0.1	566	2.86±0.2
CARTAGENA	Colombia	10.4	75.6	44	90	5.36±0.3	463	5.46±0.3
RIOHACHA	Colombia	11.6	72.9	23.8	95.8	4.86±1.1	273	4.86±1.1
AMUAY	Venezuela	11.8	70.2	33	93.4	0.26±0.5	370	0.26±0.5
LA GUAIRA	Venezuela	10.6	66.9	45	98.9	1.46±0.3	534	1.56±0.3
CUMANA	Venezuela	10.5	64.2	29	98.6	0.96±0.5	331	0.76±0.6
LIME TREE	US Virgin Islands	17.7	64.8	32.2	81.9	1.86±0.5	316	1.56±0.5
MAGUEYES	Puerto Rico	18	67.1	55	96.2	1.36±0.2	635	1.06±0.2
P. PRINCE	Haiti	18.6	72.3	12.7	100	10.76±1.5	144	12.26±1.5
GUANTANAMO	Cuba	19.9	75.2	34.6	89.9	1.76±0.4	258	2.56±0.6
PORT ROYAL	Jamaica	17.9	76.8	17.8	99.5	1.66±1.6	212	1.36±1.6
CABO CRUZ	Cuba	19.8	77.7	10	90	2.26±2.8	108	2.16±2.8
SOUTH SOUND	Cayman	19.3	81.4	20.8	87.6	1.76±1.5	219	1.26±1.5
NORTH SOUND	Cayman	19.3	81.3	27.7	89.2	2.76±0.9	296	2.26±0.9
C. SAN ANTONIO	Cuba	21.9	84.9	38.3	76.7	0.86±0.5	353	0.36±0.5
SANTO TOMAS	Mexico	15.7	88.6	20	85.4	2.06±1.3	205	1.76±1.3
P. CORTES	Honduras	15.8	87.9	20.9	98	8.66±0.6	224	8.86±0.7
P. CASTILLA	Honduras	16	86	13.3	100	3.16±1.3	160	3.26±1.3

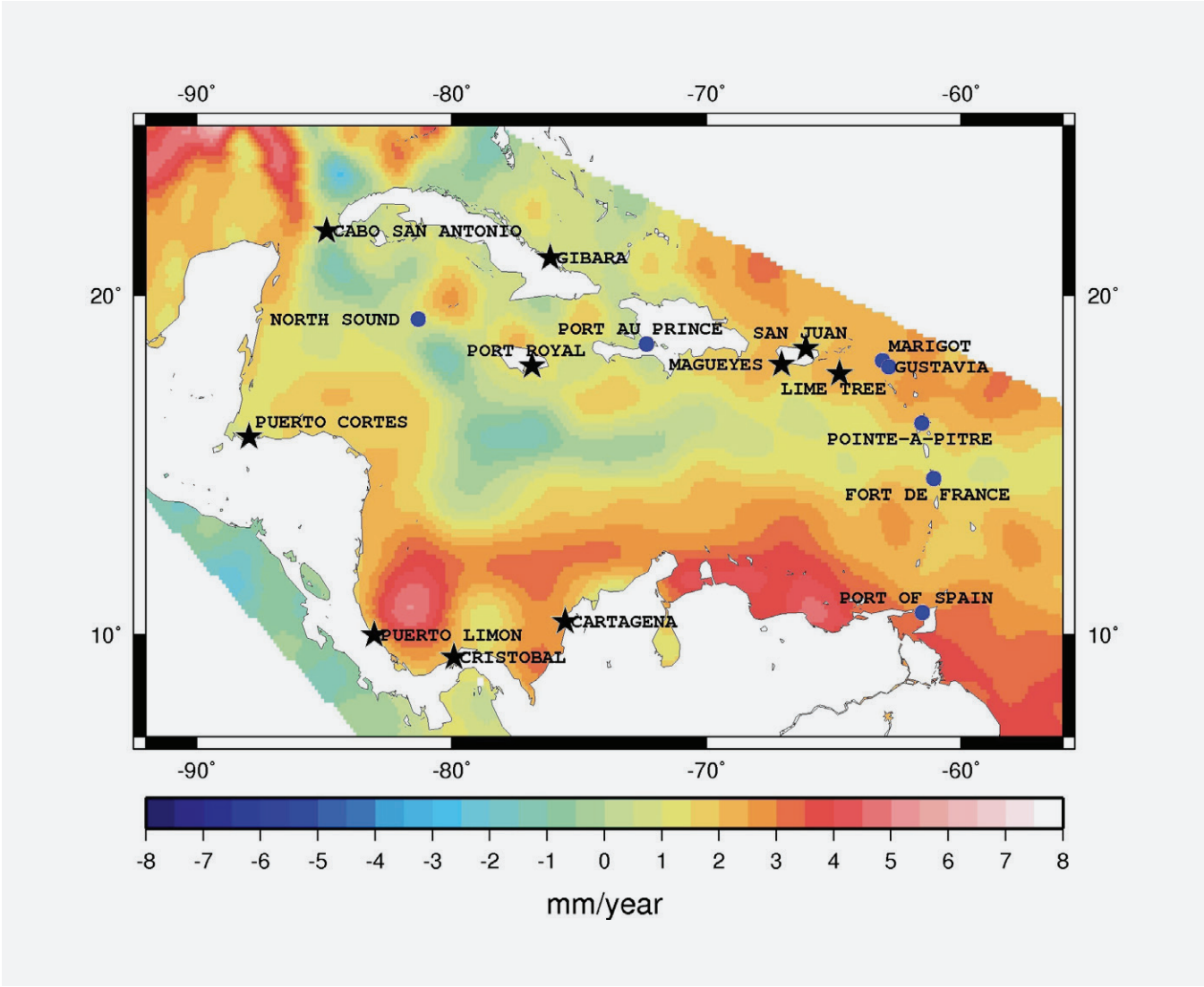


Figure 4.2: Mean Reconstruction Sea Level (MRESL) from 1950- 2009. Figure Source: Palanisamy et al. (2012).

4.3. HURRICANES

4.3.1. CLIMATOLOGY

The hurricane season in the North Atlantic spans June to November. This coincides with the period when the Gulf of Mexico, the Caribbean Sea, and the north tropical Atlantic are most conducive to convective activity. During this time of the year, the region is characterised by weak easterly trade winds, decreased vertical wind shear, and SSTs in excess of 26oC (see again Box 3.1). In tandem, these create ideal conditions for tropical cyclone (TC) activity.

The climatology of hurricanes and tropical storms in the tropical Atlantic Ocean, the Caribbean Sea, and the Gulf of Mexico is shown in Figure 4.3. It is to be noted that although storms and hurricanes generally occur between June 1 and November 30 (i.e. the official hurricane season), it does not preclude storm or hurricane activity in May or December. The peak of the North Atlantic season is from mid-August to late October, with a primary peak around September 10th. A secondary peak occurs around the middle of October, which is mainly for the Caribbean Sea and the Gulf of Mexico region, after which the number of storms drops off quickly through the end of the season.

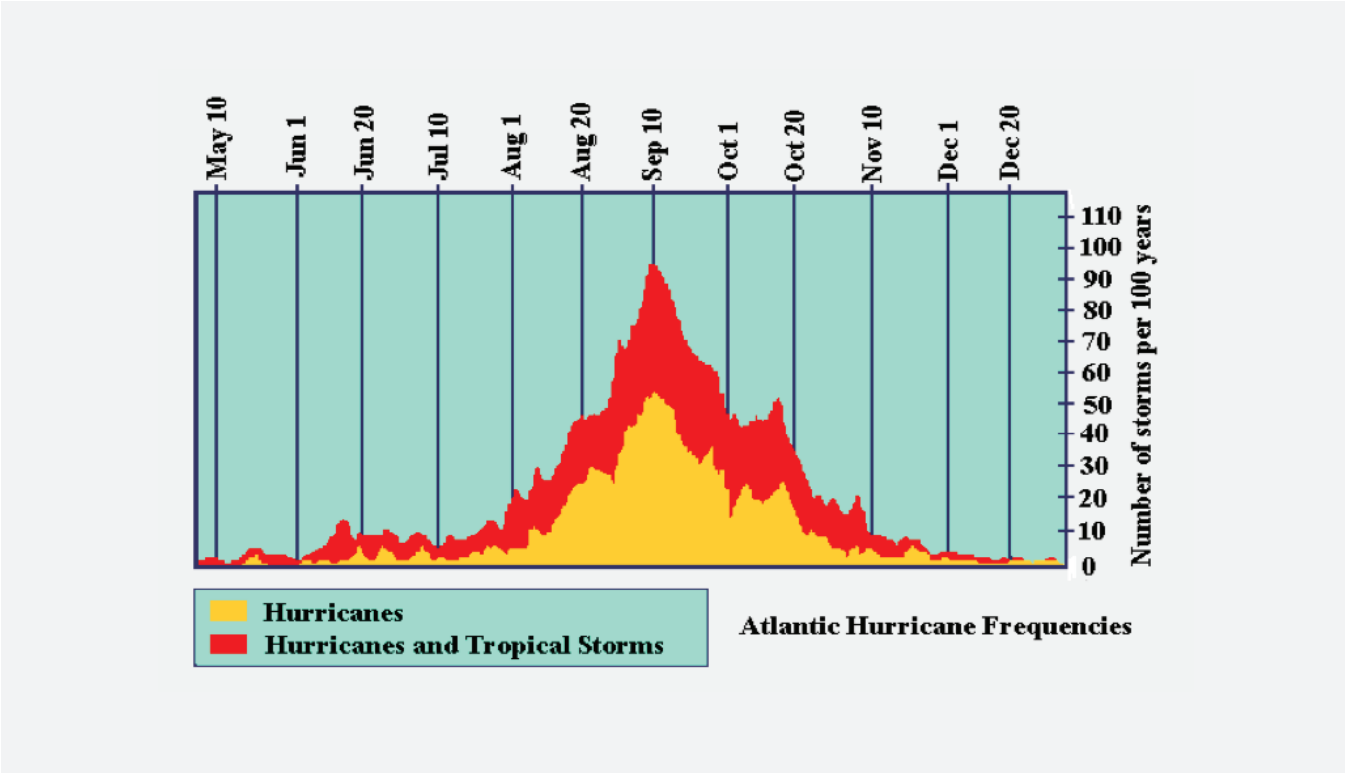


Figure 4.3: Storm frequency during the Atlantic Ocean hurricane season. Source: NOAA.

Figure 4.4 shows the mean areas of origin and prevailing tracks during selected months of the hurricane season. From June through August, the areas of origin shift from the western Caribbean Sea and Gulf of Mexico (June) into the Atlantic Ocean (August-September). This coincides with the eastward expansion of the Atlantic warm pool which results in water temperatures becoming warmer in the north tropical Atlantic (see Section 3.2.1) thereby allowing easterly waves coming off the African coast to develop into storms and hurricanes. By October, the water temperatures in the north tropical Atlantic east of the Caribbean basin start to cool and wind shear increases, and storm genesis and activity generally shifts back into the Caribbean Sea and Gulf of Mexico, where the water temperatures are still very warm.



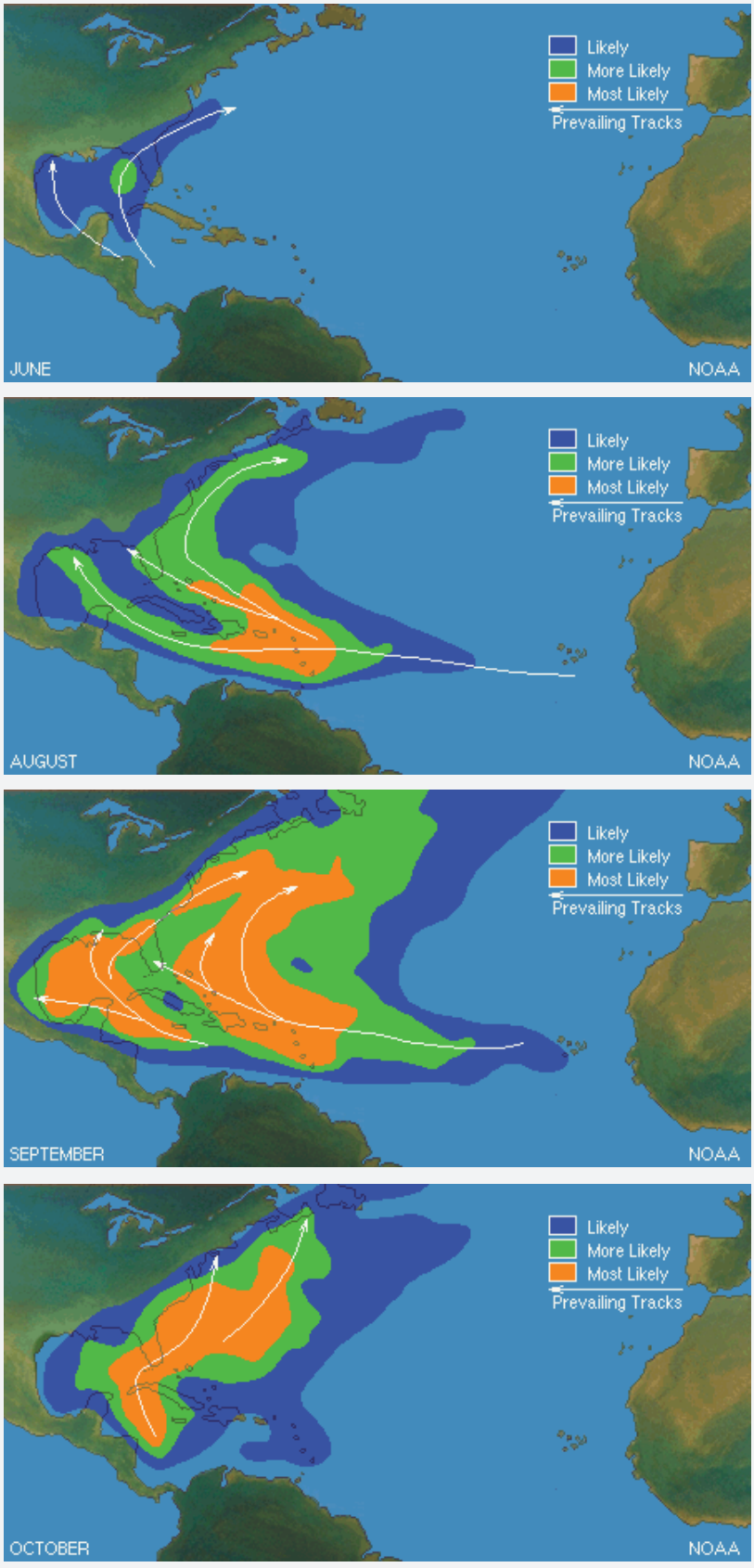


Figure 4.4: Zones of likely origin and track density of storms by month during the hurricane season from August-October. Source: NOAA.

4.3.2. TRENDS

Tropical cyclone activity can be measured with a variety of metrics for intensity, frequency, and duration. Though storm records for the North Atlantic region date as far back as the mid-1800s (see for example Figure 4.5), analysis of trends is generally restricted to the period after 1950 to coincide with the instrumental period beginning in the mid-1950s. This period signifies the start of the use of aircraft reconnaissance. Since the late 1970s satellite imagery has also been used to verify the state of tropical storms.

Most measures of Atlantic hurricane activity show a marked increase since the early 1980s when high-quality satellite data became available (Bell et al. 2012; Bender et al. 2010; Emanuel 2007; Landsea and Franklin 2013). These include measures of intensity, frequency, and duration as well as the number of strongest (category 4 and 5) storms. Figure 4.5 shows the total number of storms passing through the North Atlantic region over the period 1950-2019. The North Atlantic has seen a significant increase in tropical cyclone activity since 1995 with a distinct increase in the number of intense (category 4 and 5) storms (Webster et al. 2005). Though there is a significant increase in recent research suggesting a global warming link with recent changes in hurricane activity, in particular with increases in the number of intense hurricanes, there is still a lack of consensus on the extent of its contribution, since other long term modulators of SST in the north tropical Atlantic such as the Atlantic Multi-decadal Oscillation (AMO) are in a positive (enhancement) phase.

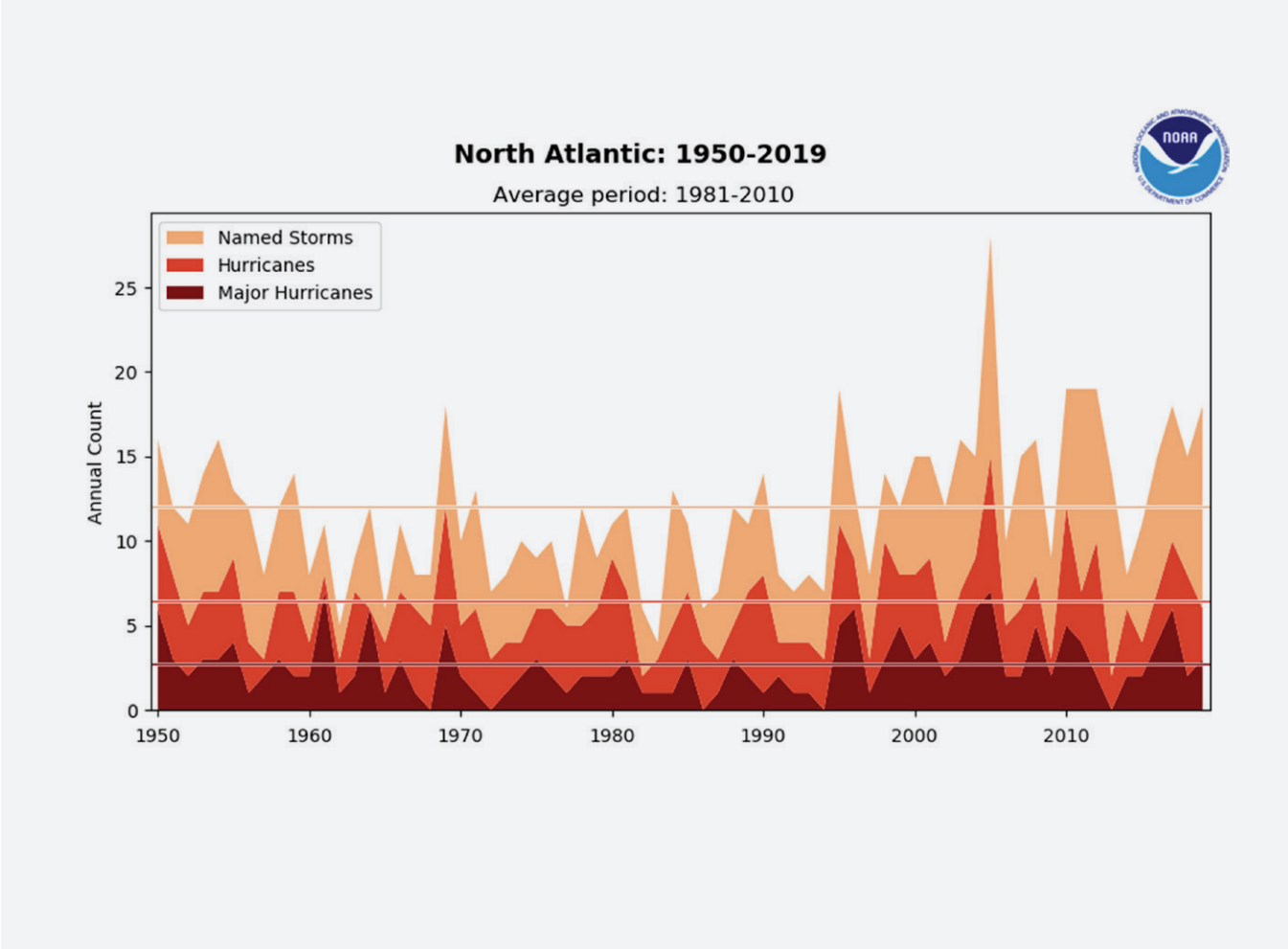


Figure 4.5: The number of named storms, hurricanes and major hurricanes per year passing through the North Atlantic and Gulf of Mexico from 1950-2019. Source: NOAA 2020.

The El Niño-Southern Oscillation phenomenon plays a significant role in modifying hurricane activity in the North Atlantic from year to year i.e. notwithstanding long term trends. El Niño contributes to fewer Atlantic hurricanes while La Niña contributes to more Atlantic hurricanes. El Niño produces upper level westerly wind anomalies and lower level easterly wind anomalies across the tropical Atlantic, which together result in higher vertical wind shear. El Niño and La Niña also influence where the Atlantic hurricanes form. During El Niño events, fewer hurricanes and major hurricanes develop in the deep Tropics from African easterly waves. During La Niña, more hurricanes form in the deep Tropics from African easterly waves, with these systems having a much greater likelihood of becoming major hurricanes and eventually threatening the U.S. and Caribbean.

Figure 4.6 shows all the named storms between 1980 and 2016 that have passed through each of the six rainfall zones previously defined in Chapter 3 and depicted in Figure 3.1. Table 4.4 gives the breakdown by category. All the zones have similar total activity except for Zones 1 and 6. Zone 2 had an even distribution of storms across all categories. Zone 4 had the largest number of category 1 storms while Zone 3 had the highest number of category 4 storms. Zones 4 and 5 have the highest frequency of storms being category 1 storms, with category 4 storms being second. Zone 3, however, has its highest frequency of storms being category 4 storms, with category 1 storms being second. Zone 3 has the most frequent storm tracks of category 4 among all the zones investigated. Zone 6 (Grenada, Guyana and Suriname) shows zero storm activity for the period.

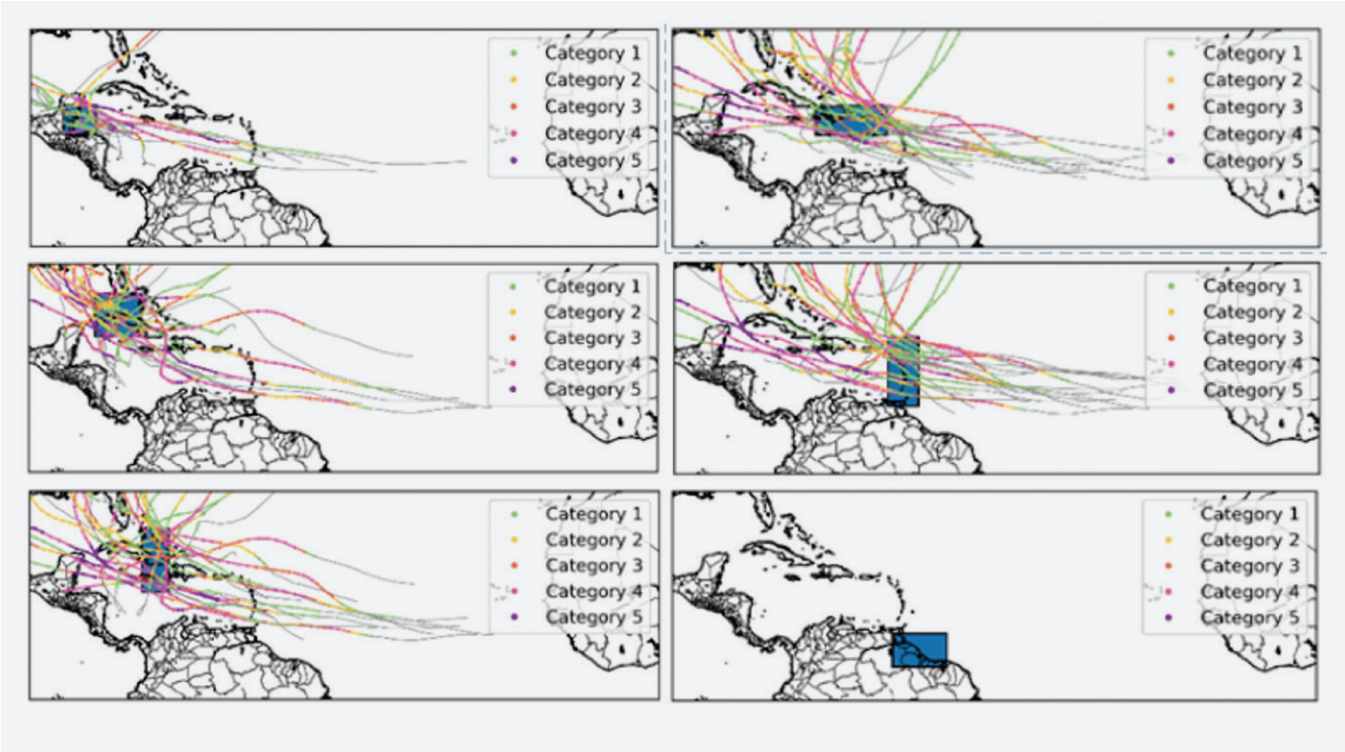


Figure 4.6: Storms and Hurricane tracks for zones 1-6 from 1980-2016. Left panels: Zones1, 2 and 3. Right panels: Zones 4,5 and 6.

Table 4.4: Named storms by decades that have passed within 200 km of the identified country representing each zone. The table also shows the category of the storm from 1980-2016.

ZONES	COUNTRIES IN ZONE	NUMBER OF HURRICANES IMPACTING THE ZONES BY CATEGORY					
		CATEGORY 1	CATEGORY 2	CATEGORY 3	CATEGORY 4	CATEGORY 5	TOTAL
1	Belize	2	3	2	4	3	14
2	-	6	5	4	5	3	23
3	Jamaica and Bahamas	9	2	3	11	0	25
4	Haiti	12	1	4	7	1	25
5	Anguilla, Antigua & Barbuda, Barbados, British Virgin Island, Dominica, Montserrat, St Kitts & Nevis, St Lucia and St Vincent, the Grenadines & Trinidad and Tobago	10	4	3	7	0	24
6	Grenada, Guyana, Suriname	0	0	0	0	0	0
TOTAL		39	15	16	34	7	111

4.4. DROUGHTS & FLOODS

4.4.1. FLOODS

The Caribbean region is prone to flooding given its susceptibility to storms and hurricanes. Burgess et al. (2018) using the EM-DAT disaster database (Guha-Sapir et al. 2015) show that there were at least 370 occurrences of meteorological related disasters between 1960 and 2013 in 22 Caribbean countries (Figure 4.7). Tropical cyclones (264 or 71.4%) and riverine flooding (59 or 15.9%) accounted for the majority of the occurrences. Tropical cyclones also accounted for 94.5% of the damages in the Caribbean countries from meteorological disasters since 1960 according to the EM-DAT database. In a similar study, Acevedo (2014) showed that at least 250 storm and flooding events impacted 12 Caribbean countries between 1970 and 2009, resulting in approximately USD20 billion in damages (2010 dollars).

Figure 4.8 shows a breakdown by country of flooding events listed in the EM-DAT database between 1900 and 2016. There is an uneven distribution across the Caribbean with the islands of the Greater Antilles experiencing the highest number of events. In particular, Haiti is shown to experience the highest number of flooding events among the countries examined.

Burgess et al. (2018) also examined how occurrences of Caribbean meteorological disasters have changed from 1960 to 2013. They find that occurrences have increased from an annual average of 1.7 events for the period prior to 1980 to 10.8 events after 1980 (Figure 4.9). They suggest there may be a link to warming in global surface air temperatures.

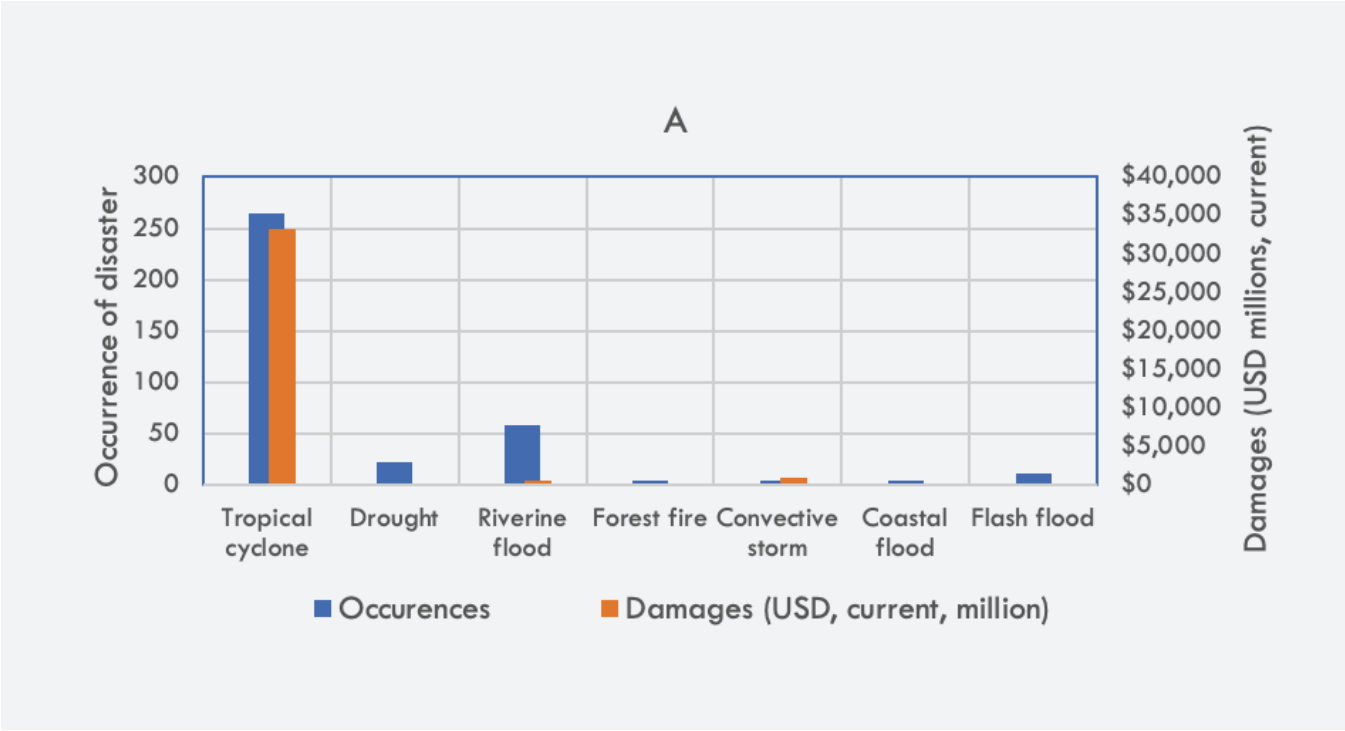


Figure 4.7: Occurrence and damages in the Caribbean (USD millions, current) categorized by disaster type for the period 1960 to 2013. Data Source: EM-DAT Database. Adapted from Burgess et al (2018).

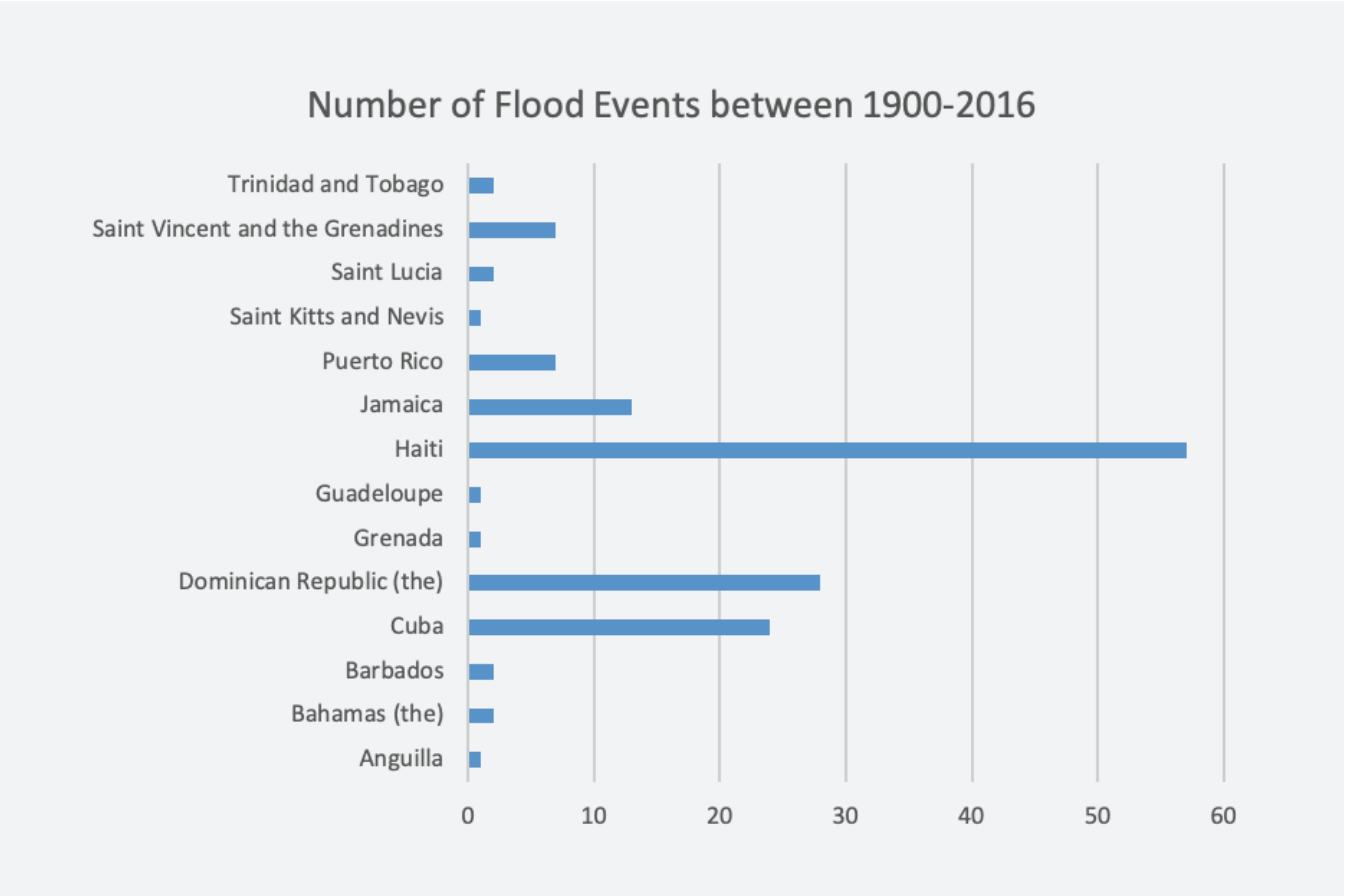


Figure 4.8: Number of flood events across selected Caribbean countries during 1900-2016. Data source: EM-DAT Database.

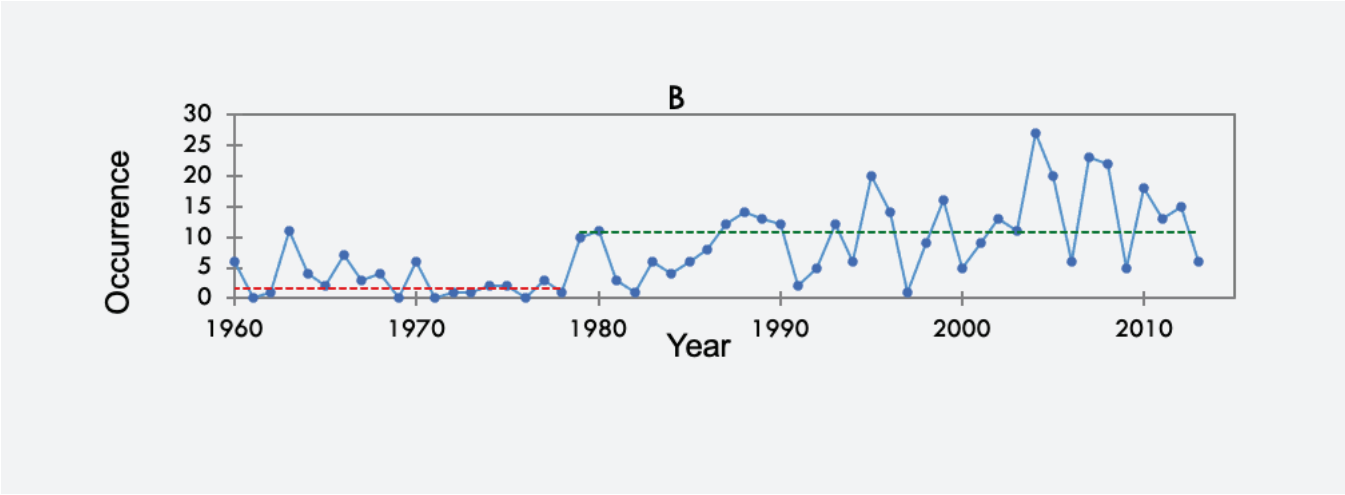


Figure 4.9: Occurrence of Caribbean meteorological disasters from 1960 to 2013. Source Data: EM-DAT database. Adapted from Burgess et al. (2018).

4.4.2. DROUGHT

The Caribbean region faces significant challenges due to drought. However, because of its slow-onset nature, it is often overlooked. During the past decades, the Caribbean has experienced several drought events, with many seemingly linked to years with El Nino events. These include events in 1957, 1968, 1976-77, 1986-1987, 1991, 1994, 1997-1998, 2009-2010, and again in 2013-2016. Numerous drought indices have been used to characterize the stage of drought or the severity of a drought episode. The following discussion draws on the conclusions of studies which use respectively the Standardized Precipitation Index (SPI) and the self-calibrating Palmer Drought Severity Index (scPDSI). In the first study (Walters 2018), SPIs are used to examine the spatial distribution of drought occurrence across the Caribbean between 1951 and 2000. In the second set of studies (Herrera and Ault 2017; and Herrera et al. 2018), scPDSI is used to focus on severe drought events between 1950 and 2016.

Walters (2018) uses the Standardized Precipitation Index (SPI) to characterize the rarity of extreme and moderate drought events in different parts of the Caribbean on a variety of time scales. SPIs were derived from time series of rainfall representing four zones in the Caribbean, which overlap with the six rainfall zones examined in Chapter 3. The four zones capture drought variation in the far north Caribbean (western Cuba and the Bahamas), a Jamaica region (eastern Cuba, Jamaica, Turks and Caicos and the western half of Hispaniola), the eastern Caribbean (Puerto Rico and the Lesser Antilles) and the southern Caribbean (Trinidad and Tobago and Guyana).

Major conclusions from the Walters (2018) study are:

- The far north Caribbean seems the least prone to extreme drought.
- There are likely different features modulating the occurrence of drought, depending on the region of the Caribbean being considered, as the SPIs across the four zones do not always behave in phase. Of the four regions, the eastern and southern Caribbean exhibit the highest degree of correlation.
- The Jamaica region experienced extreme droughts in the mid-1960s, mid-1970s, and again in the early 1990s. The far north Caribbean experienced extreme drought conditions in the 1950s, 1963 and 1972, and moderate drought after 1975. The eastern and south Caribbean experienced extreme drought conditions in the 1960s and 1970s, with the eastern Caribbean experiencing these conditions again in the mid-1990s.
- After 1983, the south Caribbean and the Jamaica region tend to have predominantly negative SPIs suggesting a shift toward drier conditions. This is also true for the eastern Caribbean after 1990.
- Though region wide droughts (i.e. when all SPIs for all zones are simultaneously negative) are not common over the period analysed (up to 2000), the mid to late 1970s stand out.

- Timescales of 2-3 years and 9-13 years characterise drought occurrence across most of the Caribbean zones. A 3-6 year timescale also occurs in the eastern Caribbean, and a 5-6 year signal occurs in the south Caribbean.
- All zones generally seem to exhibit correlations with tropical and equatorial Pacific SSTs, suggesting a potential link to El Nino events. However, whereas the El Nino event seems to bring dry conditions across most of the Caribbean, it seems to enhance wet conditions in the far north Caribbean. The Caribbean Sea is correlated with the Jamaica region, the far north Caribbean, and the eastern Caribbean, but not the south Caribbean.

In two other recent studies, Herrea and Ault (2017) and Herrera et al. (2018) use scPDSI to show that since 1950, the Caribbean has experienced a general drying trend (Figure 4.10). They however point out that the trend is not homogeneous across the region, with, in particular, the far north Caribbean seeing a tendency to be wetter. Like Walters (2018), they also confirm the tropical Pacific and tropical north Atlantic as significant modulators of drought variability in the region.

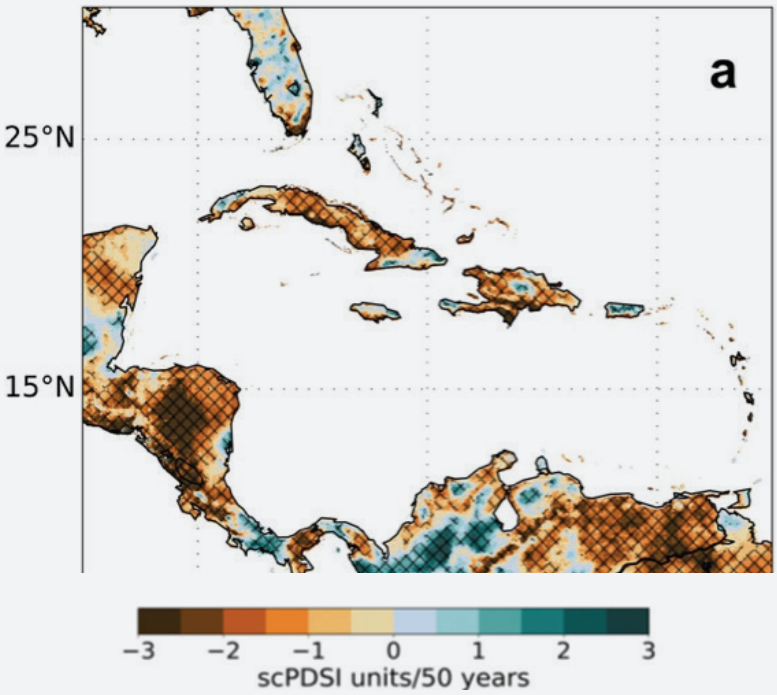


Figure 4.10: Linear trends showing the change of the scPDSI during the 1950–2016 interval Brown colours represent drying trend and cyan colours a wetting trend. In (a) and (b), the hatching means a significant trend ($p < 0.05$) at the 95% level. From Herrera and Ault (2017).

The studies also show that the region as a whole has experienced severe droughts in 1974–77, 1997/98, 2009/10, and 2013–16 (Figure 4.11). Of the four periods, the 2013-2016 drought was the most severe experienced by the Caribbean, as virtually the entire region experienced a Pan-Caribbean drought. During the three-year period, drought conditions in 2014 ranked as the most severe since 1950 due to the greater area covered. However, 2015 ranked as the driest year during the 2013–16 droughts and had the highest potential evapotranspiration (PET) and temperatures which may have added to the severity of the drought. Though the 2013-2016 Caribbean drought can be associated with the 2015/16 El Nino event, Herrera et al (2018) also suggest that global warming likely contributed to ~15–17% of drought severity for the 2013-2016 event, by increasing evapotranspiration rates and accounting for ~7% of land area under drought. That is, their results indicate that anthropogenic warming is likely already increasing drought risk in the Caribbean.

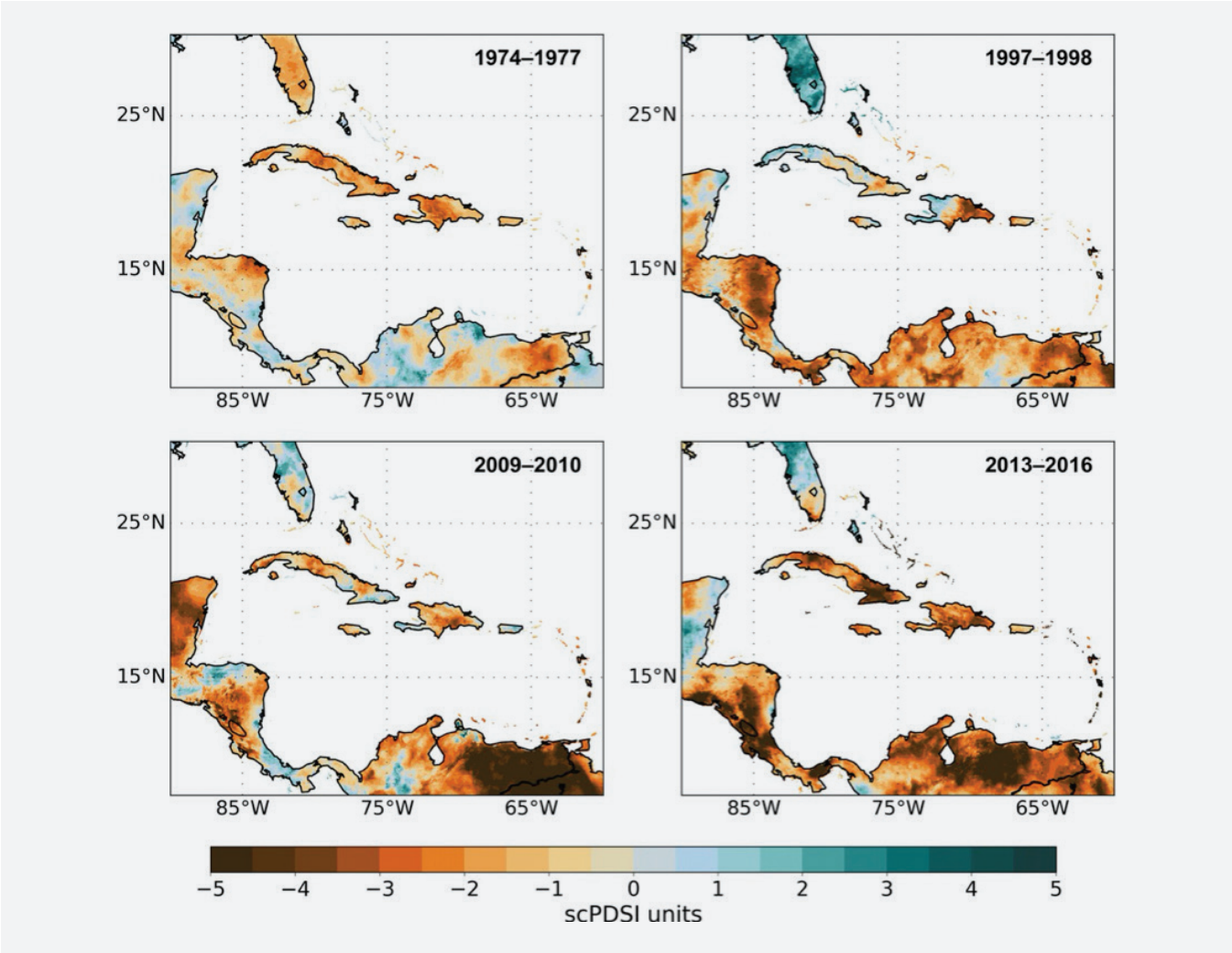


Figure 4.11: Major droughts in the Caribbean between 1950 and 2016 of at least one year in duration. From Herrera and Ault (2017).



6. CLIMATE EXTREMES AND EARLY WARNING

6.1. BACKGROUND – CLIMATE EXTREMES AND DISASTERS IN A CHANGING CLIMATE

As previously noted in Chapter 3, rainfall in the Caribbean islands and Belize is generally characterised by a wet and a dry season in each year, peaking in September-October and February-March, respectively. At least 70-80% of the rainfall occurs, on average, during the wet season which also largely coincides with the Atlantic Hurricane Season (see Section 4.2). Regional variation is seen, for example, in the coastal Guianas which has two wet and two dry seasons per year but no tropical cyclones, and the ABC Islands (Aruba, Bonaire and Curaçao) which feature a much drier climate, only having substantial rainfall from October through to January. The entire region (with the exception of northern-most portions of The Bahamas) lies within the tropics. Consequently, temperatures are relatively constant throughout the year, although an annual cycle in temperature remains discernible (Section 3.3.). Both daytime and night-time tend to be coolest around January, warm up from around March/April, and peak in August/September.

There is much variability in both the wet and dry season as it relates to the onset, duration, amount, frequency and intensity of rainfall. It is not unusual to experience significant dry spells during the wet season or very wet spells in the dry season (Trotman 1994). When such extreme climate events occur, they can impact heavily on climate sensitive sectors e.g. agriculture and food security, water resources, disaster management, health, energy and tourism (see Chapter 7). It is therefore important to try and understand what drives climate variability in the Caribbean.

A growing body of research is increasingly supporting our understanding of the nature, the drivers and temporal changes of Caribbean climate variability and extremes. For example, rainfall extremes (including droughts) are often a result of the occurrence and phase of global climatic features such as the El Niño Southern Oscillation (ENSO). (This is explored in section 6.3.) In terms of excessive heat, and in particular the occurrence of heat waves, preliminary results also suggest that the ENSO and deviations of SST to the seasonal norm are two of the main large-scale and predictable drivers. This chapter will elaborate on how knowledge of some of these drivers can facilitate the long-range prediction of some climate extremes (i.e. from weeks to years), and what efforts are underway in the region to monitor these extremes as well as to predict the likeliness of their occurrence or their impact. Tropical cyclones are also arguably one of the most costly natural hazards in the Caribbean. The chapter will examine briefly the extremely active 2017 Atlantic Hurricane Season.

The need to understand and forecast Caribbean climate extremes will only grow under projected climate change. Figure 6.1 uses changes in temperature to illustrate the potential impact on climate extremes.

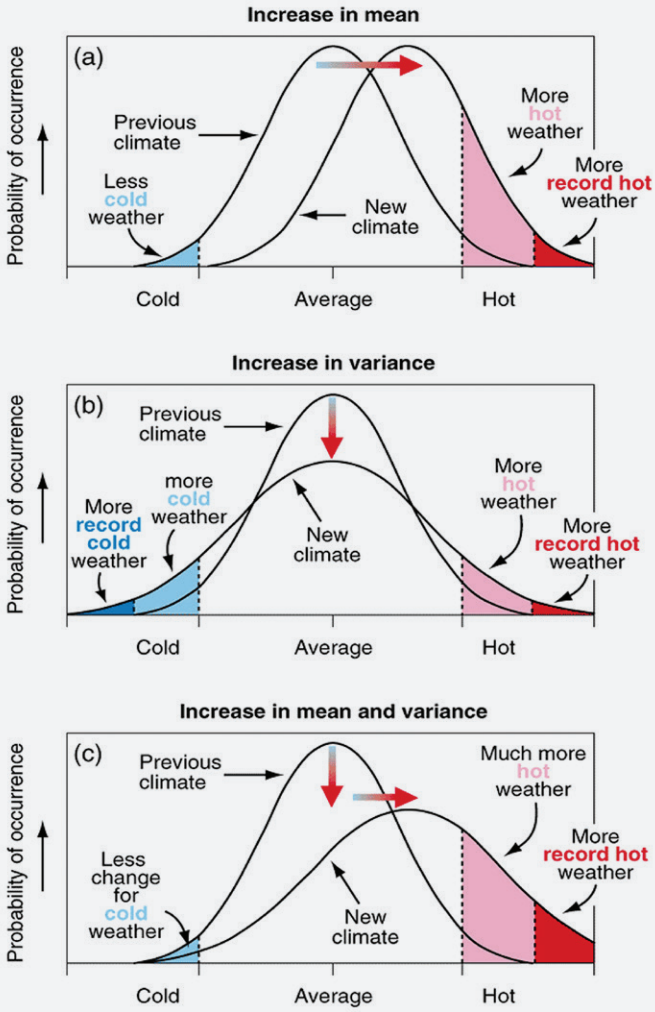


Figure 6.1: Schematic showing the effect on extreme temperatures when (a) the mean temperature increases, (b) the variance increases, and (c) when both the mean and variance increase for a normal distribution of temperature. Source: IPCC (2001).

In a warming world, the atmosphere (and the oceans) is expected to warm as a whole over time, and day-to-day temperature variations - i.e. variability related to weather patterns - are expected to become larger[9]. Figure 6.1a shows how the frequency (or probability) of a given day recording a given temperature changes when the average temperature shifts to a higher value. As seen, very cold days become less frequent and very hot days become more frequent. Figure 6.1b shows what happens to the frequency of temperatures if only the variability (expressed by the variance) increases. In such a scenario, the frequency of having near-average temperatures decreases, and the frequency of extremely low and extremely high temperatures increases. Figure 6.1c shows what happens when both the average and the variability increases (as is most likely to happen in the future). In that case, the frequency of very cold days would decrease, but the frequency of very hot days would increase. The combined shift of average temperature rise and an increase of variability appears to already be observed in the Caribbean (see Section 3.3.4), with a continuation of the trend projected to continue under global warming (Section 5.2.3).

Although there is less certainty about the projections of future rainfall trends, chapter 5 suggests decreasing rainfall totals, particularly for the Lesser Antilles toward the end of the current century. This suggests an increasing drought risk (Cooper and Bowen 2001; Taylor et al. 2018).

9 In statistical terms, day-by-day variations often follow a so-called normal distribution. This means that, if all recorded temperatures were ranked from lowest to highest, the average of all those temperatures would be also be the most frequently observed and a temperature of a number of degrees cooler or higher than that average would each occur equally frequently, but both less frequently than the average. The more extreme the temperature, the less frequently it occurs.

6.2. MONITORING AND PREDICTION

One strategy which has been incrementally implemented in the Caribbean over the past 20 years to improve our preparedness to climate extremes is the development and operation of climate early warning systems. Two major components of climate early warning systems are monitoring and prediction. The former is enabled by a network of weather observing stations that track essential climate variables such as rainfall and temperatures. Skilful climate prediction is then made possible through the development and operationalisation of statistical or physical/dynamical prediction models that depend on a good understanding of the drivers of variability in climate extremes. This section will elaborate on ongoing operational climate monitoring and prediction initiatives in the Caribbean, which are led out of the Caribbean Institute for Meteorology and Hydrology (CIMH) - a World Meteorological Organization designated Regional Climate Centre (RCC) for the Caribbean.

6.2.1. CLIMATE MONITORING IN THE CARIBBEAN

Meteorological drought (i.e. rainfall deficits accumulating over periods of weeks to years) conditions can be easily tracked since rainfall is the most widely recorded variable in climate records in the Caribbean. Meteorological drought is a slow-onset, impactful hazard which translates in time to agricultural, hydrological and socio-economic drought. Partly in response to the technological advances but also coinciding with a perceived amplification of impacts of climate variability, a strong regional focus on drought monitoring and forecasting emerged in the Caribbean leading to the establishment of the Caribbean Drought and Precipitation Monitoring Network (CDPMN). CIMH launched the CDPMN in January 2009 (Trotman et al. 2009; CIMH and FAO 2016) as a body that would seek to operationally monitor drought (and excessive precipitation), as well as provide prognostic drought information. With growing recognition of the increasing impact of heat in the region, CIMH also started operational monitoring of temperature in 2014.

6.2.2. THE CARIBBEAN CLIMATE OUTLOOK FORUM AND ITS SEASONAL CLIMATE OUTLOOKS

As a consequence of the significant impacts suffered by many, mostly tropical regions from the 1997-1998 El Niño event and the lack of effective early warning and preparedness, regional climate outlook fora were established under the auspices of the World Meteorological Organization (WMO). The Caribbean Climate Outlook Forum (CariCOF) was first held in 1998 with the task being to prepare three-month precipitation outlooks for the region indicating the probability of below-, near- or above-normal rainfall. Since 2000, CIMH has undertaken the preparation of the outlooks, with input from a wider group of regional meteorologists and climatologists since 2012. Since 2012, the CariCOF fora have been preceded by a training workshop on seasonal forecasting for National Meteorological and Hydrological Services (NMHSs) and CIMH staff. Since 2014, two CariCOFs have been held per year - just prior to the wet and the dry seasons. At the first staging in 2019, 22 countries and dependencies of France, the United Kingdom and the United States in the Caribbean participated in CariCOF's monthly seasonal forecasting activities.

The CariCOF climate outlooks examine the relative climate risk on sub-seasonal to seasonal timescales. The seasonal forecasts look at how certain weather conditions, including extreme events, become more likely or less likely during a given period of interest of typically one to six months. They, therefore, are not aimed at predicting the exact timing of a pending hazard. Each month the CIMH and the NMHSs participating in CariCOF prepare regional seasonal climate outlooks of precipitation (since 2012) and temperature (since 2013) at 0- and 3-month lead times, along with a short- to mid-term drought outlook (since 2014) (see Section 6.3), and wet days and wet spells outlooks (since 2015). The products are compiled into a newsletter that is disseminated monthly with updated information. The newsletter and outlook products can be accessed on the WMO Caribbean RCC's web page (http://rcc.cimh.edu.bb).

It is anticipated that the CariCOF's next generation of climate outlook products will be more user-driven and co-designed (such as the drought outlooks), as well as more sector-targeted, tailored and co-delivered (see Section 6.6). The next generation of generic outlook products will also aim to address other extremes such as flash flood potential (see Section 6.4) and excessive heat alerting (see Section 6.5). Coincidentally, through the sectoral Early-Warning Information Systems Across Climate Timescales (EWISACTs) programme (see Chapter 8), sector-specific climate monitoring and forecasting information products are already being derived through translation and repackaging of the generic CariCOF products which are being co-designed, co-developed and co-delivered

with sectoral partners, particularly in the agriculture, health and tourism sectors. This move to user-driven and to sectorally tailored climate early-warning information will contribute to building the Caribbean region's climate capacity and, by extension, climate risk resilience. Chapter 8 expands on the EWISACTs programme.

The following sections describe specific regional activities and developments with respect to monitoring and forecasting dry (Section 6.3), wet (Section 6.4) and hot (Section 6.5) extremes.

6.3. DROUGHT AND DRY SPELLS

6.3.1. CARIBBEAN VULNERABILITY TO DROUGHT

As of 2013, seven of the world's top 36 water-stressed countries (including e.g. Antigua and Barbuda, Barbados and St. Kitts and Nevis) are from the Caribbean (WRI 2013) and have less than 1000 m^3 freshwater resources per capita (CIMH and FAO 2016). Even within non-water-scarce countries, local communities and cities may be chronically water-scarce, especially under water-stressed conditions. Further stress is likely with the expansion of the tourism industry, population growth, urbanization, increasing societal affluence, ineffective water management practices and strategies, and declining water quality due to anthropogenic activities and climatic factors. It should be noted that, more so than rainfall itself, water availability in the islands varies seasonally as evaporation rates tend to be higher even as rainfall totals are lower in the dry season. The per capita usage of water by the tourism industry is higher than for the domestic population. Tourist arrivals in the Caribbean tend to concentrate around boreal winter, coinciding with the region's dry season. This situation seasonally increases the demand for water and, therefore, water stress. Consequently, drought early warning in the Caribbean should at least focus on the seasonal to interannual timescale.

6.3.2. DRIVERS OF DROUGHT AND DRYNESS IN THE CARIBBEAN

The activity of deep atmospheric convection - which fuels rain and thunderstorms - is low around February and March, and dry spells i.e. a large number of consecutive dry days, are commonplace during the dry season. The oceans also tend to annually cool down until reaching their lowest temperatures in February (Section 3.3.1), resulting in less evaporation of ocean water and drier air. A drier atmosphere over land takes up available soil moisture in an accelerated way compared to moist air, resulting in a tendency for evaporation rates to increase in the dry season. The result is that water availability tends to decrease during the dry season because of reduced rainfall and increased evaporation. During the wet season in much of the Greater Antilles and parts of Belize, drier spells called "mid-summer drought" are common around July-August (Section 3.2.1), which also tend to temporarily increase dryness there.

The dominant driver of regional drought in the Caribbean is El Niño, which initially tends to stabilize the atmosphere and later on increase vertical wind shear, both of which are inhibitive for deep convection. Anomalously low rainfall amounts are particularly common when sea surface temperatures are unusually warm in the eastern tropical Pacific and cool in the Tropical North Atlantic (Enfield and Alfaro 1999; Giannini et al. 2000; Giannini et al. 2001; Taylor et al. 2002; Stephenson et al. 2008; Taylor et al. 2011). Furthermore, when the North Atlantic Oscillation is in a positive mode, i.e. the Azores-Bermuda High Pressure system is larger and stronger than average (Charlery et al. 2006; Gamble et al. 2007), the atmosphere is more stable, thereby inhibiting deep convection. At the same time, stronger trade winds are blowing over the Tropical North Atlantic resulting in a cooling effect on the ocean's surface, with less evaporation taking place in ensuing months. If the winds are carrying Saharan dust across the Atlantic, rainfall tends to be further reduced. Other drivers of drought include the strength of the Caribbean low level jet on seasonal timescales (Cook and Vizy 2010; Taylor et al. 2012) and the Atlantic Multi-decadal Oscillation on an inter-decadal time scale (Stephenson et al. 2014).

6.3.3. DROUGHT MONITORING

The CDPMN drought monitoring system which was launched in 2009 immediately showed its value during one

of the worst regional droughts which occurred in 2009-2010, by providing CARICOM governments with situation analyses and advice from January 2010 (CIMH and FAO 2016). The principal monitoring tool relied on a drought index called the Standardized Precipitation Index (SPI) (McKee et al. 1993), as recommended by WMO (Hayes et al. 2011) and Deciles (Gibbs and Maher 1967). SPI monitoring maps were coupled with the three-monthly Caribbean Precipitation Outlook using an SPI calculator[10] and used to inform and advise on how the drought conditions were expected to evolve during 2010. Since then and to present, the SPI and decile monitoring maps are updated each month by the CDPMN and offer depictions of the severity of ongoing meteorological drought.

The CDPMN has enhanced their products by providing monitoring maps covering a range of different timescales. The SPI and decile maps cover five timescales: ranging from 1 month, 3 months, 6 months and 12 months, respectively (CIMH and FAO 2016; Farrell et al. 2010; Trotman et al. 2009; Trotman et al. 2017), to more recently 24 months. Given that agricultural drought results from a lack in soil moisture, which can fluctuate greatly within 1 to 3 months, a 3-month SPI is relevant. By contrast, very large water reservoirs (including aquifers) are affected by long-term rainfall deficits that last beyond six months, making a 12-month SPI more relevant. Figure 6.2 depicts the six-month SPI (also referred to as SPI-6) values calculated from rainfall deficits and excesses from October 2009 to March 2010 across the Caribbean, at the time drought impacts peaked during the 2009-2010 event (Farrell et al. 2010; CIMH and FAO 2016; Trotman et al. 2017). With an SPI value of -2 corresponding to a return period of such rainfall deficits of 40 to 50 years, it is to be noted that much of the Lesser Antilles was subject to exceptional drought resulting in widespread and severe drought impacts (Farrell et al. 2010).

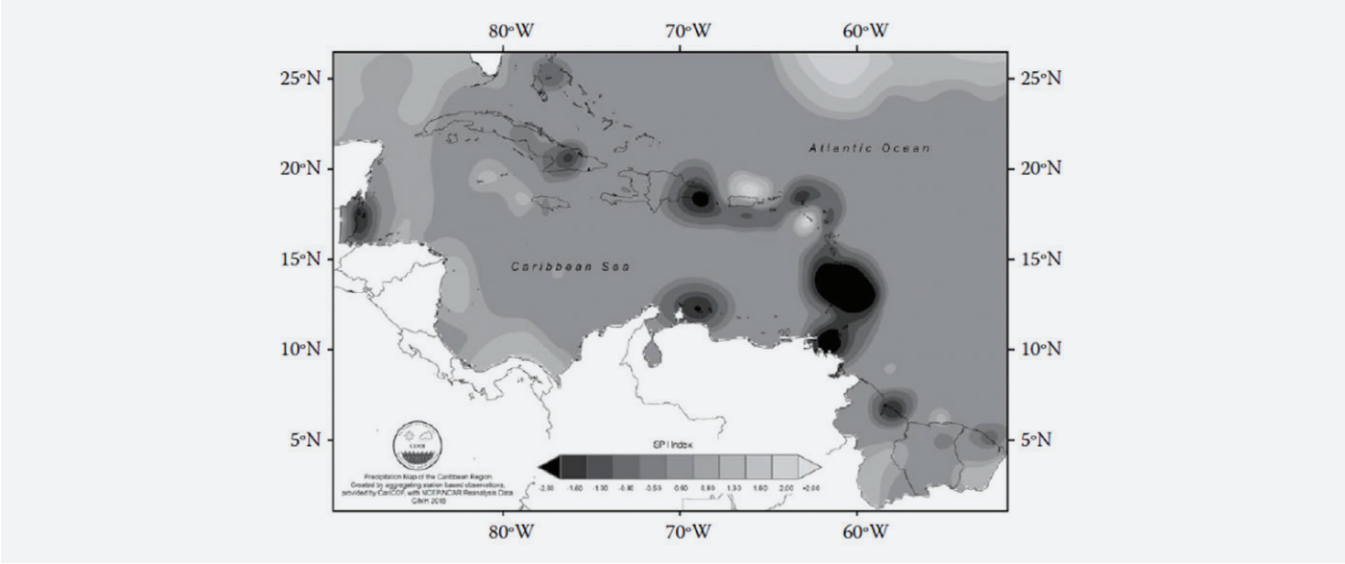


Figure 6.2: A 6-month SPI map (October 2009 to March 2010), where negative values point to increasingly severe dryness. Source: CDPMN

As more temperature records have become available through climate data sharing efforts among participating meteorological services to the CariCOF, efforts are underway to develop and operationalise a drought index that not only includes rainfall deficits and surpluses, but also the effect of anomalous temperatures on moisture loss through evapotranspiration. As such, the CDPMN has released its Standardized Precipitation-Evapotranspiration Index (SPEI) monitoring products on an experimental basis.

6.3.4. DROUGHT FORECASTING AND VERIFICATION

Led by CIMH, the CDPMN and CariCOF have developed drought prediction products on an operational basis, including the CariCOF drought outlooks[11]. Central to the drought outlooks are drought alert maps, which detail the expected impact level and suggest a corresponding preparedness action level. A brief overview of the methods

10 The SPI calculator can be acquired from the US National Drought Mitigation Center (NDMC).

11 The CariCOF drought outlooks can be downloaded from http://rcc.cimh.edu.bb/drought-outlook/ .



utilised to produce such maps is given in CIMH and FAO (2016). Different drought alert levels are generated depending on the forecasted percentage probability that the SPI over six or twelve months exceeds a value beyond which drought is expected to be impactful. Because more rainfall occurs during the wet season than in the dry season, drought impacts are expected to become significant beyond a higher threshold in the former season. SPI threshold values of -0.8 and -1.3 were adopted for the dry and wet seasons respectively, corresponding to CDPMN's drought severity scale of at least moderately dry and severely dry, respectively. Each month, two drought alert maps are produced – an SPI-6 based map for a moving 6-month period ending three months down in time, and an SPI-12 based map with a 12-month period of interest ending either in November for maps generated during the wet season or in May for maps done in the dry season.

Alerts of no drought concern, drought watch, drought warning and drought emergency speak to anticipated risk levels by the end of a forecast period. The drought outlooks therefore form actionable information for decision-support systems for the different sectors (Trotman et al. 2017). If action is to be premised on the outlooks, then the drought prediction system must demonstrate some skill. A recent verification exercise suggests that the forecasting system is able to identify at least 85% of impactful long-term droughts as far as six months in advance (Trotman et al. 2017). The same preliminary investigations found the forecast was able to predict the recent region-wide drought event of 2014-2016 (see Box 6.1) to be approximately as severe as the 2009-2010 drought. The confidence of the system increases when the severity of the expected drought increases, because risk increases with the probability and the severity of a pending impact. Since there is increasing confidence in the forecasts when the level of drought risk increases, the validation exercise therefore shows that there is merit in providing drought prediction information in terms of alert levels.

6.3.5. DRY SPELLS

The Caribbean's vulnerability due to dry spells is most obvious for rain-fed agricultural crop production. A lengthy dry spell during some significant stages of a crop's life cycle can severely limit its productivity due to water stress. On the other hand, dry periods can initiate flowering and increase productivity in some crops, as long as they are not extensive, or, as in the case of sugar cane, enhance sugar concentration. The risk of recurrent dry spells can be exacerbated by heatwaves (see Section 6.5) which increase evapotranspiration rates. Knowing a crop's dry spell tolerance thresholds – in terms of duration and frequency – can provide useful information on the risk of failure or low productivity of a crop. Depending on the type of soil, crops can likely be productive when facing up to 7 to 15 consecutive days without significant rainfall, by utilising available water retained in the matrix of the soil. A number of these spells across those sensitive phases of the growing season could result in unwelcomed reductions in yield. In fact, for even high water-retaining clay soils, a dry spell of more than 15 days could prove debilitating at least at any time within the growing season.

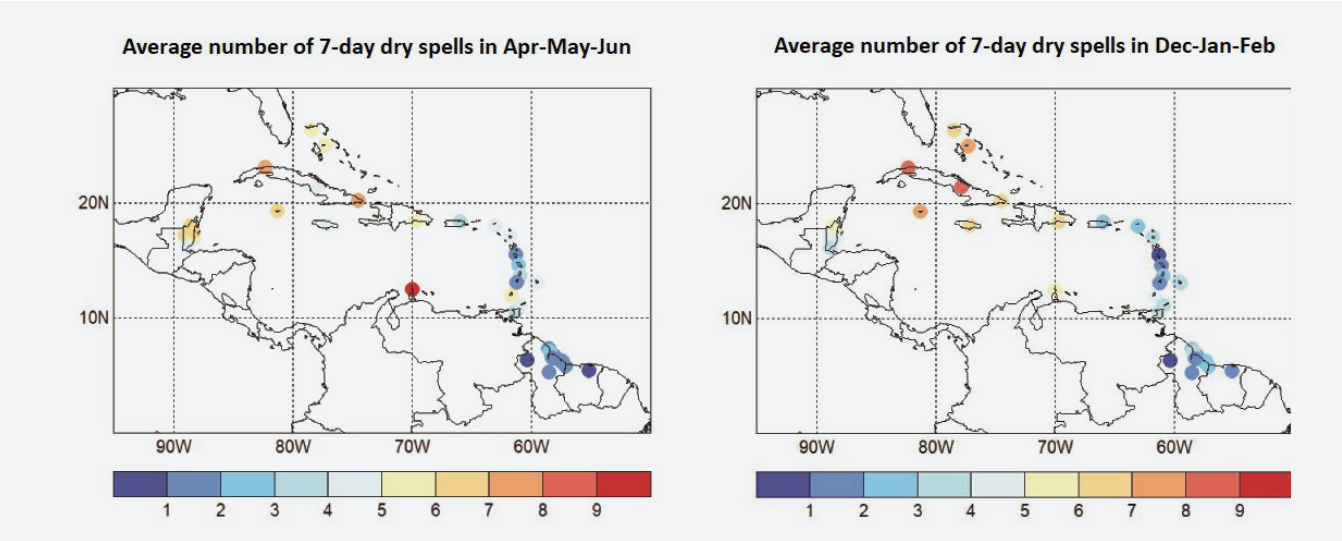
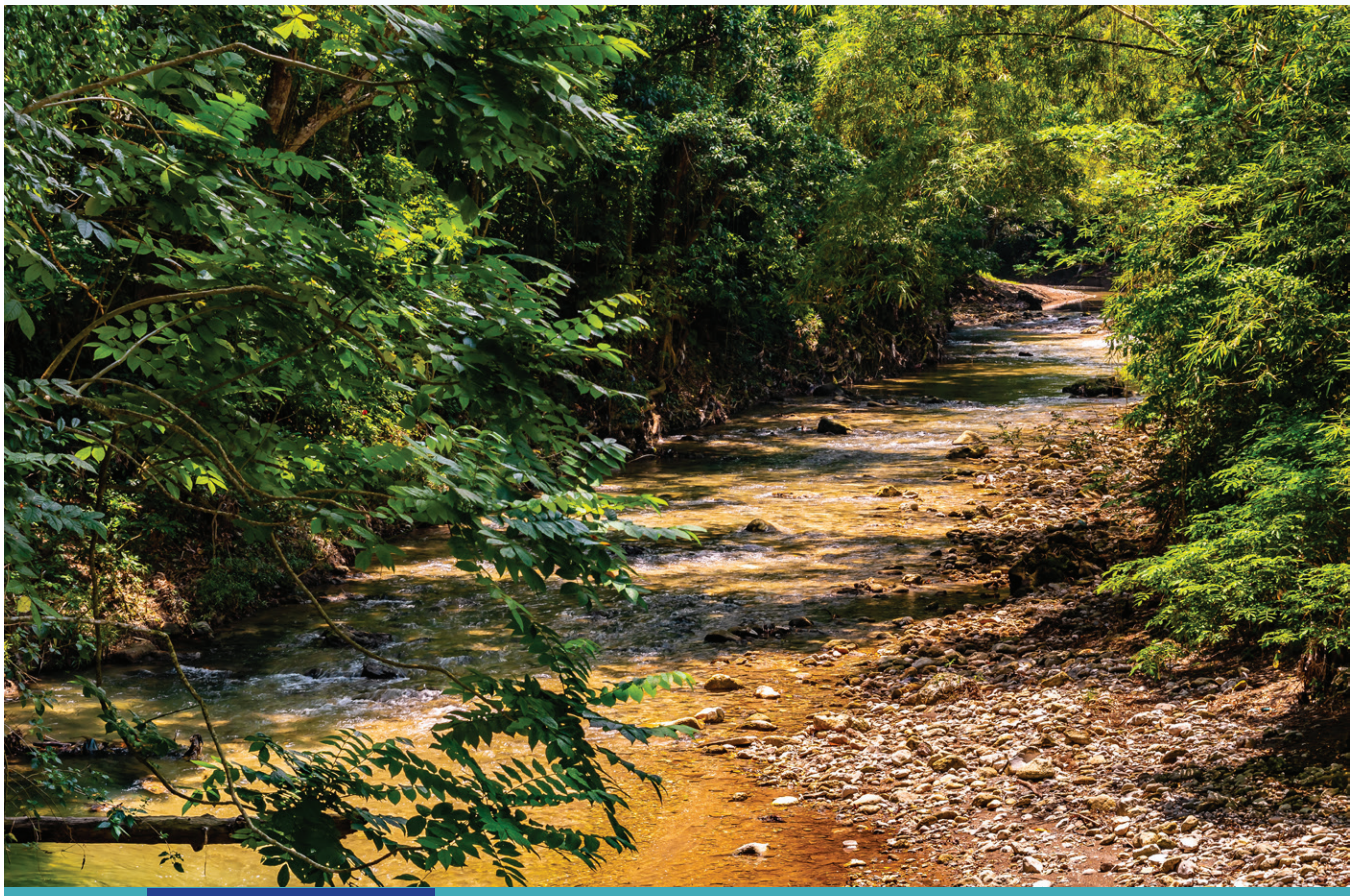


Figure 6.3: Map shows the average number of 7-day dry spell that occur during April May June (left) and December Jan February (right). The climatological period spans 1985 to 2014. Source: CIMH

Given the risk of dry spells to rain-fed agriculture in the Caribbean and a fair understanding of what causes them, there has been a push to develop an early warning system for regional dry spells. It is premised on the notion that the typical growing season of many horticultural crops is about 3 to 4 months, and a crop would find it difficult to produce high yields with either three (averaging one per month) or more 7-day dry spells or one or more 15-day dry spells within the three-month period. Caribbean rainfall records (see Figure 6.3) show many areas in the Greater Antilles where, even during the wet season, such dry spells are frequent and therefore pose a high risk for many plant species. Conversely, other locations such as northern Guyana and Dominica are relatively low risk areas for dry spells, even during the dry season. The CariCOF dry spells outlooks provide forecast maps of the probability of having at least (i) three 7-day dry spells and (ii) one 15-day dry spell in a given three month period[12]. The maximum number of 7- and 15-day dry spells within the same upcoming three-month period is also forecast. The added value of seasonal forecasts of dry spell frequency is in determining whether a particular planting season may pose too much water stress in a given year, whereas it may not in most other years.



12 For now, with the products still being in experimental stage, the same 0-month lead period is employed as for the precipitation outlooks and the wet days and wet spells outlooks.



INFORMATION BOX 6.1

THE 2014-2016 CARIBBEAN DROUGHT

Caribbean droughts within the last decades have all coincided with El Nino years, including the 2014-2016 event (see Section 4.4.2). By the end of 2014, drought impacts were observed in countries like Antigua and Jamaica. Anguilla, Antigua and Barbuda and Sint Maarten recorded below-normal rainfall from January to March 2015. Dryness during early 2015 was likely amplified by strong dust transport across the Atlantic occurred. There was rapid strengthening of the El Niño by May 2015 and by the end of the end of 2015, it was one of the two strongest El Niño events since 1950 [NOAA 2018]. By July 2015, the significant reduction in rainfall across the region resulted in dry conditions being recorded in Aruba, Barbados, Dominica, Dominican Republic, Guadeloupe, Jamaica, St. Kitts, and St. Lucia. Wet season rains brought temporary drought relief in late August/September 2015 at some locations. By late November, drought conditions were re-established, with record-low October to December rainfall being observed at several locations. 2015 became the driest year on record at many locations, including in Antigua, Tobago, Barbados, Jamaica and St Lucia (Stephenson et al. 2016), or second driest since 1973 in parts of St. Lucia and third driest since 1881 at one location in Jamaica and since 1951 in St. Croix. By the end of the dry season in 2016 much of the eastern Caribbean observed a deficit of between 20% and 60% of their cumulative rainfall for the "Water Year" June 2015 to May 2016.

The 2014-2016 drought was deemed the worst on record for Antigua with its total duration of meteorological drought being the second longest since 1928 with, by far, the greatest rainfall deficit. Trotman et al. (2017) provides an overview of reported impacts of the 2014-2016 regional drought on a diversity of socio-economic sectors, which varied by country. Throughout the Caribbean, there were many reports of reduced agricultural crop production, loss of livestock, increase in bushfires, reports of empty water reservoirs and ensuing water restrictions, as well as, reports of reduced hydropower generation, hotel cancellations and, in one nation a temporary stop in provision of water to cruise ships.

6.4. EXCESSIVE RAINFALL, EXTREME WET SPELLS AND FLASH FLOODS

The Caribbean wet season is accompanied by copious rainfall attributable to weather disturbances and weather systems (including tropical cyclones) that produce intense showers. Wet spells with intense showers occurring in a rapid succession (i.e. over a small number of consecutive days) characterise wet seasons in the Caribbean. Though the recurring heavy rains can be beneficial for replenishing major water reservoirs, extremely intense showers often lead to flash flooding. Flash floods occur when the rainfall accumulation rate exceeds the rate of soil infiltration and surface drainage.

The impacts from flash floods can range from water damage to infrastructure and property to crop losses to contamination of water supplies by waste, toxic material or biological contaminants. Flash floods can also increase landslide risk, for instance by destabilising slopes and through erosion. Two recent notable examples of flash floods impacting the region are the 2015 floods in Dominica from Tropical Storm Erika (see Box 6.2) and the 2013 'Christmas floods' between 24 and 26 December in Dominica, St. Lucia and St. Vincent and the Grenadines.

Flash flood risk management can benefit from early warning information on wet spells . Some of the hazards associated with flash floods can be partly or largely mitigated by appropriate land management practices and technologically simple solutions such as ensuring drainage channels are cleared of silt and debris. Others can be mitigated to a large extent by improving preparedness through education on the hazards and risks associated with them, as well as by the provision and uptake of early warning information. The remainder of this section focuses on (flash) flooding triggered by wet spells in the Caribbean. Specifically, the chapter addresses how early warning information on wet spells could be designed as a step toward addressing flash flood risk.

6.4.1. FLASH FLOOD POTENTIAL

In addition to climate data, flash flood risk prediction models incorporate non-climate data such as geology, exposure of the population and assets, and the appropriateness of infrastructure. This restricts operationalizing the forecasting of flash flood risk due to limited non-climatic data for developing, calibrating and validating the models throughout much of the region. A simpler alterative approach is to focus on climate alone as a trigger for flash flood risk and to estimate the flood potential. Flash flood potential specifically estimates the potential number of flash floods to be expected. Forecasts of flood potential can be later integrated with risk assessments and risk mitigation and preparedness plans in order to drive evidence-based decision-making.

6.4.2. EXTREME WET SPELLS

To provide early warning for flash flood potential at seasonal timescales, seasonal forecasts of wet spell frequency require threshold rainfall intensities that correlate well with flash flood occurrence. The threshold rainfall rate depends on exposure, geology, soil water infiltration capacity and infrastructure – in particular drainage – and is location-specific. There is limited facility to determine such thresholds for each individual location at risk of flash flooding, and such an effort would demand an increase in the amount and density of rainfall stations at each location at risk. To overcome this challenge a more time efficient, proxy-based, statistical solution is being pursued, the outcome of which would allow inference of implications due to flooding rather than accurately quantifying the risk. For instance, if the assumption is that a rainfall threshold to be exceeded to produce a flash flood is a function of its local climate (i.e. very wet in a given season, with frequent episodes of extreme rainfall), then a soft threshold of the percentile type could be adopted. So instead of selecting a generic threshold value (e.g. 100 mm in two days), the top X% of rainfall accumulations over an n-day period is calculated, i.e. the (100-X)th percentile. An obvious limitation of such an assumption is that flood potential is only a function of the relative wetness of a certain period at a given location compared to its usual rainfall. Hence, when working with percentile-based thresholds, it becomes critical to utilise only thresholds that are high enough to increase flood probability in reality.

Starting from June 2015, the CariCOF added a 3-day extreme wet spells outlook to its list of monthly operational forecast products. The 3-day extreme wet spells frequency forecasts driving these outlooks cover a three month

period with 0 months lead time[13]. A methodological setup puts the wet spell forecast alongside the 0-month lead seasonal precipitation forecasts in order to make an expert judgement on implications that follow from a combination of forecasted events. In terms of thresholds being used, a 3-day extreme wet spell is a period of three consecutive days over which the total rainfall sum exceeds the 99th percentile of all three day periods in a historical, climatological record[14]. The actual rainfall sums associated with this threshold vary from around 50mm in Aruba (the driest territory within CariCOF), to between 80mm and 120mm in most other areas, and in excess of 160mm in the wettest mountainous areas of e.g. Dominica or Jamaica.

To provide early warning for flash flood potential at seasonal timescales, seasonal forecasts of wet spell frequency require threshold rainfall intensities that correlate well with flash flood occurrence. The threshold rainfall rate depends on exposure, geology, soil water infiltration capacity and infrastructure – in particular drainage – and is location-specific.

6.4.3. CARICOF WET DAYS AND WET SPELLS OUTLOOKS AND FLASH FLOOD POTENTIAL EARLY WARNING

The effectiveness of the early warning for flash flood potential depends, in part, on how the occurrence of extreme wet spells and flash floods correlate. Efforts are currently underway at the CIMH to thoroughly examine this. For example, Table 6.1 shows five examples of flash floods during the period September to November 2016 in the countries of Barbados and Dominica. Table 6.1 suggests that there may be a very close correlation between the hazard – i.e. flash flood – and the trigger – i.e. extreme wet spell. If this verifies for much larger samples across many Caribbean countries, then extreme wet spell frequency within a season may be a good potential proxy for expected flash flood occurrence.

Further testing revolves around the skill of the extreme wet spell forecasts in discriminating periods with lower or higher relative flash flood risk, respectively. Figure 6.4 presents the September to November 2016 precipitation outlook (Figure 6.4a) and extreme wet spells frequency shift forecast map (Figure 6.4b) both issued in August, alongside the observed SPI-3 values for the same period (Figure 6.4c) as issued in December 2016. Though the rainfall totals in the Lesser Antilles were neither forecast (Figure 6.4a) nor observed (Figure 6.4c) to be well above-normal for the area as a whole, extremely high SPIs of >2.0 over Barbados and St. Vincent suggest local extreme rainfall. However, the extreme wet spell forecast map (Figure 6.4b) did indicate medium confidence of a small increase in the frequency of extreme wet spells, of which historically up to two occur in Barbados and up to two or three in St. Vincent. With two such extreme wet spells observed in Barbados and three in St. Vincent, an increased

13 A 0-month lead forecast means that a forecast made towards the end of a certain month will cover the period starting on the first day of the following month (e.g. a 3-month forecast with 0 month lead made towards the end of June will cover the forecast period of July, August and September).

14 The climatological reference period used to define the historical norm is 1981-2010, as mandated by the WMO. However, there is an insufficient amount of manned weather station based records of daily rainfall dating back to at least 1981 to allow a good geographic of the calculation of wet days and wet spells and, hence, the wet days and wet spell forecasts that depend on them. Since rainfall was shown not to have changed significantly in most areas of the Caribbean (see Chapter 3), shifting the climatological period by 5 years to 1985-2014 - for which a decent geographic coverage can be produced - should not significantly affect the forecast product.

flash flood potential for September to November 2016 was well forecast. The forecast thus enabled a qualitatively accurate assertion that there would have been enhanced concern of flash flood risk during those three months.

There are promising indications that the forecasting system proposed may be well calibrated and have useful skill. Confirming this in a statistically robust way will involve comparing hindcasts of past extreme wet spells to a database of flash flood occurrences in the past. This is currently underway, and if successful, will allow the CariCOF to build a validated flash flood early warning product at the seasonal timescale.

Table 6.1: Flash floods in Barbados and St. Vincent and the Grenadines (SVG) between September and November 2016. The 99th percentile of 3-day rainfall totals is 92mm at CIMH in Barbados, and 110mm at ET Joshua in St. Vincent). With two hits, no misses and no false alarms for Barbados, and with three hits, no misses and one false alarm, the occurrence of extreme wet spells at the two weather stations correlates well with – and appears to be a good proxy for – flash flood occurrence in their respective surroundings in this very small sample.

LOCATION	DATE	WEATHER STATION 3-DAY RAINFALL	EXTREME WET SPELL?
BARBADOS	28 Sep 2016	CIMH: 109mm	Yes
SVG		ET Joshua: 150mm	Yes
SVG	8-10 Nov 2016	ET Joshua: 306mm	Yes
BARBADOS	29 Nov 2016	CIMH: 171mm	Yes
SVG		ET Joshua: 110mm (27-29 Nov)	Yes

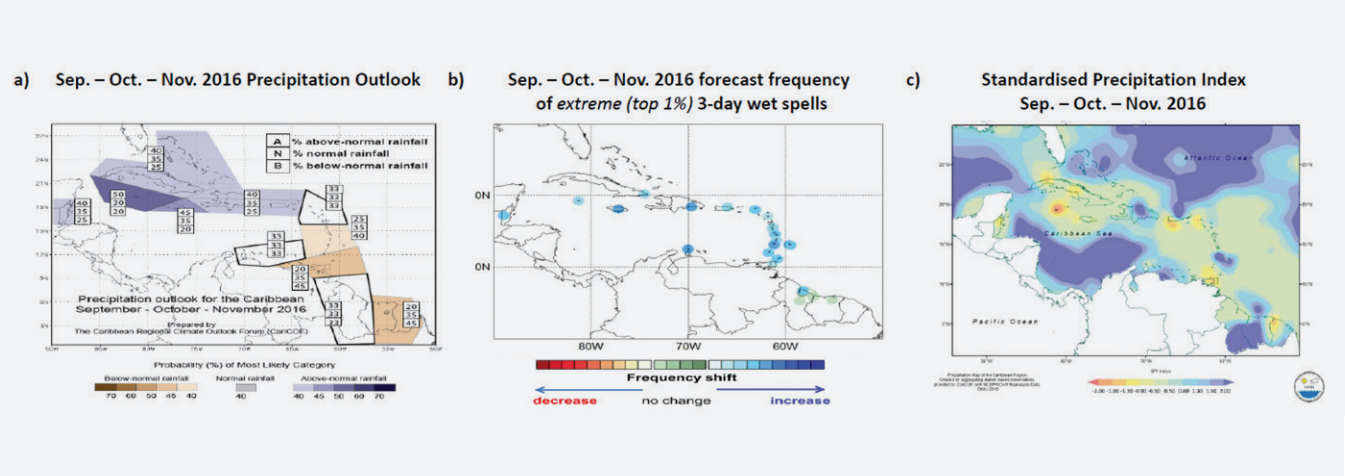


Figure 6.4: The forecasted and the observed rainfall patterns across the Caribbean for September to November 2016. In panel (a) the Precipitation Outlook depicts the average probabilities of the three-month rainfall total to be above-normal (i.e. wetter than usual), normal (i.e. the usual), or below-normal (i.e. drier than usual) for different areas across the Caribbean. Panel (b) shows a forecast for each weather station of the shift in the numbers of extreme wet spells as compared to the historical norm. Panel (c) is the CDPMN's three-month Standardised Precipitation Index map. Source: Caribbean Regional Climate Centre at CIMH (rcc.cimh.edu.bb)



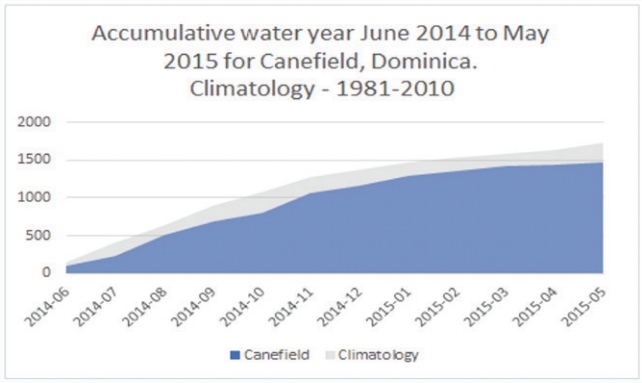
INFORMATION BOX 6.2

AMPLIFICATION OF RISK DUE TO THE IMPACT OF SUCCESSIVE DROUGHT AND WET SPELLS

As mentioned in Box 6.1, the 2014-2016 Caribbean drought impacted most of the region. By the beginning of the 2015 wet season, the Commonwealth of Dominica was suffering from an ongoing drought. A long-term drought started with below-normal rainfall recorded during 2014 wet season and was amplified between May and July 2015, when the dry season seemed to never end. The drought was one of the worst experienced since 1999 and saw the cumulative rainfall water year for June 2014 to May 2015 for two rainfall stations in Dominica, Canefield and Douglas-Charles being 85% (see Figure B6.1a) and 72% of average, respectively. Soils began to crack due to a deficit in soil moisture.

As Dominica was in its 8th month of record dryness, Tropical Storm Erika struck Dominica on the night of Monday, August 25, 2015. It dumped over 320.5 mm of rain in 12 hours, with 225.0 mm in less than six hours. Erika's rainfall contributed to half of the monthly rainfall total measured for August. Rainfall in August, however, did not end the drought, with cumulative rainfall by the end of the year still showing large deficits (see Figure B6.1b).

a)



b)

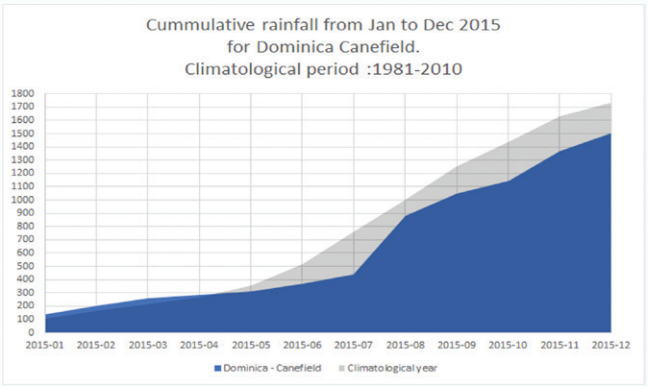


Figure B6.1: Charts shows the cumulative rainfall totals for (a) the water year June 2014 to May 2015 and (b) January to December 2015 in relation to the historical norm (i.e. climatology) for Canefield, Dominica. The climatological period spans 1982 to 2010. Source: CIMH

With excessively dry cracked soil and slow infiltration rates due to soil compaction from the drought, the short and intense downburst of rainfall from Erika caused excessive surface runoff. There were many landslides and rock fall which covered villages and blocked major roads. Approximately twelve major rivers broke their banks and caused severe flooding taking out vital bridges, and disrupting water, electricity and telecommunications. This disaster resulted in thirty confirmed deaths and 271 homes damaged or destroyed (Pasch and Penny 2016). Nine villages were declared as "Special Disaster Areas" with Petite Savanne being the most significantly affected. As of August 31, many roadways on the island remained impassable, several bridges were destroyed or unsafe, and many communities remained without electricity or potable water.

Up to September 8, 360 people were staying in seven different shelters across five communities. Most of the country lacked access to water, and there were concerns over waterborne diseases (PAHO and WHO 2015). The Dominican Water and Sewage Company Limited (DOWASCO) stated that 100% of the national water system was affected by the disaster. 54 cases of gastroenteritis, 8 cases of acute respiratory illness, 11 cases of undifferentiated fever and 1 case of tetanus were reported. Residents in 3 communities were using unsafe streams as water supply, and water infrastructure and water quality remained a problem in 2 other communities. Up to a year after the event, there were cases of post-traumatic stress disorder observed in many youths (Tavernier 2016).

The events ensuing from the drought and TS Erika in 2015 are indicative of a climate in which multiple hazards may, whether or not catastrophically, impact Caribbean nations. The case thereby forms an example of enhanced vulnerability to compounded risk of climate hazards related to extremes that coincide or follow in rapid succession. If the Caribbean is to work towards climate resilience in the face of climate change, it will have to take this risk caused by an anticipated increase in extremes into close consideration.

6.5. EXTREME TEMPERATURE AND HEAT WAVES

Heat is an increasing concern globally and in the region. Global Warming increases both frequency and intensity of heat waves over time in many locations. Chapter 3 showed that for the Caribbean there has been an increase in intensity, duration and frequency of warm and hot days and nights between 1961 and 2010.

Heat stress impacts, in increasing order of severity, can comprise general discomfort, heat rash to heat cramps, heat exhaustion, heat stroke and death. The mounting evidence of increasing heat stress implies that the availability and adoption of appropriate mitigation and adaptation mechanisms to excessive heat are warranted. There is need for heat action plans, which comprise heat preparedness measures and heat early warning systems (HEWSs). The development of an operational HEWS at weather time scales and a program of seasonal preparedness measures - including heat preparedness systems at the seasonal time scales - for the Caribbean can offer a timely and resource efficient strategy to manage excess heat risk now and for the future. At the global level, this has been called for by both the World Health Organization and the World Meteorological Organization. The current thrust provided by the Global Framework for Climate Services, which has adopted Dominica as a pilot country for climate services for health, makes such development in the Caribbean even more timely.

The following section describes a first attempt at developing a predictive framework to form part of an operational, seasonal heat preparedness system for the Caribbean. The focus is initially on the seasonal to sub-seasonal scale (S2S) i.e. between two weeks and six months, which is the focal time scale of most operational climate early-warning systems. As such, it is meant to alert, with ample lead-time for effective mitigation and/or adaptation response, periods during which excess heat will be likely.

6.5.1. TEMPERATURE MONITORING

CIMH developed temperature monitoring maps in 2015. The maps depict the monthly, 3-monthly, 6-monthly, and 12-monthly anomalies of the average temperature near the surface. When put side-by-side with maps of historical average temperatures the maps give a first order indication of heat intensity experienced during that period, and how the heat during the given period differed from the norm. Figure 6.5 is an example of a map and shows the mean temperature anomaly for 2016, the hottest year on record at many Caribbean locations. It is noteworthy that even though the anomalies depicted in Figure 6.5 were extreme in terms of rarity, the small magnitude of the anomalies temperatures can easily lead to a false conclusion that excessive heat may not be a major issue in the Caribbean.

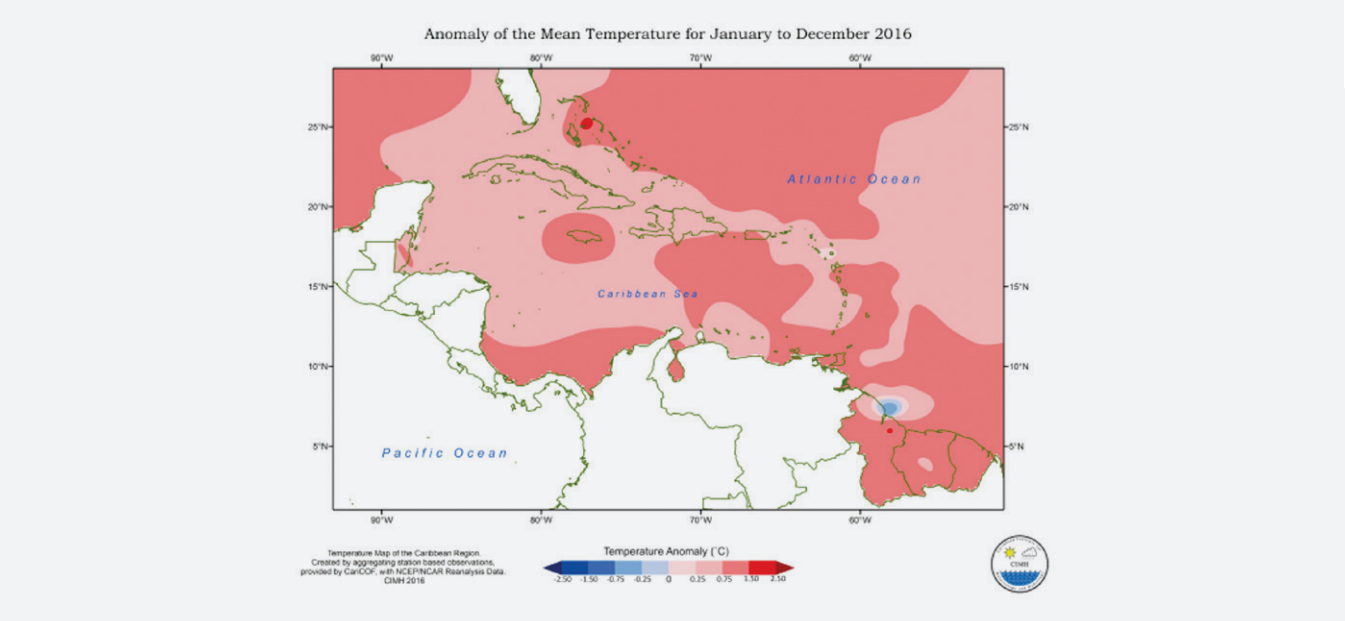


Figure 6.5: A 12-month mean near-surface air temperature anomaly map for 2016. Source: CIMH

6.5.2. DEVELOPING A PROTOTYPE HEAT OUTLOOK FOR THE CARIBBEAN

The first step in developing a heat prediction framework is the selection of an appropriate metric of heat stress which will be of value to the user of the forecast product. That is, a suitable metric should be related to relevant outcomes in a sector that may be impacted by heat e.g. health, energy or agriculture. For example, while elevated maximum temperature is the most common condition used to classify a heat wave, humidity, wind speed, solar radiation and duration of hot weather are known to mediate the effect of heat on human health in complex ways.

A heat prediction system must also be operationally feasible, accounting for requirements of resource efficiency and practicality. Many heat early warning systems opt for simple measures of heat impacts based on temperature alone, or on temperature and humidity, as though more sophisticated indices of heat burden exist (e.g. the Universal Thermal Climate Index[15]) and may more accurately reflect the true heat burden, they also tend to require a wealth of data that are unavailable in much of the Caribbean region. Studies comparing a variety of heat stress indicators have concluded that the simple measures can be as, or even more, effective than more complex measures at predicting general heat stress across a population (Vaidyanathan et al. 2016; Nissan et al. 2017). Ease of understanding is also a major advantage when developing a system that is intended for use across different sectors of society.

From the point of view of food security in the Caribbean, it is noteworthy to mention that a number of regional studies are emerging which show a clear link between poor livestock productivity and heat stress, with species specific metrics and thresholds becoming available (see for e.g. Lallo et al. (2018)). It seems plausible that heat outlook products tailored for small livestock, and heat susceptible poultry, can readily be developed premised on metrics such as the Temperature Humidity Index which relies on both temperature and air humidity data, which have been regionally recorded in many territories for at least two decades.

Recent research (IRI 2017) has also revealed that extreme heat in the Caribbean is a local phenomenon, with nearby islands, and sometimes even nearby stations, often observing heat waves on different days. Consequently, skilful predictions for the hottest days will likely only be possible at lead-times of typical weather forecasts (up to a few days). However, less extreme hot days (defined by exceedance of the 90th percentile of summertime maximum temperatures over a period of at least two days) appear to be more coherent across particular sub-regions of the Caribbean, and are therefore likely to be a better choice for sub-seasonal to seasonal forecasts. Further research is required to determine appropriate heat metrics for different applications.

CariCOF's experimental seasonal heat outlooks are delivered each month during the heat season from May to October i.e. over the six months during which all areas in the Caribbean experience at least two or three months with a regular recurrence of heatwave days. The outlooks present the heat forecasts as probabilities of the number of heat wave days exceeding thresholds such as 14 days, 30 days, and or 60 days. Figure 6.6 is an example of an experimental forecast for the summer of 2018. Figure 6.6a & 6.6b suggests that the summer of 2018 was not forecast to be particularly warm as compared to the average for all summers between 2001 and 2015. This was in stark contrast with, for example, the recent summers of 2015 and 2016, which were very warm across most of the region (in some places record warm), in part driven by the 2014-2016 El Niño. It should be noted, however, that heatwaves are common from July to September in the entire region (see Figure 6.6c). The forecast (Figure 6.6d) then suggested a 50% chance or more that there will be "**at least 7 heatwave days** from July to September 2018 in the Greater Antilles and for some locations in the Windward Islands, with a few of these stations [possibly] recording 14 heatwave days or more" (CIMH, 2018). The final heat outlook formulated the following statement on the expected implications with respect to heat:

15 A comprehensive list may be found in: World Meteorological Organization / World Health Organization (2015). Heatwaves and Health: Guidance on Warning-System Development. WMO-No. 1142. ISBN 978-92-63-11142-5

"Heat stress [is expected] in the vulnerable population and small livestock until October (or November in the Guianas), but [is] unlikely to the same extent as in recent years. By consequence, cooling needs until October are reduced compared to recent years. Nevertheless, the occurrence of a few heatwaves in many locations is likely to temporarily increase heat stress in human populations or livestock" [CIMH, 2018]

Note that at present to obtain a reasonable assessment of expected heat stress as well as associated implications (as indicated by Figure 6.6) it is necessary to compare a significant amount of information. It is also recognized that more detail is needed to adequately express expected levels of heat stress. CIMH and its research partners - in particular the International Research Institute for Climate and Society and the University of the West Indies - and sectoral partner institutions have committed to working towards providing more tailored heat early warning information so that in turn CariCOF can provide detailed implications for at least the health and the poultry and small livestock sectors initially, but potentially also the energy sector (in terms of energy demand for cooling), amongst others.

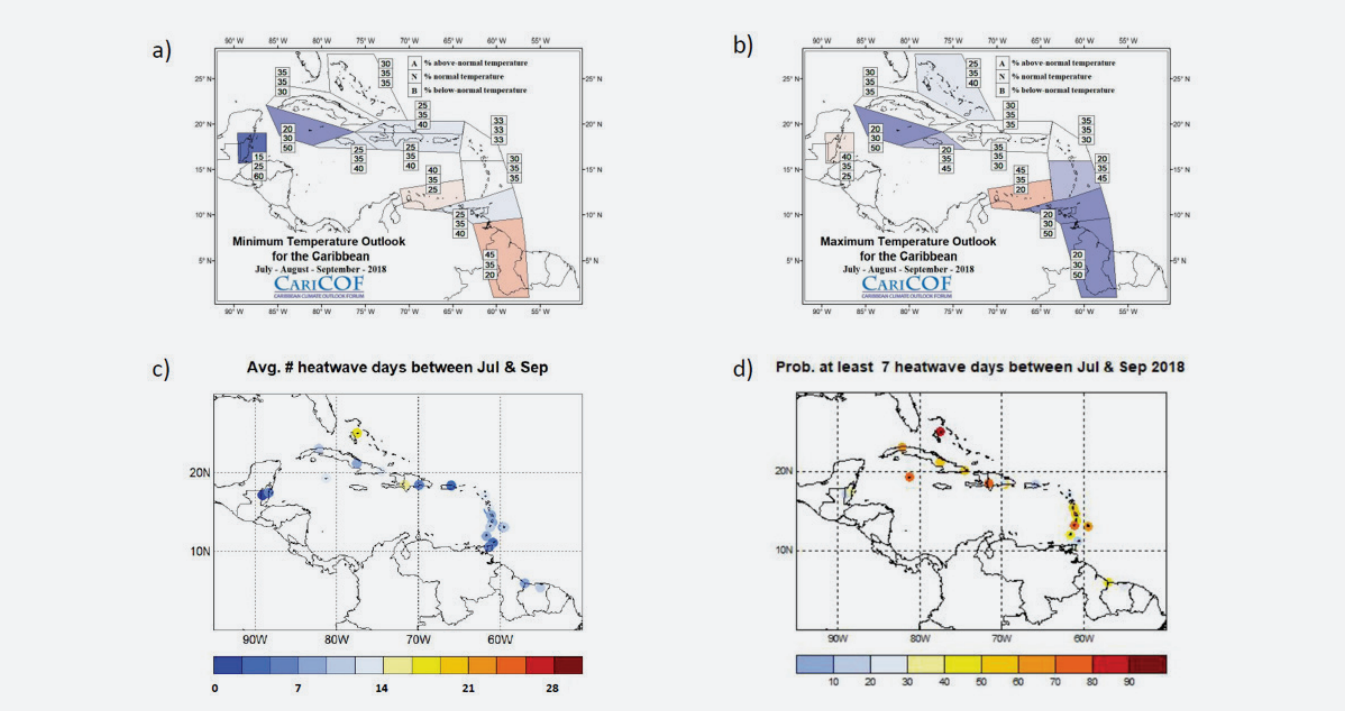


Figure 6.6: Excerpts from the CariCOF July to December 2018 Experimental Heat Outlook. Panels (a) and (b) depict the July to September minimum (nighttime) and maximum (daytime) temperature outlook maps in terms of the forecast probability of warmer than usual (above-normal), usual (normal) or cooler than usual (below-normal) temperatures as averaged over those three months. Panel (c) shows the historical average number of heatwave days during the July to September period, and (d) provides the forecast probability that at least 7 heatwave days would occur between July and September 2018. Source: CIMH (2018)

6.6. THE FUTURE OF EARLY WARNING ON CLIMATE EXTREMES IN THE CARIBBEAN

6.6.1. SECTOR DRIVEN INFORMATION ON CLIMATE EXTREMES

Climate information holds great potential to inform often complex decision-making across a wide range of climate-sensitive sectors in the Caribbean, and the general public, thus reducing their vulnerability to climate impacts, particularly from climate extremes. Arming climate-sensitive sectors in the Caribbean with specialised early warning information on climate extremes is now a priority for the Caribbean. This mandate has been taken on by the CIMH, as the Caribbean RCC, in its current and future research efforts. In association with its sectoral and other technical partners, the aim is to increasingly address the lack of localised, integrated empirical indices and models linking climate and sector-specific outcomes in a range of sectors.

The health sector is useful for illustrating the need for prioritised sector information. Among the health-climate challenges faced by the Caribbean is the recent unprecedented public health crisis of co-occurring epidemics due to Aedes aegypti mosquito borne viruses. Illness due to the dengue (DENV), chikungunya (CHIKV) and Zika (ZIKV) viruses has historically placed a high socio-economic burden on Caribbean countries. A conservative estimate for example, suggests that dengue costs the Caribbean about US$321 million annually. Moreover, the Caribbean remains the area within the Americas with the highest cost per capita (International dollars $8.70) (Shepard et al. 2011), and about 9,000 years of lost time due to ill health and premature deaths as a result of dengue (Carrington 2013). Results from a Barbados case study found that information on climate extremes such as drought positively influenced dengue relative risk at longer lead-times of up to five months while excess rainfall increased the risk at shorter lead times between 1-2 months (Lowe et al. 2018). Subsequently, a modelling approach that utilises the CariCOF drought and temperature forecasting methods was built and tested for its skill in predicting dengue cases, with the new approach significantly outperforming a modelling approach that does not account for climate extremes. There is scope for this modelling approach to now be employed in the designing of an operational dengue risk forecasting system for Barbados. With further investigation, the modelling approach could potentially also be extended to other arboviruses and to other islands in the Caribbean (Lowe et al. 2018).

There are other sectors which are being targeted using the same approach. For example, building energy demand models that include considerations of enhanced cooling need during periods of excessive heat exposure e.g. due to heatwaves, will better inform energy producers and distributors than perhaps current models do. Such investigations are ongoing at CIMH, in collaboration with the University of the West Indies.

6.6.2. DATA AND CAPACITY BUILDING NEEDS

In order to capitalise on the potential benefits of improved preparedness through longer lead time and outlooks for pending hazards such as flooding, flash floods, drought, dry spells and heat waves, significant and sustained investment is needed. A recent comparative study of the climate information production capacity of 22 NMHSs in the Caribbean (Mahon et al. 2019) shows need for (i) investments that result in enhanced and specific climate and sectoral data collection; (ii) hazard specific monitoring and prediction systems; (iii) policies and plans to respond to the early warning information; (iv) expansion or shifting of institutional mandates; and (v) education and outreach activities to allow the intended audience to respond to early warning information. Each of these capacity building needs to contain technical components and rely on data and evidence driven information. Building such capacity will furthermore require intensive engagement of a broad range of public and private, sectoral stakeholders.

To alleviate major bottlenecks in the provision of reliable, actionable early warning information services for climate extremes, critical investment needs are:

Climate data: sufficient long spanning, good quality, freely accessible and exchangeable, hazard-relevant climate data records other than records of monthly rainfall totals. A relatively good spatial and temporal coverage exists for monthly rainfall across the region, with 169 records routinely utilised and exchanged across NMHSs within the context of CariCOF. These enable drought early warning systems to be developed (Section 6.3.4). However, most NMHSs are not in the position to produce sufficient records at daily or hourly resolution for rainfall, temperature, humidity, wind speeds, etc., needed to deliver monitoring or prediction services related to hazards such as flash floods, dry spells, heat waves. Commonly, those variables are only measured at the manual station located at the

territory's major airport(s), and long-term records are maintained at even fewer of those airports. Having records of hourly or daily rainfall from locations that are geographically and geologically very different from those at the airports are needed. However, obtaining such data can be very costly. In the case of manned stations, much of the cost, apart from the initial deployment of instruments, arises from travel time needed to reach the station to make measurements, and also to maintain the instruments. In case of Automatic Weather Stations (AWSs), travel time is not as critical a factor. However, in order for the AWSs to routinely report correct values for the variables they measure, maintenance costs tend to increase, as do costs related to greater time spent on data quality control.

Data sharing: A data sharing policy is needed for data at a sub-monthly resolution, e.g. hourly and daily data. Through the years, data sharing agreements for weather forecasts have been forged, but this is not yet the case for climate data. Often, this stems from the notion that, since NMHSs or other stakeholder institutions bear the significant cost of maintaining instrumentation and sustaining observations of weather and climate variables, they should protect the ownership of their climate data which is deemed as valuable. Moving the region forward requires NMHSs to be able to access data "owned" by other institutions within their country, and data "owned" by other stakeholder institutions in neighbouring countries. This requires the development of data sharing policies. Data sharing policies usually struggle to advance because it is not clear that there are viable cost-recovery options for data production and maintenance.

Instrumentation: Install, maintain and augment instrumentation for weather stations. Perhaps for the same reason i.e. a lack of clarity of cost-recovery in climate data generation, insufficient investment is currently made at the national level in most, if not all countries in instrumentation. This is in spite of some initiatives that are providing automatic weather stations in many Caribbean countries.

Climate Monitoring and Prediction Systems: Provide operational monitoring and prediction information of extremes such as wet spells, dry spells and heatwaves. Whereas the CDPMN operationally monitors drought, and the Caribbean RCC operationally monitors temperatures at monthly, seasonal and (inter-)annual timescales, operational systems that monitor extremes at hourly or daily timescales in near-real time, critical to hazards early warning, are not yet widely available. It is also very challenging for individual NMHSs to operate national level monitoring systems. At the regional scale, a programmatic approach to investment is likely needed as innovative techniques can be developed that reduce the time demand on human resources to generate monitoring information, e.g. through automation. Furthermore, a programmatic approach allows for institutions such as CIMH to build the procedural capacity of NMHSs to adopt good practices in operations that are very time efficient, through training campaigns. Recent examples of such have been pre-CariCOF training workshops in the generation, communication and quality verification of seasonal climate outlooks, as well as similarly themed in-country training workshops on drought monitoring and prediction, climate products development, and climate information presentation. Such trainings have equipped even the smallest NMHSs in the region with the basic tools needed to produce seasonal climate outlooks, with national seasonal precipitation outlooks now produced in a regionally standard way every month by a large majority of NMHSs. Finally, investments into the sustainability of the CariCOF programme and, specifically, in its technical training capacity can therefore help support the regional roll-out of climate prediction systems geared at early warning of climate extremes.

At the regional scale, a programmatic approach to investment is likely needed as innovative techniques can be developed that reduce the time demand on human resources to generate monitoring information, e.g. through automation.

Research: A good understanding is needed of Caribbean Climate and its drivers. Though the body of literature related to this is steadily growing, the equivalent literature related to understanding climate extremes is trailing. There is need for investment in academic research on historical, ongoing and future trends in climate extremes, the drivers of such extremes as well as in R&D into designing resource efficient and reliable monitoring and prediction systems.

In terms of institutional capacity, a major need identified is expansion of the legal mandates of NMHSs to include the provision of climate services. Chapter 8 provides further discussion on how the Caribbean sectors approach the climate services agenda.

Finally, Caribbean NMHSs often have small operational budgets, with budget expenditures per capita in this region ranging from a low of US$1.63 to a high of US$8.23 per capita (2013 year dollars) (Mahon et al. 2018). As a result, it is not uncommon for NMHSs to have difficulty in maintaining suitable expertise for the delivery of climate services. While all Caribbean NMHSs have been able to push forward with their climate services agenda, with a few of them - invariably the larger ones - pushing forward at an accelerated rate, there is a notably large gap between countries' financial resources and human resource allocation dedicated to climate services delivery when compared to their very positive perceptions of the value of and the need for the roll-out of a climate services agenda.





INFORMATION BOX 6.3

THE 2017 ATLANTIC HURRICANE SEASON

From as early as May, several monitoring and forecast agencies predicted that the 2017 Atlantic Hurricane Season's activity would likely be near-normal to above-normal. In most cases the extent of the activity was revised upwards during the season. On August 5th, the US National Oceanic and Atmospheric Administration (NOAA)'s Climate Prediction Center predicted a total of 14 to 19 named storms, 5 to 9 hurricanes and 2 to 5 major hurricanes. They further warned their audience that the 2017 Season could be one of the most active since 2005. Their forecasts were corroborated by the August 4th updates produced by Colorado State University's group.

The 2017 Atlantic hurricane season saw a total of 17 named storms of which 10 were hurricanes and 6 further intensified to major hurricanes. Low vertical wind shear and warmer than usual sea surface temperatures were two of the drivers behind the extremely active season. Some notable things about the season were:

- It was the third year in a row in which the first named storm occurred before June 1st.
- On 19th June, 2017, Tropical Storm Bret caused damage and loss of life in Trinidad, an island thought to be south of the Hurricane Belt.
- It was the sixth most active on record based on the accumulated cyclone energy (ACE) index[16].
- In the Atlantic, September was the most active month on record, with 10

16 The ACE is a hurricane season activity metric that depends on two variables, namely duration and maximum wind speeds. The index reflects how energy generated by all storms accumulate over time. While the ACE can be also easily computed for an entire season (by summing the ACE of each individual storm), this index does not, however, take storm size, rainfall or storm surge indicators into consideration.

consecutive named storms and an ACE of 175.

- Hurricane Ophelia was the farthest east that a major hurricane was observed in the Atlantic.

Perhaps, the three of the most notable systems of the season were Hurricanes Harvey, Irma and Maria all of which attained category 5 status. Irma and Maria severely affected the eastern Caribbean.

Hurricane Irma – Irma was an impressive "Cape Verde" type hurricane[17].

History: On Wednesday, August 30th, the NOAA - National Weather Service's National Hurricane Center (NHC) had indicated that tropical storm Irma had formed in the eastern Atlantic. By Tuesday 5th September, the system was a powerful category 5 hurricane heading toward the Leeward Islands. By 2AM Eastern Caribbean Time (ECT) on Wednesday September 6th, the eye of Irma had passed over the island of Barbuda. The system then moved on to make landfall in St. Martin and Virgin Gorda of the British Virgin Islands. On the 7th September, the centre of Irma passed to the north of Puerto Rico and the Dominican Republic. By 8pm ECT on September 7th, Irma had passed south of Turks and Caicos and was headed toward Bahamas and Cuba. Dr. Phil Klotzbach[18] noted that (i) Irma's highest wind speeds averaged 180 mph – the third strongest winds of all time for Atlantic hurricanes –, sustained for a world record 37 hours; (ii) Irma single-handedly generated an ACE of 67.5, more than some entire seasons and the highest ACE on record by a tropical cyclone in the tropical Atlantic (7.5-20°N, 60-20°W), excluding cyclones crossing the Caribbean Sea.

The three of the most notable systems of the season were Hurricanes Harvey, Irma and Maria all of which attained category 5 status. Irma and Maria severely affected the eastern Caribbean.

Impacts[19]: In the Caribbean islands 37 deaths were attributed to Irma. Barbuda, Saint-Martin/St. Maarten and the British Virgin islands all took direct hits from Hurricane Irma while St Barthelemy was impacted by the southern eyewall and Anguilla by the northern eyewall. On Barbuda, Irma was at peak intensity and the winds left 95% of the structures damaged or destroyed, while crippling the water and communication sectors. Property damage there was estimated at US $150-300million and the island became deserted for the first time in 300 years. In Saint-Martin (the French side of the island of St. Martin), 90% of structures were damaged and estimates of losses total US $1billion, versus 70% of structures damaged, including a severely damaged airport in St. Maarten (the Dutch side). On nearby Saint-Barthélemy, economic loss was estimated to be over US $480million. In Anguilla, most properties were damaged, including schools, homes and the only hospital,

17 Cape Verde hurricanes are hurricanes that canonically develop in the Main Development Region of the Atlantic not too far from the Cape Verdean islands, mostly from disturbances coming off of Africa. Those hurricanes typically migrate east to west or north-west across the Tropical North Atlantic Ocean for several days before reaching the Antilles or passing north of this island chain. Cape Verde type hurricanes can grow to some of the most devastating hurricanes

18 The scientist in charge of CSU's Atlantic Hurricane Season outlook. He took over the work of famous hurricane specialist Bill Gray - whose outlooks people were perhaps most familiar with - after his passing. The information presented here was found on https://twitter.com/philklotzbach as accessed on 30th June 2018.

19 This section is based on the NHC Irma report as of 30th May, 2017 [Cangialosi et al., 2018].



with estimated economic losses of at least US $190million. In the Turks and Caicos Islands damage to structures and the islands communication was sustained, causing estimated total losses of at least US $500million. Nine persons lost their lives in Cuba, and ten people died in the United States. Irma's trail of damage and losses continued until it finally dissipated over Georgia on September 12th.

Hurricane Maria–Like Irma, Hurricane Maria was a Cape Verde type. Some of the same islands threatened by Irma had to issue new warnings only a few days later after Irma.

History: By 2PM ECT on September 16th, the US National Hurricane Center had indicated that the tropical depression in the Atlantic had been upgraded to Tropical Storm Maria. On September 18th, the system explosively intensified into a Category 5 Hurricane, attainting this strength hours before landfall in Dominica. After this, Maria weakened slightly due to land interaction with Dominica then regained strength to peak at 175mph. Maria weakened slightly before landfall over Puerto Rico and further weakened as it crossed the island. By September 22nd, the system emerged from Puerto Rico and re-intensified before passing east of the Turks and Caicos Islands. Some notable facts on Maria are: (i) it increased in sustained wind speeds from 85mph to 165mph in 24hours; (ii) it had a record low minimum pressure of 908mb for the Eastern Caribbean; (iii) it was the first category 5 hurricane on record to affect the island nation of Dominica; (iv) it dumped 22.8inches (579.1mm) of rainfall on Dominica and 38 inches (965.2mm) at one location on Puerto Rico.

Impacts[20]: In the Caribbean, the direct deaths from Maria totalled 108. Dominica sustained catastrophic damage, with total losses estimated at US $1.31billion, or over 220% of GDP. The agriculture sector was severely impacted and most roofs were either damaged or blown off. Roads were impassable and the communication system was destroyed. In Guadeloupe, an estimated 80,000 homes lost electricity, most of the banana crops were destroyed and officials estimated loss at US$120 million. The US Virgin Islands which was still recovering from Irma experienced heavy rainfall accumulations and mudslides. On the island of Puerto Rico, Maria was the most destructive hurricane in modern times. The energy sector was crippled due to downed power lines and extensive damage to infrastructure. This resulted in the loss of electricity to the island's 3.4 million inhabitants. The winds also destroyed the islands only radar system, reducing the capacity of the National Weather Service's local office to deliver early warning for any pending adverse weather post-hurricane. Unprecedented river flooding in an entire alluvial valley resulted in the rescue of hundreds of families from roof tops. Officials estimated total losses in the US Virgin Islands and Puerto Rico at US$ 90 billion, making Maria the third costliest hurricane in US history, trailing only Harvey (2017) and Katrina (2005).

20 This section is based on the NHC Maria report as of 10th April, 2017 [Pasch et al., 2018].


Revenue Structure
Cost trends
Jan
Feb
Mar
Apr
May
Jul
Aug
Sep
Oct
Nov
Dec

Annex 45

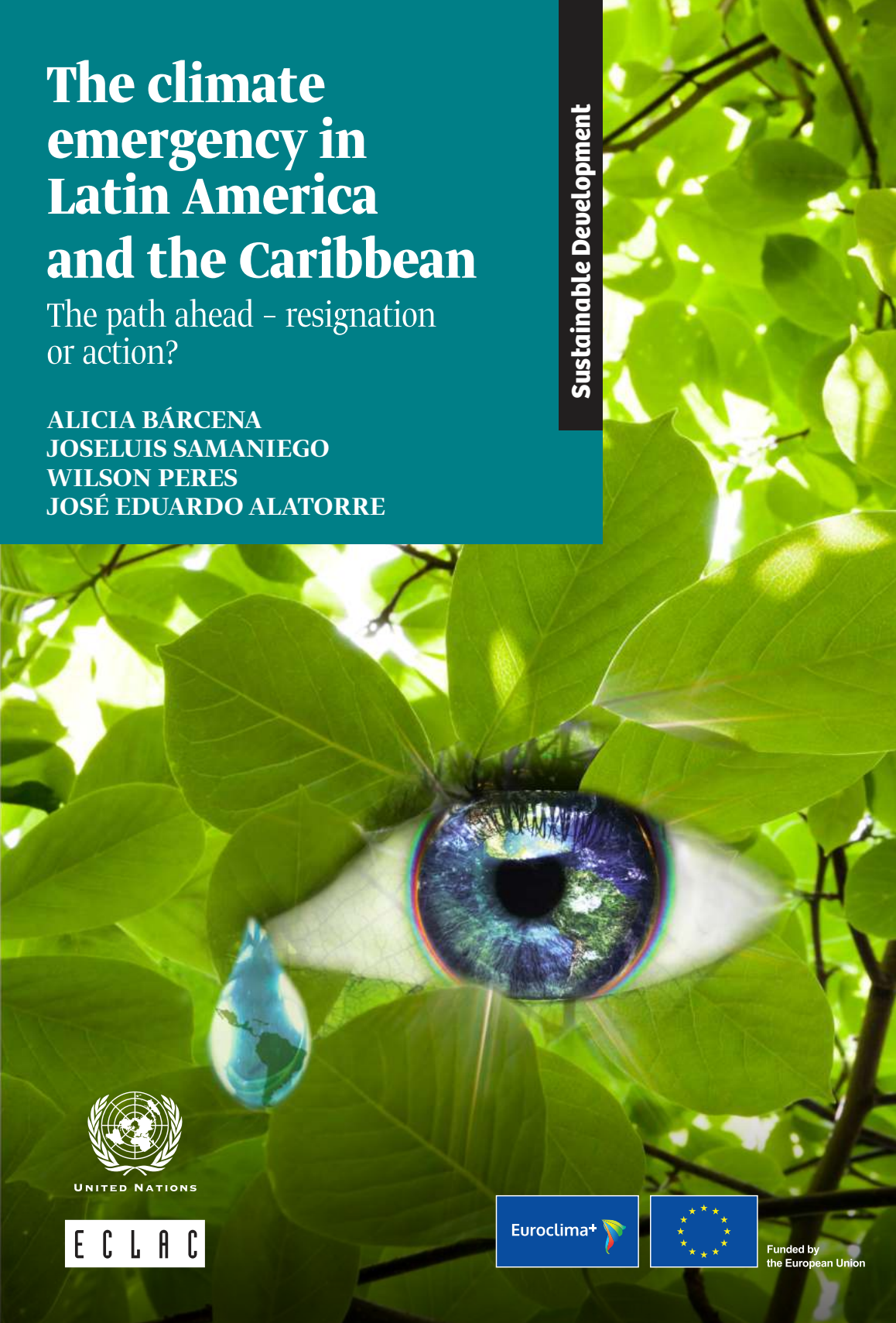
A. Bárcena et al., *The climate emergency in Latin America and the Caribbean: the path ahead - resignation or action?* (ECLAC Books, No. 160 (LC/PUB.2019/23-P), Economic Commission for Latin America and the Caribbean, 2020), pages 94-95, 122-149, 157-159

The climate emergency in Latin America and the Caribbean

The path ahead – resignation or action?

ALICIA BÁRCENA
JOSELUIS SAMANIEGO
WILSON PERES
JOSÉ EDUARDO ALATORRE

Sustainable Development



UNITED NATIONS
ECLAC
Euroclima+
Funded by the European Union

The climate emergency in Latin America and the Caribbean

The path ahead – resignation or action?

Alicia Bárcena
Joseluis Samaniego
Wilson Peres
José Eduardo Alatorre

UNITED NATIONS

ECLAC

Euroclima+

Funded by
the European Union

ECLAC Books

160

Alicia Bárcena
Executive Secretary

Mario Cimoli
Deputy Executive Secretary

Joseluis Samaniego
Chief, Sustainable Development
and Human Settlements Division

Ricardo Pérez
Chief, Publications and Web Services Division

This document was prepared by Alicia Bárcena, Executive Secretary of the Economic Commission for Latin America and the Caribbean (ECLAC), Joseluis Samaniego, Chief of the Sustainable Development and Human Settlements Division of the Commission, José Eduardo Alatorre and Wilson Peres. The authors wish to convey thanks for information and valuable conceptual contributions made by the following staff members of that Division: David Barrio, Carlos de Miguel, Jimy Ferrer, Luis Miguel Galindo, José Javier Gómez, Luiz Krieger, Mauricio Pereira, Orlando Reyes, Heloisa Schneider and Nicole Tondreau. The text is based on research carried out by ECLAC between 2009 and 2019, forming a corpus that merits the summarized presentation offered here. The documentation built up over this long reference period has served as a source of information for several organizations of the United Nations system and beyond and, above all, for the countries of Latin America and the Caribbean.

The boundaries and names shown on the maps included in this publication do not imply official endorsement or acceptance by the United Nations.

United Nations publication
ISBN: 978-92-1-122032-2 (print)
ISBN: 978-92-1-047956-1 (pdf)
ISBN: 978-92-1-358269-5 (ePub)
Sales No. E.19.II.G.17
LC/PUB.2019/23-P
Distribution: G
Original: Spanish
Copyright © United Nations, 2020
All rights reserved
Printed at United Nations, Santiago
S.19-00710

This publication should be cited as: A. Bárcena and others, *The climate emergency in Latin America and the Caribbean: the path ahead – resignation or action?*, ECLAC Books, No. 160 (LC/PUB.2019/23-P), Santiago, Economic Commission for Latin America and the Caribbean (ECLAC), 2020.

Applications for authorization to reproduce this work in whole or in part should be sent to the Economic Commission for Latin America and the Caribbean (ECLAC), Publications and Web Services Division, publicaciones.cepal@un.org. Member States and their governmental institutions may reproduce this work without prior authorization, but are requested to mention the source and to inform ECLAC of such reproduction.

H. Management of risk associated with extreme weather events

Extreme weather events can prove disastrous for economic activities, social conditions and ecosystems. Their effect, then, is that of a shock that is random in its scale and geographical location, disrupting economic and social stability (Murlidharan and Shah, 2001; ECLAC, 2015a). The overall effects will depend on national and local conditions and the period considered. In general, extreme weather events have a negative short-term effect on the well-being of the population, not necessarily reflected in the path of GDP,[16] and a weak or not easily quantifiable effect in the medium term and long term.[17] [18] The main factors determining the effect are the type and severity of the disaster, the sector affected, the structure and composition of the economy and per capita income.[19]

The effects of natural disasters are greater in developing countries than in advanced ones, and the agriculture sector usually suffers most (Fomby, Ikeda and Loayza, 2013; Benson and Clay, 2004; ECLAC, 2015a). For example, the most severe droughts reduce GDP growth by 1% and agricultural growth by 2.2% (see table II.7), suggesting that regions such as Central America and the Caribbean are particularly sensitive to natural disasters (Martine and Guzman, 2002) because of their smaller size and their exposure. Larger countries have more options for offsetting the effects. Extreme weather events and ecosystem degradation trigger feedback processes; for example, deforestation and mangrove destruction increase vulnerability in coastal and other geographical areas (Ruth and Ibarrarán, 2009; Mechler, 2009).

Table II.7
Effects of natural disasters on economic growth
(Percentages)

Natural disaster	Effect on growth of GDP	Effect on growth of agriculture	Effect on growth of industry	Effect on growth of services
Droughts	-1.0***	-2.2***	-1.0*	0.3
Flooding	0.3	0.6	0.1	0.4
Earthquakes	-0.0	-0.1	0.3	0.0
Storms	-0.9**	-0.8**	-0.9	-0.9

Source: N. Loayza and others, "Natural disasters and growth: going beyond the averages", *Policy Research Working Paper*, No. 4980, Washington, D.C., World Bank, 2009.
Note: * significant at 10%; ** significant at 5%; *** significant at 1%. The effects are estimated in relation to the output growth rate and not the level of output. Thus, a severe drought might reduce growth in overall GDP and industrial GDP by 1%, while reducing agricultural GDP growth by 2.2%.

[16] Flooding in some regions is an exception in that it leads to higher agricultural productivity (Loayza and others, 2009).
[17] By the medium term are meant periods of one to three years. Long-term effects are hard to identify because of problems in establishing a baseline (Kahn, 2005).
[18] Albala-Bertrand (1993), Benson and Clay (2003), Hochrainer (2006), Loayza and others (2009), Murlidharan and Shah (2001).
[19] Haab and McConnell (2003), Freeman, Herriges and Kling (2003), Ruth and Ibarrarán (2009), Loayza and others (2009), Hallegatte and Przyluski (2010), Charvériat (2000), Rasmussen (2004).

Natural disasters also have collateral effects, for example on the public finances and infrastructure and in the form of property losses, lifestyle changes and disruption of transport and international trade, while reinforcing poverty traps (Caballeros-Otero and Zapata, 1995; Murlidharan and Shah, 2001; Mechler, 2009). Natural disasters have a negative impact on social conditions, with the poor (particularly children and the elderly) generally being hardest hit because they usually live in high-risk areas, depend on a single income source, do not have a cushion of assets or savings, do not have access to credit or insurance and are less educationally equipped to deal with such disasters (Kalkstein and Sheridan, 2007; Pelling, Özerdem and Barakat, 2002; Kahn, 2005; Kelly and Adger, 2000). Climate variability is one of the main factors causing fluctuations in farm incomes, as discussed in the section dealing with the impact on agriculture, and this most strongly affects lower-income groups, who may require up to a decade to replenish their livestock after a climate shock (Dercon, 2006; Rosenzweig and Binswanger, 1993; Rasmussen, 2004).

Natural disasters also have long-term repercussions; for example, they affect education by increasing school absenteeism, which is not then recovered, and they contribute to malnutrition, which reduces cognitive skills (World Bank, 2010), with all the attendant effects on productivity and long-term incomes (ECLAC, 2015a). The assessment of these effects should always take into account the fact that a high proportion of the region's population live in conditions of vulnerability (Cecchini and others, 2012; Galindo and others, 2014a).

Consequently, strengthening infrastructure with engineering works and by restoring systems such as corals and mangroves is critical to the proper functioning of the region. As will be seen in the next section, this will depend on whether the financial resources are available to meet this new demand for adaptation.

C. The Caribbean: negative effects of climate change in a context of high borrowing

The Caribbean relies heavily on economic activities such as tourism and agriculture, which are particularly sensitive to climatic conditions (ECLAC, 2010). Agriculture generates a large number of jobs, and the rural population continues to constitute a substantial percentage of the total population (ECLAC/MINURVI/UN-HABITAT, 2016). It is therefore relevant that, in different climate scenarios, yields of cassava, banana, sweet potato and tomato plantations are predicted to fall by between 1% and 30% by 2050, with rice crop yields ranging from a 3% decrease to a 2% increase. Lower yields would have negative consequences in a number of areas, such as growth in output and investment in agriculture, the external sector, poverty reduction and food security (Clarke and others, 2013; ECLAC, 2015a).

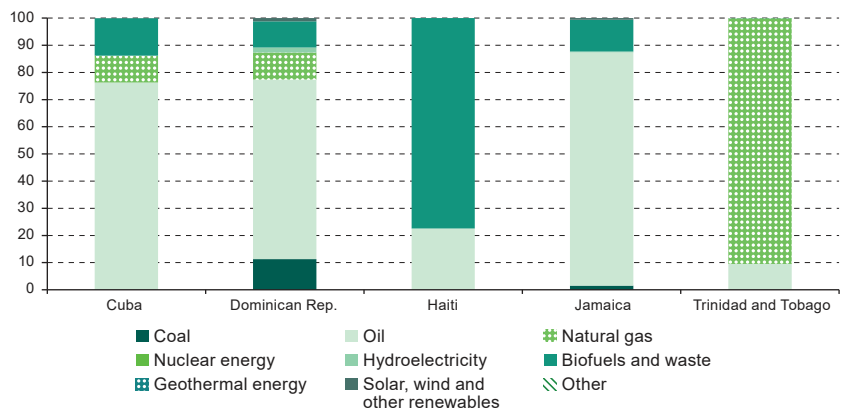
Between 1950 and 2000, the number of warmer days and nights increased, the number of colder days and nights decreased, the number of drier days and rainier days increased, and the sea temperature rose by 1.5 ºC. The climate scenarios of IPCC (2013b) show representative concentration pathways (RCPs) for the period 2016–2035 that would lead to a temperature increase of between 0.5 °C and 0.7 °C above the base period average. A further increase of between 0.8 °C and 3 °C is forecast by 2081–2100. In the first period, annual precipitation would decrease by an average of between 1% and 3% relative to the base period average, while in the second period the decrease would be between 5% and 16% (UNFCCC, 2007; ECLAC, 2015a). Like Central America, the Caribbean will be warmer and drier.

As noted in the previous section, Caribbean countries are particularly exposed to rising sea levels and extreme weather events, such as hurricanes and storms, that exacerbate the loss and erosion of coastal areas, the deterioration of marine ecosystems, the alteration of marine habitats and the loss of mangroves or corals. In particular, it is estimated that the entire coral ecosystem will have collapsed by 2050. Biodiversity loss has negative effects on economic activities and the welfare of the population: less tourism, destruction of coastal infrastructure, population movements and debt. In addition, climate change is expected to affect people's health through heat waves, natural disasters caused by extreme weather events, and communicable diseases such as malaria, dengue, leptospirosis and gastroenteritis (Clarke and others, 2013).

1. The emissions of the Caribbean

In contrast to the path being followed in Central America, the energy mix of the Caribbean countries is dominated by oil. In the case of Haiti, biofuels predominate, while in Trinidad and Tobago it is natural gas (see figure III.12).

Figure III.12
The Caribbean (5 countries): energy mix, 2016
(Percentages)

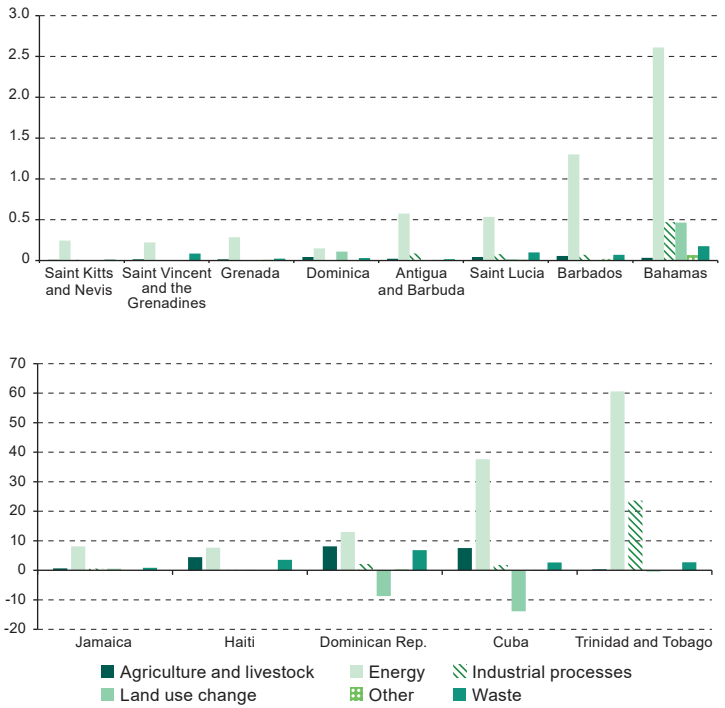


Source: Economic Commission for Latin America and the Caribbean (ECLAC), on the basis of J. Gütschow and others, "The PRIMAP-hist national historical emissions time series", *Earth System Science Data*, vol. 8, Göttingen, Copernicus Publications, 2016; Food and Agriculture Organization of the United Nations (FAO), Corporate Database for Substantive Statistical Data (FAOSTAT) [online] http://www.fao.org/faostat/en/.

The level of emissions by country varies, but energy is usually the largest category (see figure III.13).[9] Trinidad and Tobago and Cuba are the countries with the most emissions, at 87 Mt of CO_2 eq and 36 Mt of CO_2 eq, respectively. At the same time, the forest cover of Cuba and the Dominican Republic absorbs emissions.

[9] Currently, the information available in the countries on greenhouse gas emissions is based on national inventories; however, this information covers different years, so the database of Gütschow and others (2018) and FAO (2019) is used to harmonize the analysis.

Figure III.13
The Caribbean (13 countries): emissions by country and by sector, 2014
(Megatons of CO_2 equivalent)

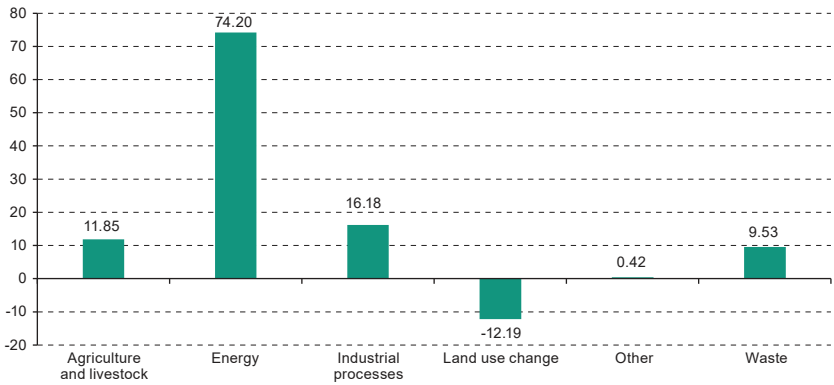


Source: Economic Commission for Latin America and the Caribbean (ECLAC), on the basis of J. Gütschow and others, "The PRIMAP-hist national historical emissions time series (1850–2016)", Potsdam, 2018 [online] http://dataservices.gfz-potsdam.de/pik/showshort.php?id=escidoc:3842934.

With regard to the sectoral composition of emissions, in 2016 the burning of fossil fuels accounted for 90% of these: most emissions came from the energy sector (74%), followed by industrial processes (16%) and agriculture (12%). On the other hand, the subregion captures carbon because of land use change (see figures III.14 and III.15). In contrast to other regions of Latin America and the Caribbean, the transport sector still accounted for a relatively minor share in the Caribbean as of 2017. At the aggregate level, 179 Mt of CO_2 eq were emitted in the Caribbean in 2016,[10] and the average annual growth rate was 3.8%. Emissions from the waste sector and the industrial processes sector were the fastest-growing between 1990 and 2016, and emissions from land use change fell by an average of 2.8% annually over the same period (see figure III.16).

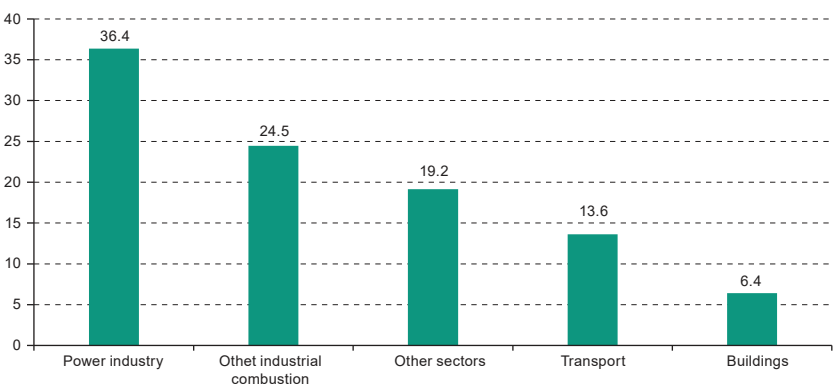
[10] This means that emissions per capita were 4.6 t of CO_2 eq, which compares favourably with the world average of 6.7 t of CO_2 eq.

Figure III.14
The Caribbean: sectoral emissions shares, 2016
(Percentages)



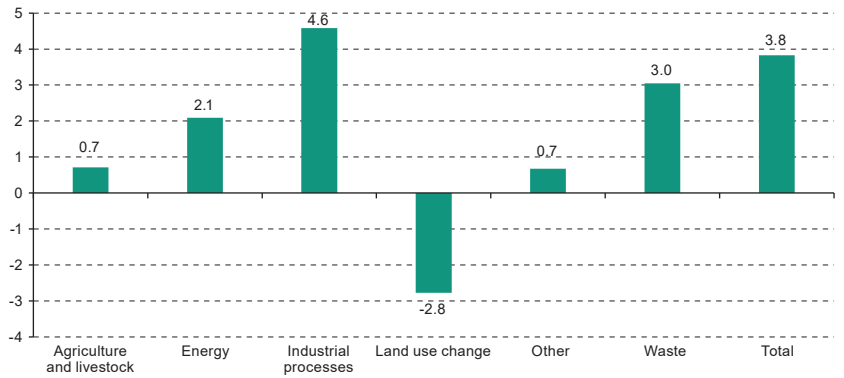
Source: Economic Commission for Latin America and the Caribbean (ECLAC), on the basis of United States Securities and Exchange Commission, EDGAR database [online] https://www.sec.gov/edgar.shtml.

Figure III.15
The Caribbean: composition of energy sector emissions, 2017
(Percentages)



Source: Economic Commission for Latin America and the Caribbean (ECLAC), on the basis of United States Securities and Exchange Commission, EDGAR database [online] https://www.sec.gov/edgar.shtml.

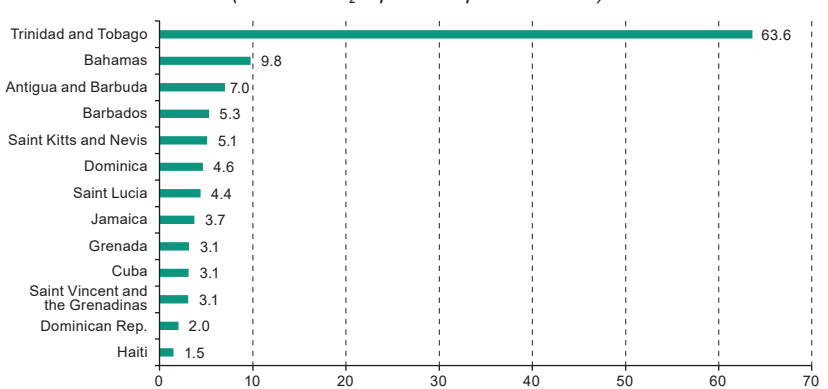
Figure III.16
The Caribbean: growth in emissions by sector, 1990–2016
(Percentages)



Source: Economic Commission for Latin America and the Caribbean (ECLAC), on the basis of J. Gütschow and others, "The PRIMAP-hist national historical emissions time series (1850–2016)", Potsdam, 2018 [online] http://dataservices.gfz-potsdam.de/pik/showshort.php?id=escidoc:3842934.

Figure III.17 ranks the countries by their per capita emissions in 2016. Several of them have exceeded the limit of 5 tons per capita and it will be necessary to reduce emissions to achieve the target of not exceeding that value by 2030. However, as noted above, in absolute terms, total emissions from the Caribbean represent only those of a medium-sized economy in the region, and the emissions of each individual country represent approximately 10% of those of a medium-sized continental country.

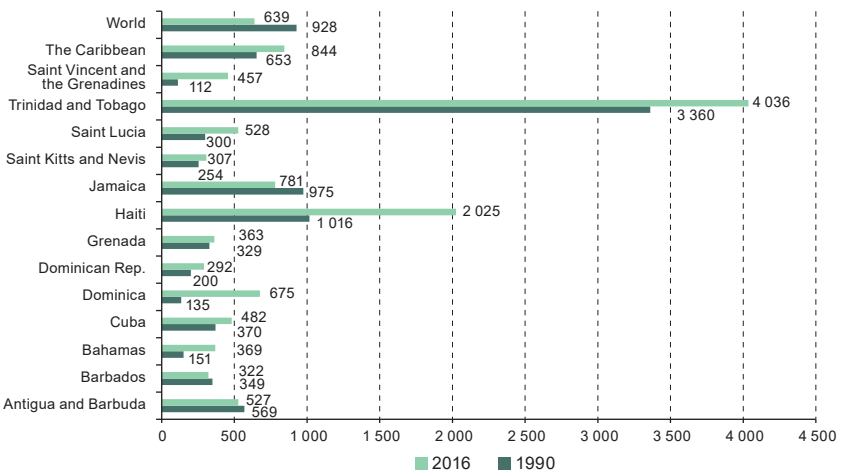
Figure III.17
The Caribbean (13 countries): emissions per capita, 2016
(Tons of CO_2 equivalent per inhabitant)



Source: Economic Commission for Latin America and the Caribbean (ECLAC), on the basis of J. Gütschow and others, "The PRIMAP-hist national historical emissions time series (1850–2016)", Potsdam, 2018 [online] http://dataservices.gfz-potsdam.de/pik/showshort.php?id=escidoc:3842934.

The ratio between total emissions and GDP is 844 t of CO_2 eq for every million 2010 dollars, which is higher than the world average of 639 t of CO_2 eq (see figure III.18). The region has also seen a coupling process of 1% per year since 1990, with the exceptions of Jamaica, Antigua and Barbuda and Barbados, where carbon intensity has been reduced.

Figure III.18
The Caribbean (13 countries): carbon intensity of the economy, 1990 and 2016
(Tons of CO_2 equivalent per million 2010 dollars)



Source: Economic Commission for Latin America and the Caribbean (ECLAC), on the basis of J. Gütschow and others, "The PRIMAP-hist national historical emissions time series (1850–2016)", Potsdam, 2018 [online] http://dataservices.gfz-potsdam.de/pik/showshort.php?id=escidoc:3842934.

As already mentioned in the section on Central America, it is estimated that, in order to meet international commitments and stabilize the global temperature increase at no more than 2 °C, it is necessary to reduce global emissions from 50 Gt of CO_2 eq, which is what is currently emitted, to 40 Gt of CO_2 eq by 2030. This means reducing per capita emissions from approximately 7 t of CO_2 eq to less than 5 t of CO_2 eq per inhabitant in the same period (UNEP, 2018). As in the case of Central America, the regional mitigation effort can be calculated on the basis of the following three hypothetical scenarios for 2030:

(i) A business as usual scenario, which is constructed by taking the historical performance of carbon intensity and a GDP projection of 2.8% per year (S1).

(ii) A scenario without greater carbonization, which in this case is better than the historical performance (S2).

(iii) A scenario of compliance with nationally determined contributions (NDCs), in which it is estimated that emissions are reduced by 20% compared to the business as usual scenario by 2030 (S3).

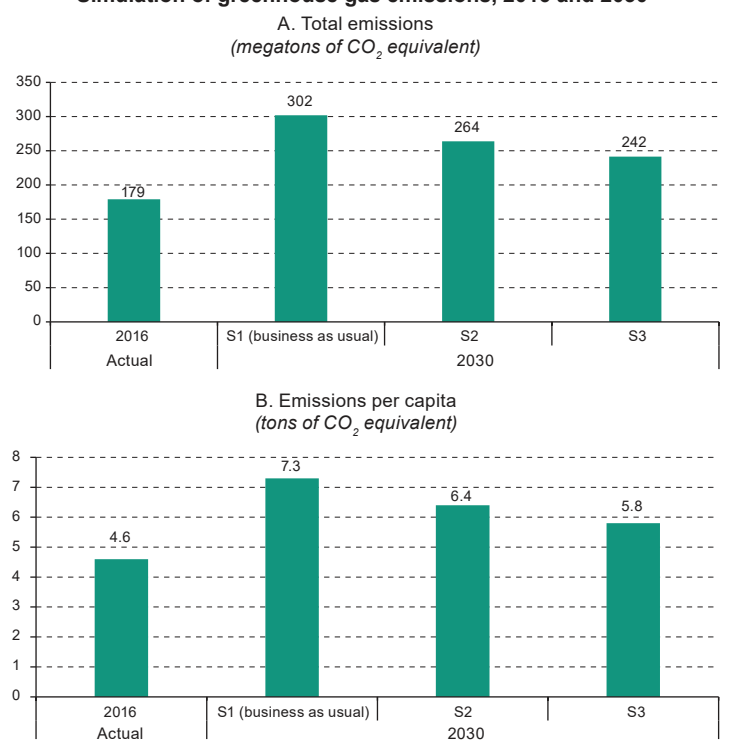
The results of evaluating the above scenarios for 2030 are summarized in table III.4 and figure III.19.

Table III.4
Scenarios and assumptions, 2030

Scenario	Assumed average annual growth, 2016–2030		Greenhouse gas (GHG) emissions outcomes, 2030			
	ΔGDP_t	$\Delta\left(\frac{GHG}{GDP}\right)_t$	ΔGHG_t	*GHG (megatons of CO_2 equivalent)*	*GHG per capita (tons of CO_2 equivalent per inhabitant)*	Difference from scenario S1 *(percentages)*
Scenario S1	2.8	1	3.8	302	7.3	-
Scenario S2	2.8	0	2.8	264	6.4	-13
Scenario S3	2.8	-0.6	2.2	242	5.8	-20

Source: Economic Commission for Latin America and the Caribbean (ECLAC).
Note: S1 is the business as usual scenario, S2 is one in which the decarbonization rate is zero, and in S3 emissions are cut by 20% relative to the business as usual scenario.

Figure III.19
Simulation of greenhouse gas emissions, 2016 and 2030



Source: Economic Commission for Latin America and the Caribbean).
Note: S1 is the business as usual scenario, S2 is one in which the decarbonization rate is zero, and in S3 emissions are cut by 20% relative to the business as usual scenario.

In the business as usual scenario (S1), a total of 302 Mt of CO_2 eq of greenhouse gases would be emitted by 2030 (it was previously noted that 179 Mt of CO_2 eq were emitted in 2016), owing to increased carbon intensity in the countries. Per capita emissions would increase from the current 4.6 t of CO_2 eq to 7.3 t of CO_2 eq by 2030, and carbon intensity would increase at the observed rate of 1% per year. If the observed rate of historical decarbonization or evolution of the carbon intensity of GDP were maintained, international commitments would be far from being met. In the case of scenario S2, where the decarbonization rate is zero, i.e., where the increase in the carbon intensity of GDP is zero or emissions are growing at the same rate as the economy, per capita emissions would reach 6.4 t of CO_2 eq. In scenario S3, where the commitment to reduce emissions by 20% compared to the business as usual scenario is met, per capita emissions would be 5.8 t of CO_2 eq. However, in order to reach this value, it would be necessary for the carbon intensity of GDP to decrease. In this scenario, the goal of keeping per capita emissions in the subregion below 5 t of CO_2 eq, which is what is needed to achieve the climate targets, would be within sight.

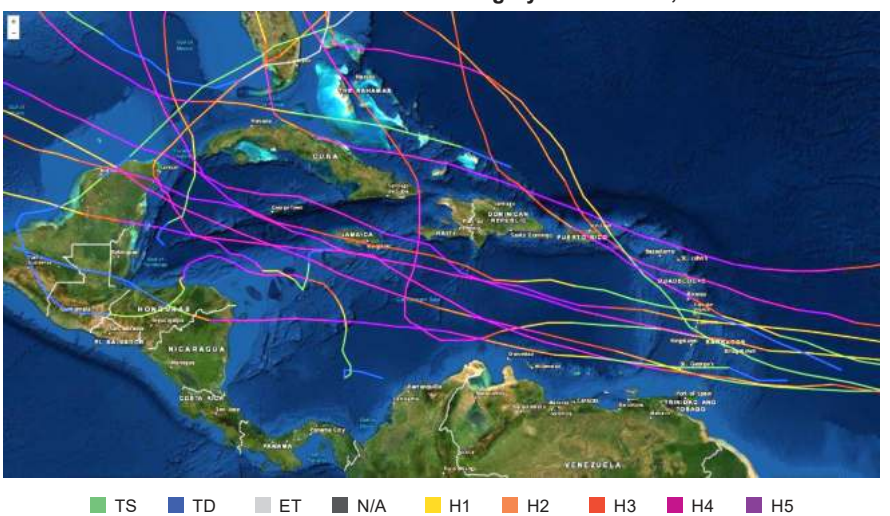
This indicates that, with a marginal effort to decarbonize the electricity mix, i.e., a modest rate of renewable energy penetration, especially in countries with higher carbon intensity, coupled with the electrification of industry and an effort to improve the efficiency of mobility systems and agriculture, the Caribbean countries would be on track to meet the goal of keeping emissions down to 5 tons per capita. Alternatively, restoring ecosystems, such as mangrove forests, would increase carbon capture, creating scope to burn fossil fuels. The local co-benefits for the subregion are obvious, since this would provide gains in terms of energy sufficiency and independence in addition to increased space in the external sector in the medium term (once the phase of importing equipment for generation with renewables had been completed) and improved mobility systems, which would be more efficient and emit fewer pollutants hazardous to health. The option of improved ecosystem management and afforestation would be very helpful in preventing and mitigating the destructive effects of the extreme events referred to in the following section. In combination, as can be appreciated, these actions would substantially improve the development style in the Caribbean countries.

2. Extreme events in the Caribbean

As in the Central American countries, the fundamental asymmetry of climate change can be observed in an extreme form in the small island developing States of the Caribbean: 0.36% of global greenhouse gas emissions are

generated in those States,[11] but their vulnerability is particularly high because of their socioeconomic, geographical and climatic conditions. Almost all the islands are in the hurricane corridor and, naturally, a large proportion of the population and economic activities are located in coastal areas (see map III.7).

Map III.7
The Caribbean: historical tracks of category 5 hurricanes, 1980–2018



Source: National Oceanic and Atmospheric Administration (NOAA), Historical Hurricane Tracks [online] https://coast.noaa.gov/hurricanes/#/search/basin/2/filter/categories/H5/pressure/years.

Note: H stands for hurricane, TS for tropical storm, TD for tropical depression and ET for extratropical storm, while N/A means "not applicable" (i.e., not corresponding to any of the meteorological systems listed here). The tracks of the 14 category 5 hurricanes that occurred in the Caribbean between 1980 and 2018 are shown. In date order, they are: Hurricane Allen, 31 July to 11 August 1980; Hurricane Gilbert, 8 to 20 September 1988; Hurricane Hugo, 10 to 25 September 1989; Hurricane Mitch, 22 October to 9 November 1998; Hurricane Ivan, 2 to 24 September 2004; Hurricane Emily, 11 to 21 July 2005; Hurricane Rita, 18 to 26 September 2005; Hurricane Wilma, 15 to 26 October 2005; Hurricane Dean, 13 to 23 August 2007; Hurricane Felix, 31 August to 6 September 2007; Hurricane Matthew, 28 September to 10 October 2016; Hurricane Irma, 30 August to 13 September 2017; Hurricane Maria, 16 September to 2 October 2017; and Hurricane Michael, 6 to 15 October 2018.

[11] The Caribbean's annual emissions are 179,000 tons of CO_2 equivalent, about half of this being explained by hydrocarbon-related activities in Trinidad and Tobago. Of the other countries, the four most populous in the region are, in order, the largest emitters: Cuba, the Dominican Republic, Haiti and Jamaica. In all of them, the largest emissions come from the energy sector. This is because they depend heavily on imports of fossil fuels and because renewable sources play little part in electricity generation. This contrasts with the situation in the countries of Central America, which, together with Uruguay, are leaders in renewable electricity generation.

There were 408 disasters associated with extreme events in the subregion between 1990 and 2017, an average of 14.6 a year.[12] Disasters were recorded every year during this period, but the highest incidence was observed in 2004 and 2017 (30 and 29 disasters, respectively). The countries suffering the most disasters were Haiti (90), the Dominican Republic (59) and Cuba (53). In the English-speaking Caribbean, Jamaica was the country with the most disasters (26). Of the disasters during this period, 90.4% were associated with hydroclimatic hazards, particularly storms (58.1%) and floods (27.2%) (see table III.5). The years with the most storm-related disasters were 2017 and 2004, with 25 and 23 disasters, respectively.

Table III.5
The Caribbean: number of disasters, by type, 1990–2017
(Numbers)

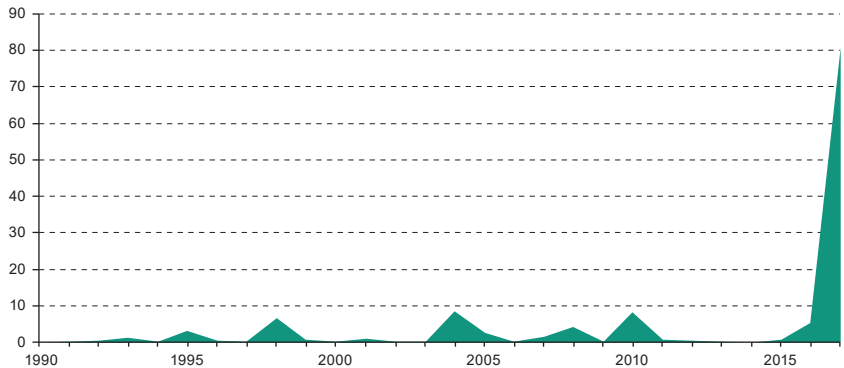
Biological	20
Geophysical	14
Flooding	111
Storm	237
Drought	21
Earth movement	2
Other	3
Total	408

Source: Economic Commission for Latin America and the Caribbean (ECLAC), on the basis of Centre for Research on the Epidemiology of Disasters (CRED), EM-DAT International Disaster Database [online] https://www.emdat.be/; Economic Commission for Latin America and the Caribbean/Latin American and Caribbean Institute for Economic and Social Planning (ECLAC/ILPES), *Planning for sustainable territorial development in Latin America and the Caribbean* (LC/CRP.17/3), Santiago, 2019.

In terms of impact and damage, the highest values were in 2016 and 2017, when 9 and 11 million people, respectively, were affected by some disaster, while 85.9% of all asset destruction in the period from 1990 to 2017 occurred in those two years. The peak came in 2017 because of the effects of Hurricanes Irma and Maria, which caused losses of US$ 80.8 billion or 63.4% of the total damage for the period (see figure III.20). With respect to the types of disasters, storms were responsible for the greatest destruction of assets and caused 91.3% of all damage. The set of expected effects is shown in box III.3.

[12] The data on the frequency of extreme events in the Caribbean countries were taken from ECLAC/ILPES (2019).

Figure III.20
The Caribbean: damage caused by disasters, 1990–2017
(Billions of 2017 dollars)



Source: Economic Commission for Latin America and the Caribbean (ECLAC), on the basis of Centre for Research on the Epidemiology of Disasters (CRED), EM-DAT International Disaster Database [online] https://www.emdat.be/; Economic Commission for Latin America and the Caribbean/Latin American and Caribbean Institute for Economic and Social Planning (ECLAC/ILPES), *Planning for sustainable territorial development in Latin America and the Caribbean* (LC/CRP.17/3), Santiago, 2019.

Box III.3
The Caribbean: impact expected as a result of vulnerability to the effects of climate change, sea level rise and extreme events

- Deterioration of coastal conditions, e.g., beach erosion and coral bleaching negatively affecting local resources, such as fisheries, and reducing the value of beaches as a tourist destination.
- Floods, storm surges, erosion and other coastal hazards, which are exacerbated by rising sea levels and threaten vital infrastructure, settlements and facilities that contribute to the livelihoods of local communities.
- Increased invasion of non-native species, such as sargasso in the Caribbean.
- Economic losses from lower agricultural yields.
- Loss of mangrove forests and coral reefs due to rising sea levels.
- Ocean discoloration and acidification.
- Damage to forests caused by extreme events.
- Reduction in freshwater availability due to reduced precipitation and saltwater intrusion.
- Flooding of coastal settlements and croplands.
- Decrease in tourism due to the increased frequency and severity of extreme weather events.
- Resort to external borrowing to compensate for losses caused by extreme weather events.

Source: Economic Commission for Latin America and the Caribbean (ECLAC), on the basis of Intergovernmental Panel on Climate Change (IPCC), *Climate Change 2007: Impacts, Adaptation, and Vulnerability*, Cambridge, Cambridge University Press, 2007; United Nations Framework Convention on Climate Change (UNFCCC), "Vulnerability and adaptation to climate change in small island developing states", Bonn, 2007; Economic Commission for Latin America and the Caribbean (ECLAC), *The economics of climate change in Latin America and the Caribbean: paradoxes and challenges of sustainable development* (LC/G.2624), Santiago, 2015.

3. The situation of cities in the Caribbean[13]

Growing urbanization in the Caribbean is increasing the vulnerability of the subregion, as cities are low-lying and exposed to rising sea levels. Increasing their resilience is therefore a necessity. Urban growth is expected to increase the risk to inhabitants, owing to the exploitation of nearby resources (McHardy and Donovan, 2016) and the increasing pace of sea level rise (Kopp and others, 2016), which, as measured by satellite altimetry, is already taking place at ±3.4 mm per year. For example, in the Bahamas, which were terribly affected by Hurricane Dorian in 2019, 82.8% of the population live less than 10 m above sea level and 94.9% live within 5 km of the coast (Mycoo and Donovan, 2017). The document prepared by the Latin American and Caribbean Institute for Economic and Social Planning (ILPES) for the 2019 Regional Council for Planning states: "In addition to the increased risks to low-lying coastal zones and the exposure of people living in coastal areas, the vulnerabilities of SIDS are also spreading to other critical sectors because of the loss of biodiversity and the destruction of natural protection systems such as reefs and mangroves […] Freshwater aquifers in the great coastal plains of Belize, Guyana and Suriname are also vulnerable to saline intrusion […] At the same time, unsustainable production and consumption patterns are putting more and more pressure on resources such as land, water and biodiversity.[14] Failure to pay attention to these factors may have severe environmental and socioeconomic consequences" (ECLAC/ILPES, 2019, p. 52).

ECLAC/ILPES (2019) points out how heavily the population is concentrated in cities, with 18 of the 30 capital cities of the Caribbean being home to more than half the urban population of the country or territory concerned. There are six capitals that contain the whole of the urban population of the country or territory in question, namely Bridgetown, Road Town, Willemstad, Saint George's, Brades Estate and Philipsburg. While 89% of total population of Curaçao live in Willemstad, 81.9% of the population of Antigua and Barbuda live in Saint John, Nassau is home to 70% of the population of the Bahamas, and 67% of the population of Puerto Rico reside in San Juan. In the Cayman Islands and the United States Virgin Islands, about half the population lives in the capital city (see table III.6).

---

[13] This section takes information and text from ECLAC/ILPES (2019).

[14] Mycoo and Donovan (2017) describe harmful land use practices caused in part by unresolved conflicts arising from inherited land tenure systems associated with plantation economies, obsolete land records, poor execution of physical development plans and environmental policies and regulations, poor site selection for urban settlements, inadequate application of urbanization standards and building codes, deep governance and infrastructure deficits, economic and social inequality and limited application of tools for measuring the value of environmental resources in protecting urban assets (ECLAC/ILPES, 2019).

Table III.6

The Caribbean: population of urban and rural areas, capital cities and urban percentages, 2018

(Thousands of people and percentages)

Region or country	Urban population[a] *(thousands of people)*	Rural population *(thousands of people)*	Total *(thousands of people)*	Urban population[a] *(percentages of total)*	Capital city	Population living in capital *(thousands of people)*	Population living in capital *(percentages of total)*	Urban population living in capital[a] *(percentages of total)*
Latin America and the Caribbean	526 057	125 955	652 012	80.7		100 786	15.5	19.2
The Caribbean[b]	32 540	13 673	46 213	70.4		12 942	28.0	39.8
Anguilla	15	0	15	100.0	The Valley	1	9.3	9.3
Antigua and Barbuda	25	78	103	24.6	Saint John	21	20.1	81.9
Aruba	46	60	106	43.4	Oranjestad	30	28.3	65.1
Bahamas	332	68	399	83.0	Nassau	280	70.0	84.4
Barbados	89	197	286	31.1	Bridgetown	89	31.1	100.0
Belize	175	208	382	45.7	Belmopan	23	6.0	13.1
Bermudas	61	0	61	100.0	Hamilton	10	16.5	16.5
British Virgin Islands	15	17	32	47.7	Road Town	15	47.7	100.0
Cayman Islands	62	0	62	100.0	George Town	35	55.9	55.9
Cuba	8 851	2 638	11 489	77.0	Havana	2 136	18.6	24.1
Curaçao	144	18	162	89.1	Willemstad	144	89.1	100.0
Dominica	52	22	74	70.5	Roseau	15	20.1	28.5
Dominican Republic	8 823	2 060	10 883	81.1	Santo Domingo	3 172	29.1	36.0
French Guiana	247	43	290	85.3	Cayenne	58	19.8	23.3
Grenada	39	69	108	36.3	Saint George's	39	36.3	100.0
Guadeloupe	442	7	449	98.5	Basse-Terre	58	13.0	13.2
Guyana	208	574	782	26.6	Georgetown	110	14.1	52.8
Haiti	6 143	4 970	11 113	55.3	Port-au-Prince	2 637	23.7	42.9
Jamaica	1 614	1 285	2 899	55.7	Kingston	589	20.3	36.5
Martinique	343	42	385	89.0	Fort-de-France	79	20.6	23.1

Table III.6 (concluded)

Region or country	Urban population[a] *(thousands of people)*	Rural population *(thousands of people)*	Total *(thousands of people)*	Urban population[a] *(percentages of total)*	Capital city	Population living in capital *(thousands of people)*	Population living in capital *(percentages of total)*	Urban population living in capital[a] *(percentages of total)*
Montserrat	0	5	5	9.1	Brades Estate	0	9.1	100.0
Puerto Rico	3 424	235	3 659	93.6	San Juan	2 454	67.1	71.7
Saint Kitts and Nevis	17	39	56	30.8	Basseterre	14	25.8	84.0
Saint Lucia	34	146	180	18.7	Castries	22	12.4	66.3
Saint Vincent and the Grenadines	58	53	110	52.2	Kingstown	27	24.2	46.3
Sint Maarten	41	0	41	100.0	Philipsburg	41	100.0	100.0
Suriname	375	193	568	66.1	Paramaribo	239	42.1	63.8
Trinidad and Tobago	730	643	1 373	53.2	Port of Spain	544	39.7	74.6
Turks and Caicos Islands	33	2	36	93.1	Cockburn Town	5	15.1	16.3
United States Virgin Islands	100	4	105	95.7	Charlotte Amalie	52	49.9	52.1

Source: United Nations, *World Urbanization Prospects: The 2018 Revision*, New York, 2018; Economic Commission for Latin America and the Caribbean/Latin American and Caribbean Institute for Economic and Social Planning (ECLAC/ILPES), *Planning for sustainable territorial development in Latin America and the Caribbean* (LC/CRP.17/3), Santiago, 2019.

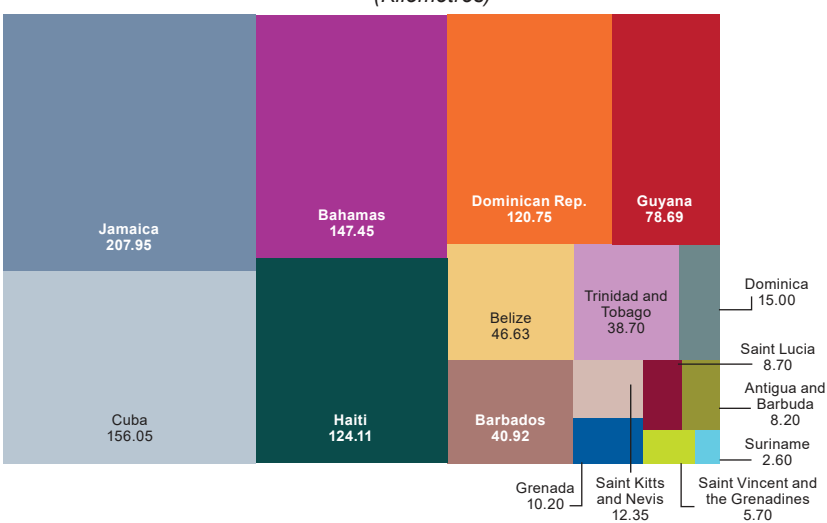
[a] The definition of "urban" is the one used in each country.

[b] Includes the 30 member countries and associate members of the Caribbean Development and Cooperation Committee (CDCC).

With regard to the exposure of settlements to the effect of rising sea levels and hurricanes, the Bahamas, Cuba, the Dominican Republic, Haiti and Jamaica have more than 100 km of urban coastline (see figure III.21), and many cities are less than 5 metres above sea level (see map III.8). Flood risks are exacerbated by the complexity of water systems and the incipient nature of countries' adaptive capacity.

In addition, according to ILPES, by 2050 the Caribbean will have an urbanization rate of 82.5%, higher than the rest of the region's. This rate will represent an increase of at least 15%, in a dispersed pattern that will form "city-regions" and "urban corridors". "Urban expansion in the Caribbean will result in a two- to fivefold increase in the current total urban area, in response to an estimated increase of some 10 million new urban inhabitants by 2050"[15] (ECLAC/ILPES, 2019, p. 45).

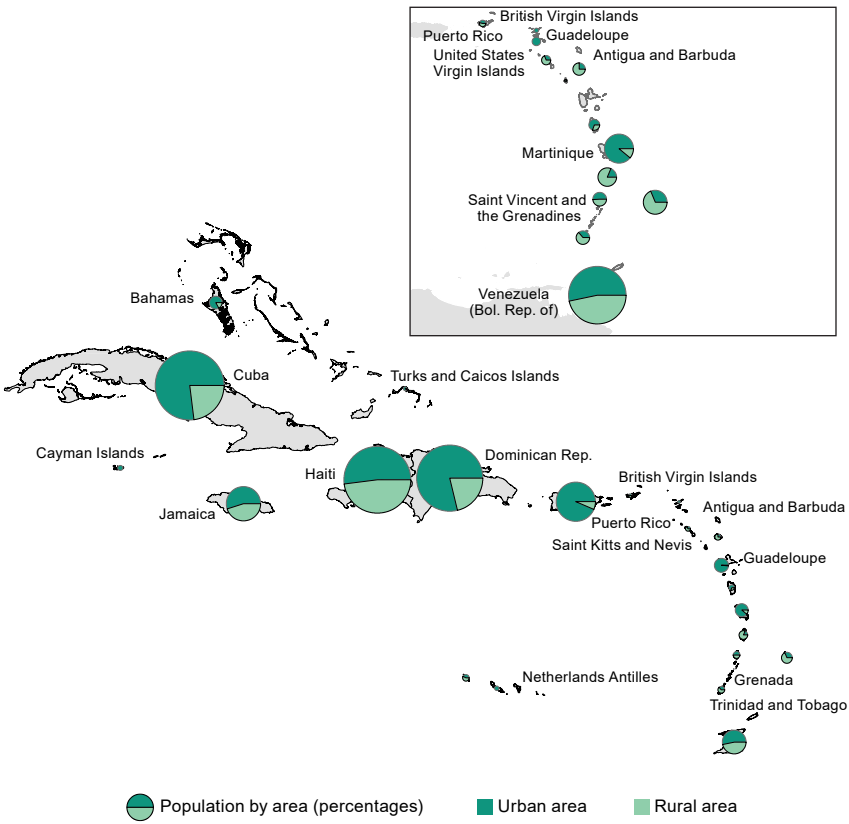
Figure III.21
The Caribbean: urban coastline, 2013
(Kilometres)



Source: M. Mycoo and M. Donovan, *A Blue Urban Agenda: Adapting to Climate Change in the Coastal Cities of Caribbean and Pacific Small Island Developing States*, Washington, D.C., Inter-American Development Bank (IDB), 2017; Economic Commission for Latin America and the Caribbean/Latin American and Caribbean Institute for Economic and Social Planning (ECLAC/ILPES), *Planning for sustainable territorial development in Latin America and the Caribbean* (LC/CRP.17/3), Santiago, 2019.

[15] According to research by McHardy and Donovan, in 2050 the urban area of the Caribbean will be equivalent to an area between three times the size of Barbados and the whole of Trinidad and Tobago (see McHardy and Donovan, 2016). Studies by Angel and others (2010) have projected significant increases in urban land cover in the Caribbean and in Pacific small island developing States between 2000 and 2050. For example, Trinidad and Tobago is expected to experience a seven-fold increase in urban land cover (ECLAC/ILPES, 2019, p. 45).

Map III.8
The Caribbean: spatial distribution of population, 2018



Source: Latin American and Caribbean Institute for Economic and Social Planning (ILPES), on the basis of Economic Commission for Latin America and the Caribbean (ECLAC), CEPALSTAT [online database] http://estadisticas.cepal.org/cepalstat/WEB_CEPALSTAT/Portada.asp; Economic Commission for Latin America and the Caribbean/Latin American and Caribbean Institute for Economic and Social Planning (ECLAC/ILPES), *Planning for sustainable territorial development in Latin America and the Caribbean* (LC/CRP.17/3), Santiago, 2019.

In such a scenario, pressures on land, services and infrastructure will also increase, and policies to anticipate these pressures, such as improved security of land tenure, public land management, housing policy, transport, waste management and water security, will be crucial (see box III.4). As long as territories are unprepared and these phenomena are unplanned, the development style will multiply existing vulnerabilities by adding those created by the uncontrolled growth of informal settlements.

Box III.4
Planning and risk

Disaster risk reduction (DRR) has been integrated into a number of development frameworks and international agreements, such as the Hyogo Framework for Action 2005–2015: Building the Resilience of Nations and Communities to Disasters, and its successor, the Sendai Framework for Disaster Risk Reduction 2015–2030. It was also integrated into the Samoa Pathway and into the 2030 Agenda for Sustainable Development. In addition, given the Caribbean's vulnerability to disasters, stakeholders in the subregion also need to improve their capacity to incorporate disaster risk management components into sectoral and budget planning. Disaster risk management consists of five pillars with their respective outcomes (GFDRR, 2013):

(i) Risk identification. Improved identification and understanding of disaster risks through building capacity for assessment and analysis.

(ii) Risk reduction. Avoided creation of new risks and reduced risks in society through greater disaster risk consideration in policy and investment.

(iii) Preparedness. Improved capacity to manage crises through developing forecasting and disaster management capacities.

(iv) Financial protection. Increased financial resilience of governments, private sector and households through financial protection strategies (parametric insurance, traditional insurance and budgetary provisions).

(v) Resilient recovery. Quicker, more resilient recovery through support for reconstruction planning.

Although progress has been made with disaster risk management planning (Bahamas, Barbados, Belize, Dominican Republic, Guyana, Haiti, Jamaica, Saint Lucia, Suriname and Trinidad and Tobago), this approach has not yet permeated the regulatory and institutional frameworks governing sectoral and territorial institutions or planning and budgeting processes, as reported in the following paragraphs:

- **Information for decision-making on disaster risk management.** Although most development and sectoral policies acknowledge this need for data and identify important gaps, there are no clear guidelines for the generation and dissemination of disaster risk management-related information. The countries analysed have institutions responsible for the study and monitoring of geological and hydrometeorological hazards, but this information is not necessarily accessible or used to guide actions and decisions. Information is still being primarily used in the academic sector and in early warning systems. Nevertheless, it should be noted that most countries already have laws ensuring access to public information. Therefore, it is necessary to clarify the role of disaster risk management in this regard and build upon the accomplishments of such laws. As expressed in most disaster risk management instruments, it is recommended that disaster risk management information systems should be implemented, as well as technical guidelines to support sectoral and territorial engagement, and that consistency in the collection of data should be ensured. It is important to highlight the importance of consistently collecting sectoral baseline data, as they are useful not only for identifying and reducing risks, but also for assessing the effects and impacts of disasters. On the subject of sectoral data, the Economic Commission for Latin America and the Caribbean and World Bank have evaluated a number of disasters in the subregion, thereby consolidating a baseline in a range of sectors that should be kept continually updated.
- **Integration of disaster risk management into the project preparation and evaluation cycle.** The standards and instruments used in some countries for carrying out environmental impact assessments already integrate disaster risk analysis, as well as the design and implementation of disaster risk reduction measures. However, the lack of national information systems or technical guidelines makes it difficult to properly consider disaster risk management in the preparation and evaluation cycle of public investment and development projects in general. A combination of improved data and strengthened technical capabilities is crucial to incorporating disaster risk management into public investment projects. The incorporation of a multi-hazard disaster risk management component throughout the life cycle of a project would increase its resilience and sustainability, and contribute to protecting public investments, while ensuring continuity in the provision of public services and products.

Box III.4 (concluded)

- **Territorial approach.** In some countries, the development of regional, provincial or municipal disaster risk management plans has been promoted, while in others the approach has been to incorporate them into development plans, or for both types of instruments to coexist. However, the territorial approach and the definition of sectoral roles and responsibilities where disaster risk management is concerned has not always been accompanied by the allocation of financial resources or budget incentives. It is suggested that countries strengthen the territorial component of their disaster risk management strategies, as it is observed that most local authorities are tasked primarily with emergency preparedness and response tasks. This requires an update of disaster risk management frameworks to establish binding responsibilities for territorial levels and strengthen areas such as risk identification, planning of mitigation measures, data gathering and considerations for reconstruction processes that do not reproduce recognized risks and vulnerabilities.
- **Sectoral approach.** The countries of the subregion have evolved from having a national institution in charge of disasters to creating national systems of disaster risk management. These systems have generated normative and institutional frameworks that have gradually defined the roles and responsibilities of the different sectors and institutions in charge of matters related to disaster risk management. Some specific sectors such as agriculture, environment, infrastructure and health show advances in the incorporation of such management. Perhaps one of the strongest links identified is between environment, climate change and disaster risk management. It is also observed that, to the extent that a country has updated frameworks for climate change adaptation and mitigation, there is linkage with the principles and activities of disaster risk management. Similarly, several development and sectoral policies recognize the importance of land use and territorial planning to increase resilience and adapt to or mitigate the effects of climate change. Furthermore, some aspects of disaster risk management have been considered in environmental impact studies, in particular the identification of natural hazards that may affect a given project, as well as the elaboration of mitigation measures to ensure its sustainability. Sectors that have modified their norms and structures to incorporate a disaster risk management strategy show better performance through the incorporation of specific actions into planning and sectoral budgets.
- **Macroeconomic policies.** Some normative frameworks for disaster risk management in the subregion provide for the creation of national funds. Some of these are qualified for the financing of ex ante activities and others are only qualified to meet the emerging needs of disaster response. However, the fact that legal frameworks mandate the creation of these funds does not necessarily mean that the required resources have been estimated or actually allocated. When ministries of economy and finance have well defined disaster risk management roles and responsibilities, the design and establishment of national financial protection strategies has been facilitated, which also contributes to both the sustainability and the acquisition of funds. In addition, many countries have arranged catastrophe insurance facilities in the international market.
- **Integration of disaster risk management into development policies and other instruments.** Different degrees of progress have been attained in the countries of the subregion, opening up a variety of opportunities for sharing experiences and cooperating. Post-disaster recovery processes represent an opportunity to rectify the previously followed course and rebuild with resilience by incorporating disaster risk management into development strategies.

Source: O. Bello and others, "Mainstreaming disaster risk management strategies in development instruments: policy briefs for selected member countries of the Caribbean Development and Cooperation Committee", *Studies and Perspectives series*, No. 58 (LC/TS.2017/80; LC/CAR/TS.2017/6), Santiago, Economic Commission for Latin America and the Caribbean (ECLAC), 2017; C. Weekes and O. Bello, "Mainstreaming disaster risk management strategies in development instruments (II): policy briefs for Barbados, Guyana, Saint Lucia, Suriname, and Trinidad and Tobago", *Studies and Perspectives series*, No. 75 (LC/TS.2019/7), Santiago, Economic Commission for Latin America and the Caribbean (ECLAC), 2019; Economic Commission for Latin America and the Caribbean/Latin American and Caribbean Institute for Economic and Social Planning (ECLAC/ILPES), *Planning for sustainable territorial development in Latin America and the Caribbean* (LC/CRP.17/3), Santiago, 2019; Global Facility for Disaster Reduction and Recovery (GFDRR), *Managing Disaster Risks for a Resilient Future: A Strategy for the Global Facility for Disaster Reduction and Recovery 2013–2015*, Washington, D.C., 2013.

As can be seen in relation to the dynamics of human settlements, adaptation and mitigation go hand in hand in the urban context, since to be less exposed cities would have to have a shorter sea frontage and thus a higher density, which would at the same time make them more compact. This would reduce the intensity of emissions and allow for mobility options that would have a smaller environmental footprint. Similarly, the role of natural defences is critical in curbing the impact of climate phenomena, be they mangroves, reefs or ground vegetation.

4. Estimates of the economic impact of climate change

The cost of climate-related disasters in the period 2000–2017 was substantial, as can be seen in figure III.22, where it is expressed as a proportion of GDP. In 2017, the impact of Hurricane Maria in Dominica was estimated at 260% of GDP, while in 2004 the effects of Hurricane Ivan in Grenada amounted to 148% of GDP. This type of extreme event has caused damage equivalent to two-digit percentages of GDP in Antigua and Barbuda, the Bahamas, Haiti and Saint Vincent and the Grenadines, while in Cuba, the Dominican Republic, Jamaica, Saint Lucia and Saint Kitts and Nevis there has been at least one event that has cost more than 1% of GDP.

Figure III.22
The Caribbean (13 countries): economic cost of natural disasters, 2000–2017
(Percentages of GDP)

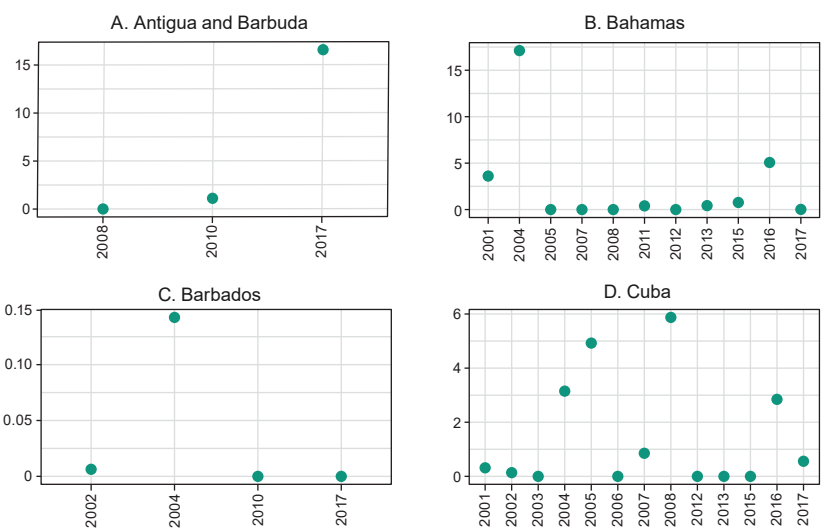
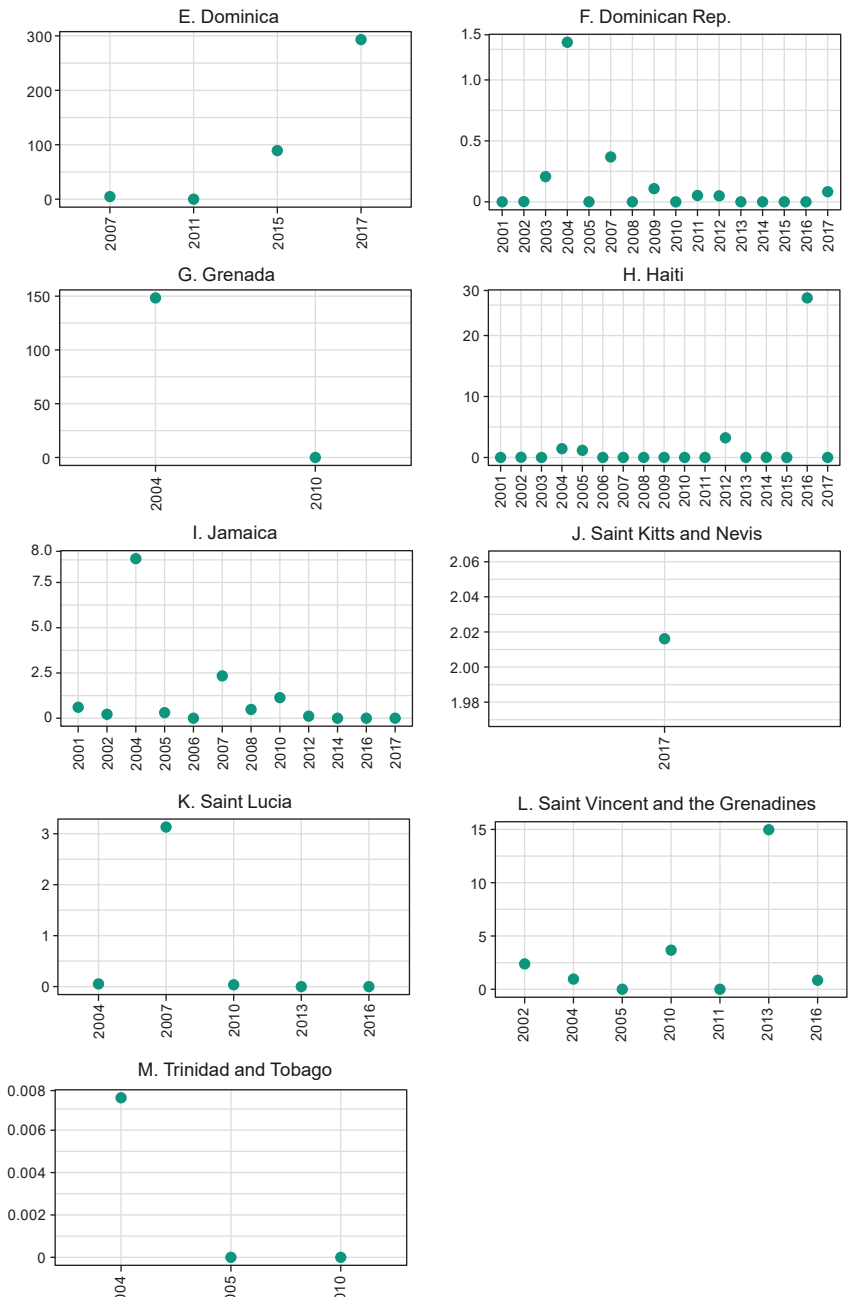


Figure III.22 (concluded)



Source: Economic Commission for Latin America and the Caribbean (ECLAC), on the basis of Centre for Research on the Epidemiology of Disasters (CRED), EM-DAT International Disaster Database [online] https://www.emdat.be/.

The loss of human life has been high and increasing (see figure III.23). In the period 2000–2012 there were more deaths from floods and storms than in 1980–1989 (ECLAC, 2019c). Greater urbanization and the increase in agricultural land are lethality risk factors in the nations of the Caribbean Community (CARICOM).

Figure III.23
The Caribbean: disaster-related fatalities, 2000–2019
(Numbers)

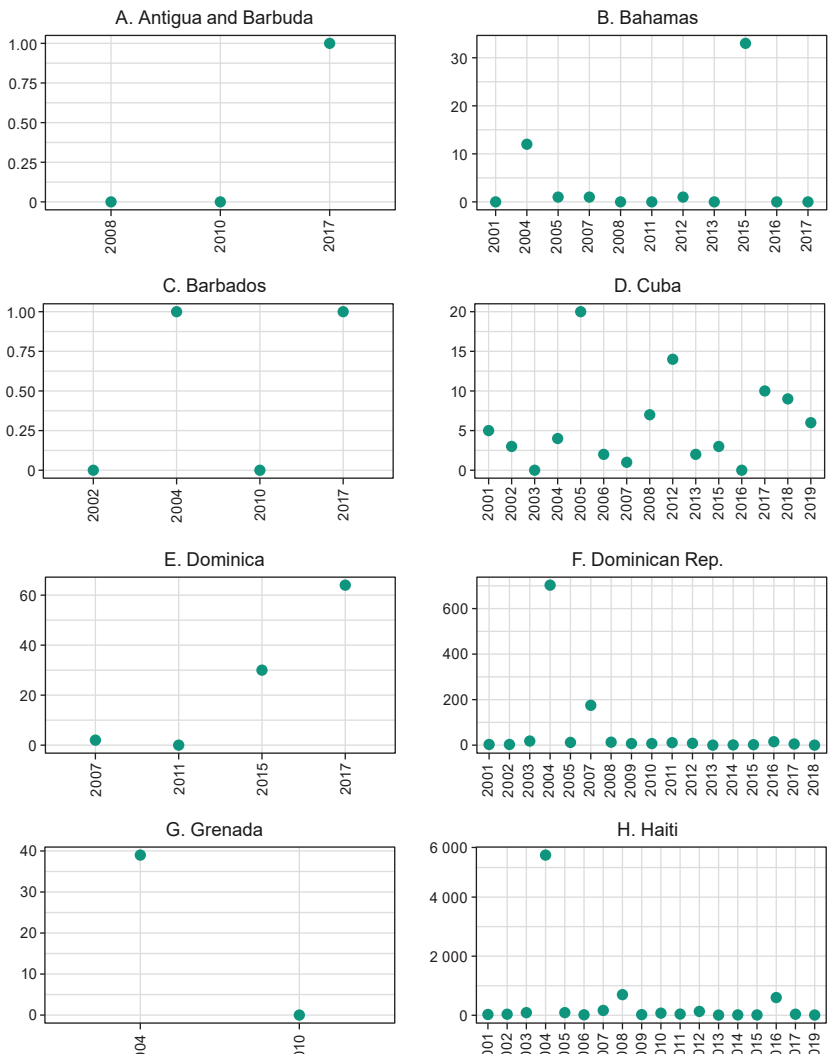
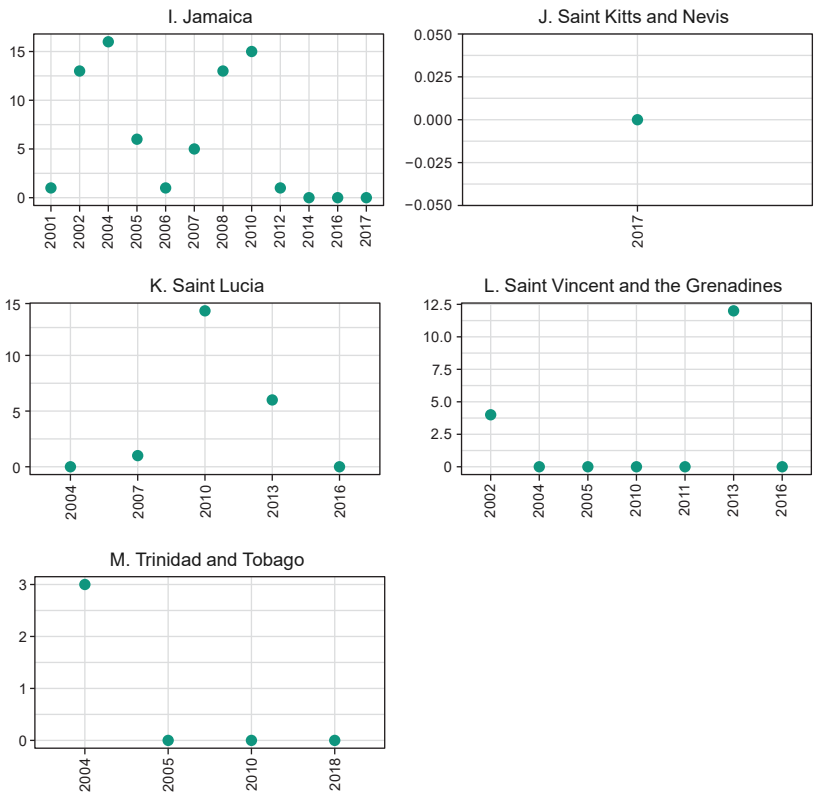


Figure III.23 (concluded)



Source: Economic Commission for Latin America and the Caribbean (ECLAC), on the basis of Centre for Research on the Epidemiology of Disasters (CRED), EM-DAT International Disaster Database [online] https://www.emdat.be/.

Another effect of this type of extreme event is to increase the pressures that drive emigration, which has a strong female component in the region. For example, Hurricane Maria caused between 20.5% and 27.3% of Dominica's total population to migrate, while 861 men and 773 women had to be evacuated from Barbuda and taken to Antigua (Lebrechtta, 2019). As in Central America, extreme events negatively affect women's economic autonomy, reducing their livelihoods and increasing the burden of reproductive work and unpaid care. In the Caribbean, many poor women are employed at the lower end of the tourism sector: when disasters cause severe damage to the sector, many are left unemployed because they do not have the skills to take up other jobs (ECLAC, 2019c).

According to Bello and De Meira (2019), the Caribbean countries were more affected than other types of small island developing States in the period 1990–2018 in terms of the number of disasters, the ratio of affected

population to total population, and the ratio of damage to GDP. The ratio of affected population to total population was 5.8% in Caribbean small island developing States, 3.5% in the Pacific and 2.1% in the Atlantic, the Indian Ocean, the Mediterranean and the South China Sea. "As regards the damage/GDP ratio, the highest average value was in the Caribbean, followed by SIDS in the AIMS region (3.7%) and SIDS in the Pacific (2.8%)" (ECLAC/ILPES, 2019, p. 47). Where Central America and South America are concerned, the average value of the damage-to-GDP ratio in countries where a disaster occurred during the period 1970–2010 was 6.9% in the Caribbean, 3% in Central America and 0.4% in South America (Bello and others, 2017).

The Caribbean is an outlier for the economic impact of disasters relative to the size of economies. For example, in four assessments of the disasters[16] occurring in the Atlantic during the 2017 hurricane season, the total cost was found to have exceeded 40% of GDP;[17] in three of them, it was over 100%. External shocks of this magnitude mean that social and economic gains may be lost, underscoring the importance of including resilience components in development policies.

5. The challenge of debt in the Caribbean

The Caribbean region faces difficulties arising from high debt and slow growth. The structurally high level of debt in the countries of the region is periodically compounded by economic losses caused by extreme weather events. The Caribbean small island developing States are among the most indebted in the world, and the level of public debt to GDP is particularly severe in Antigua and Barbuda, Barbados, Grenada, Jamaica and Saint Kitts and Nevis. The situation is exacerbated by declining foreign direct investment (FDI) flows, high unemployment, especially among youth, and slow economic growth.

---

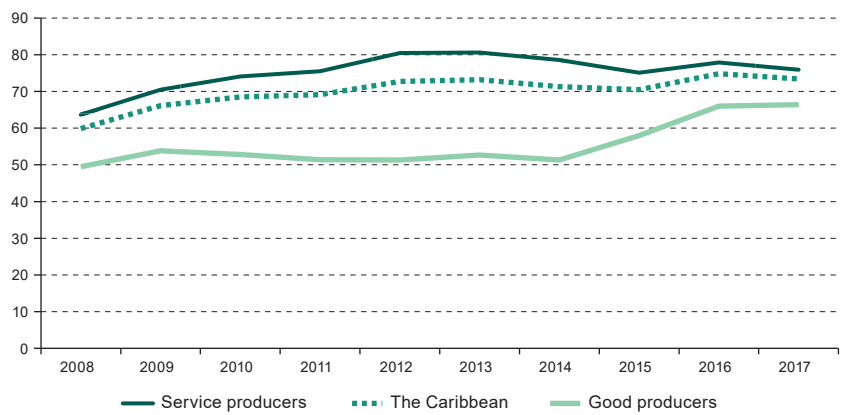
[16] The Economic Commission for Latin America and the Caribbean (ECLAC) has been a pioneer in disaster assessment and the development of a methodology for this purpose. The damage and loss assessment (DaLA) methodology serves to calculate the losses, damages and additional costs associated with a specific event. The main references used in this section are the disaster assessments carried out by ECLAC in the following countries: Bahamas (2015, 2016 and 2017), Belize (2016), Anguilla (2017), Turks and Caicos Islands (2017), British Virgin Islands (2017) and Sint Maarten (2017). The 2016 assessments of Belize and the Bahamas were conducted jointly with the Food and Agriculture Organization of the United Nations (FAO) and the Pan American Health Organization (PAHO). The 2015 and 2017 assessments of the Bahamas were conducted in conjunction with PAHO, and those of Anguilla and Sint Maarten with the Caribbean Development Bank.

[17] Reported damage underestimates the effects of disasters, since the EM-DAT International Disaster Database only contains information on damage defined as partially or totally destroyed physical assets. ECLAC evaluations include losses (the monetary value of goods that go unproduced and services that go unprovided) and additional costs incurred in producing goods and temporarily providing interrupted services, in addition to the costs of dealing with the emergency (ECLAC, 2014a). From this other point of view, losses from hurricanes Irma and Maria in Anguilla, the Bahamas, the British Virgin Islands, the Turks and Caicos Islands and Sint Maarten represented 48% of the total cost.

In fact, the slowness of growth is partly attributed to the debt burden, as it restricts fiscal space and has made it difficult to finance the Sustainable Development Goals (SDGs). High debt has induced a period of fiscal consolidation that restricts the ability to sustain social spending and the much-needed investment in infrastructure that precedes private investment. The economic situation in the subregion has been aggravated by the long decline of foreign direct investment, which is an important source of funding.

Figure III.24 shows the debt path from 2008 to 2017, distinguishing between countries that export goods and countries that export services, such as tourism or financial services. It should be noted that the debt of goods exporters has increased as a result of declining commodity prices and falling tax revenues.

Figure III.24
The Caribbean: total public debt, 2008–2017
(Percentages of GDP)



Source: Economic Commission for Latin America and the Caribbean (ECLAC), on the basis of official data from the countries; Economic Commission for Latin America and the Caribbean (ECLAC), *Fiscal Panorama of Latin America and the Caribbean, 2019* (LC/PUB.2019/8-P), Santiago, 2019; *Fiscal Panorama of Latin America and the Caribbean*, 2018 (LC/PUB.2018/4-P), Santiago, 2018; *Fiscal Panorama of Latin America and the Caribbean*, 2017 (LC/PUB.2017/6-P), Santiago, 2017; *Fiscal Panorama of Latin America and the Caribbean*, 2016 (LC/L.4140), Santiago, 2016.

The average debt burden has increased since the global crisis of 2008–2009 despite the implementation of adjustment programmes, whether domestically initiated or agreed with the International Monetary Fund (IMF). In 2017, the average debt in the Caribbean was equivalent to 73.6% of GDP: 66.4% in goods-producing countries and 75.9% in service providers. Seven Caribbean countries had debts exceeding 70% of GDP; considering that the debt sustainability threshold according to the IMF is 60% of GDP, it is no exaggeration to say that the region is in difficulties. Debt service is also critical. Total service represented 27% of the subregion's GDP: 26% in goods-producing countries and 27% in service providers. In one extreme case, interest and repayments represented about 60% of government revenue.

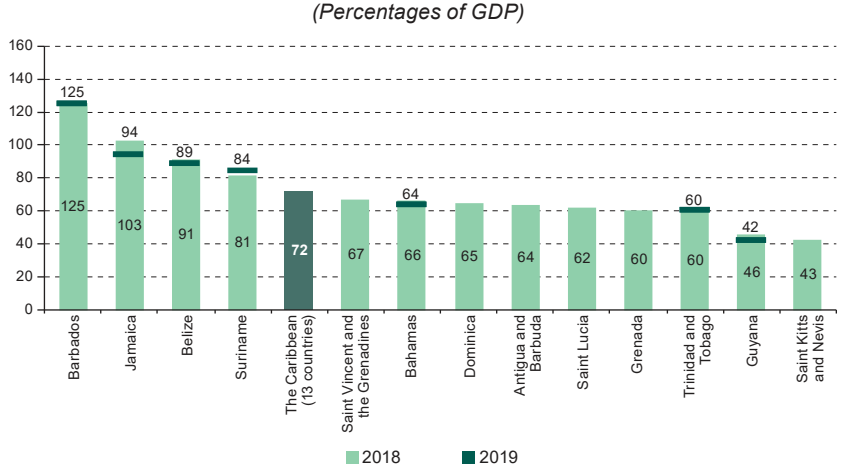
Heavy borrowing is the result of structural weaknesses and vulnerabilities inherent in small island developing States, in particular heavy exposure to natural disasters. ECLAC therefore recognizes that the build-up of debt is explained by several factors and not only by fiscal excesses. These factors include the impact of negative external shocks and the effects of climate change and extreme events. As demonstrated in the 2017 hurricane season, these phenomena represent the greatest threat to Caribbean countries. The number of countries affected and the magnitude of the damage caused by extreme events in the region has increased significantly since the 1970s. "This fiscal situation is a factor that could lead to a vicious circle in which reconstruction is not completed after a disaster and such reconstruction as is carried out is not resilient because of a lack of financial resources. This would increase vulnerability, and the effects and impacts of a further disaster would be greater" (ECLAC/ILPES, 2019, p. 70).

In this context, ECLAC is proposing a debt for climate adaptation swap initiative to help countries reduce debt burdens while strengthening growth.

6. The ECLAC debt for climate adaptation swap initiative

The ECLAC proposal recognizes that generating the large surpluses needed to stabilize debt is also a cause of low growth and that debt servicing limits the ability of Caribbean countries to address the sustainable development agenda (see figure III.25).

Figure III.25
The Caribbean (13 countries): gross central government public debt, 2018–2019[a]
(Percentages of GDP)



Source: Economic Commission for Latin America and the Caribbean (ECLAC), *Economic Survey of Latin America and the Caribbean, 2019* (LC/PUB.2019/12-P), Santiago, 2019.
[a] The 2018 figures are for the year's end and the 2019 figures are for March.

The debt relief approach proposed by ECLAC has two dimensions:

(i) In the case of countries that are heavily indebted to official creditors, funds interested in fostering resilience and adaptation would be persuaded to acquire multilateral and bilateral debt at negotiated discount rates.

(ii) In the case of countries that are heavily indebted to private creditors, a repurchase and debt swap mechanism would be applied. The Caribbean countries' debt repayments would be deposited in a fund earmarked for climate resilience, in order to finance investments in green industries clearly aimed at adaptation and mitigation projects, in accordance with the countries' own priorities.

The role of climate funds is crucial, as the funds committed would already be discounted in donors' budgets and would represent a resource that could be drawn on. These funds would be among the few sources of concessional financing for middle-income countries such as the small island developing States of the Caribbean.

The resilience fund would provide financing to obtain a mix of public and private resources for green industries able to meet the requirements of climate funds and oriented towards the development of greener value chains. Such industries would encompass production, marketing, regulation, and research and development.

The ECLAC proposal may also be attractive to creditors: it would offer lower payment risk, strengthen the resilience of Caribbean countries and help to build up a fund that could be gradually increased through investments with positive returns. It is also an opportunity for member countries to secure the fiscal space needed to generate the requisite investment, while pursuing adaptation and mitigation strategies. The proposal could inspire a broad approach in the region whereby fiscal management can be improved and a future debt build-up prevented, while providing a coordination framework for financing more sustainable growth in the region.[18]

The twenty-sixth meeting of the Caribbean Development and Cooperation Committee (CDCC), held in April 2016, supported the ECLAC proposal. The initiative was also endorsed by CARICOM heads of government at the thirty-eighth session held in July 2017. To move towards the resolution, the CDCC recommended the creation of a working group that has now met twice. The latest meeting recommended three countries to test the initiative, illustrate its benefits and initiate dialogue with major creditors and sources of climate financing. The recommended countries were Antigua and Barbuda, Saint Lucia and Saint Vincent and the Grenadines, owing to their debt profile and

[18] ECLAC recognizes the need to improve fiscal management and has worked with several countries in the Caribbean to develop their capacity to carry out fiscal expenditure assessments so that government priorities are better aligned with budget allocations.

the impact that Hurricanes Irma and Maria had on Barbuda. The dialogue is proceeding cautiously to avoid premature announcements that could affect the collaboration of creditors. The respective debts are being analysed using the World Bank framework and the IMF debt sustainability analysis to determine how the initiative would work. This will provide guidance on the level of discount needed to operationalize the proposal. ECLAC is to study the impact of debt relief on progress towards compliance with the SDGs and contrast the gap between repayment and the financing needed to achieve that objective.

The heart of the initiative is that multilateral institutions forgive part of the debt of the smaller economies and that an amount equivalent to the annual payment be contributed in the local currency of the debtor countries to the aforementioned Caribbean Resilience Fund, whose purpose is to finance mitigation and adaptation processes for 10 years. This instrument, which would advance the 2030 Agenda for Sustainable Development, requires the solidarity of Latin American countries that have a vote at IMF, the World Bank and the Inter-American Development Bank (IDB) (ECLAC, 2016a).

Although they are financially fragile and investment efficiency is low, many Caribbean countries have limited access to concessional external financing because they are considered middle-income. Restricted access to financing and adjustments arising from their debt situation make it difficult to adopt and implement projects aimed at mitigating and adapting to climate change. In addition to debt relief, the external constraint needs to be eased in other respects in the Caribbean; for example, reliance on energy-linked imports needs to be reduced and mobility and coastal protection based on ecosystem solutions need to be improved, all of which would help expand the scope for the countries' development.

D. Conclusions

When it comes to climate change, the countries of Central America and the Caribbean are more vulnerable than the rest of the region because of a combination of factors such as the occurrence of extreme weather events, the small size of their territories, their relatively limited economic structures and the constraints of their fiscal position.

This is compounded by a limited capacity for planning, information generation and prevention, all of which has cumulative effects that reduce the development capacity of these countries. The situation in the Caribbean is particularly serious because of the heavy debt burden, the recurrence of hurricane damage and losses, and the increasing rate of urbanization. The type of urban growth, which is rapid and unplanned and has significant infrastructure deficits, increases vulnerability owing to high exposure to the sea and the low elevation of human settlements.

Disaster risk reduction and the response to sea level rise, i.e., adaptation, has multiple fronts ranging from information generation to financial protection and public participation. In these countries, ecosystem-based adaptation plays a particularly important role in coastal protection. At the same time, adaptation actions are in some cases inseparable from mitigation actions, examples being mangrove and coral recovery and urban densification. A pattern of consumption that was less dependent on imports, such as one based on renewable energy and better public mobility systems, could help alleviate the burden of the external constraint.

In the face of this scenario, it is essential to increase the scope for financial action to promote adaptation and resilience in the Caribbean countries, whence the ECLAC initiative of reducing debt by swapping it for investment in resilience. The idea is that this would break the vicious circle of failure to fully address vulnerabilities and lack of resilience because there are not enough fiscal resources for investment, which interacts with social dynamics to create chronic barriers to development and perpetuate and even worsen vulnerability.

C. The benefits and estimated costs of adaptation

1. The costs of adaptation

Latin America and the Caribbean is a region that is highly vulnerable to extreme weather events, as was seen in chapter III. According to the Centre for Research on the Epidemiology of Disasters (CRED),[3] 84,000 people died because of them between 1990 and 2017, and over 163 million were directly affected (ECLAC, 2019a).

Identifying and measuring the economic cost of adaptation measures is a complicated process, not least because it is difficult to identify a specific adaptation baseline distinct from existing development gaps (Agrawala and Fankhauser, 2008; World Bank, 2010). The Economic Commission for Latin America and the Caribbean (ECLAC) underscores the importance of progress in implementing climate change adaptation measures as part of development strategy: such measures should respond to the nature of climate change and the collateral risks it creates, such as growing demand for energy, food and raw materials and continuous pressures on the environment. Furthermore, conditions of vulnerability and poverty should be considered when implementing the measures, as should projected climate trends for the twenty-first century (ECLAC, 2018b). The costs of efficient adaptation processes for the region are lower than those associated with inaction in the face of the impact of climate change. Investing in adaptation is an economically efficient option that is consistent with the guidelines of the 2030 Agenda for Sustainable Development.

There are preliminary estimates of the costs of adapting to climate change in the region, although they are highly uncertain. In 2010, the World Bank estimated these annual costs at between US$ 16.8 billion and US$ 21.5 billion between 2010 and 2050.[4] The estimate includes agriculture, water resources, infrastructure, coastal zones, health, extreme weather events and fisheries. This expenditure is equivalent to less than 0.3% of regional GDP and would mainly go on protecting coastal zones (World Bank, 2010; Galindo and others, 2014c). Agrawala and others (2010) put adaptation costs at around 0.24% of regional GDP. This estimate included irrigation, water infrastructure, coastal protection, early warning systems, investment in climate-resilient settlements, cooling, treatment of diseases and investment in adaptation research and development.

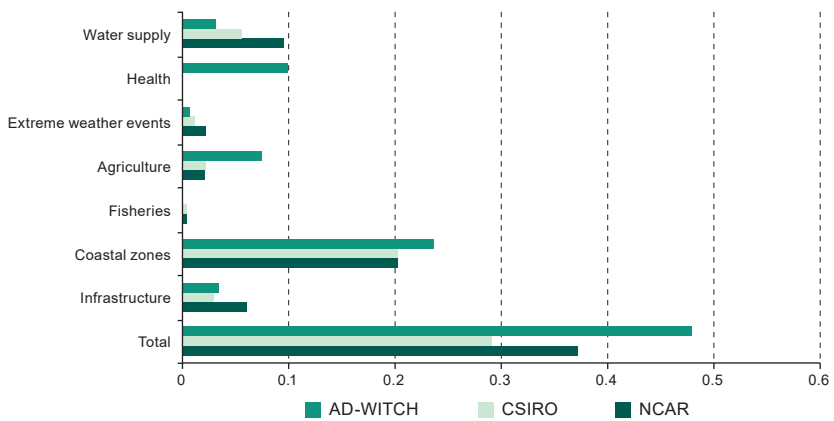
---

[3] See Centre for Research on the Epidemiology of Disasters (CRED), EM-DAT International Disaster Database [online] http://www.emdat.be/.

[4] Undiscounted figures.

Going by these figures, the cost of adaptation would be less than 0.5% of the region's GDP as of the end of the first decade of this century (World Bank, 2010; Vergara and others, 2013). However, these estimates have limitations, are subject to significant uncertainties, are difficult to compare and are likely to underestimate the costs of adaptation, as losses without a market value are ignored. They mainly include hard adaptation measures, namely infrastructure works (Agrawala and Fankhauser, 2008; Stern, 2007; ECLAC, 2014b) and underestimate nature-based options (see figure IV.2).

Figure IV.2
Latin America and the Caribbean: average annual cost of adaptation, 2010–2050
(Percentages of regional GDP)



Source: W. Vergara and others, *The Climate and Development Challenge for Latin America and the Caribbean: Options for Climate-Resilient, Low-Carbon Development*, Washington, D.C., Inter-American Development Bank (IDB), 2013; World Bank, *Natural Hazards, UnNatural Disasters: The Economics of Effective Prevention*, Washington, D.C., 2010; S. Agrawala and others, "Plan or react? Analysis of adaptation costs and benefits using integrated assessment models", *OECD Environment Working Papers*, No. 23, Paris, Organization for Economic Cooperation and Development (OECD), 2010.

Note: The total adaptation costs come from World Bank (2010) and Agrawala and others (2010). The former reflect the scenarios of the National Centre for Atmospheric Research (NCAR) and the Commonwealth Scientific and Industrial Research Organization (CSIRO) and run up to 2050. Those of the study by Agrawala and others (2010) are for 2105. AD-WITCH is the adaptation module of the WITCH global dynamic model, which integrates interactions between the economy, technological options and climate change.

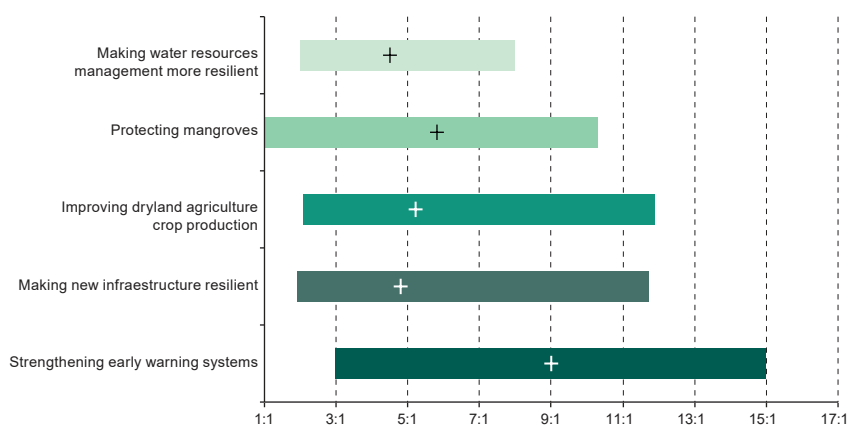
The common ground between adaptation and sustainable development make the two processes synergetic (Osman-Elasha and others, 2009). However, to achieve these synergies, timely and efficient climate change adaptation processes would have to be incorporated into national development plans, with their mechanisms for monitoring and evaluating measures implemented by local and national governments. In addition, there should be common metrics to make adaptation processes and progress with them comparable at the regional level (ECLAC, 2017). In a context of rising global temperatures and their regional effects, implementing efficient and equitable climate

change adaptation processes should be a priority. This means inducing the necessary changes in the behaviour of economic and social agents through public policies, economic incentives or changes in individual characteristics that trigger or induce these adaptation processes (OECD, 2012; Artikov and others, 2006; Knowler and Bradshaw, 2007; Prokopy and others, 2008; Galindo and others, 2014a).

2. Potential economic benefits

Investment in adaptation, like any investment, has multiplier effects on the rest of the economy: it is essentially preventive and offers an opportunity not only to reduce the negative impact of climate change but also to narrow development gaps and boost economies. The report of the Global Commission on Adaptation (2019) led by Ban Ki-moon, which was published in September 2019, states that investment in adaptation has a very high total rate of return: the cost-benefit ratio ranges from 2:1 to 10:1 and in some cases is even higher (see figure IV.3).

Figure IV.3
Cost-benefit ratios of some illustrative investments in adaptation, 2020–2030



Source: Economic Commission for Latin America and the Caribbean (ECLAC), on the basis of Global Commission on Adaptation, *Adapt Now: A Global Call for Leadership on Climate Resilience*, Amsterdam, 2019.

Note: Approximate global net benefits to be gained by 2030 from an illustrative investment of US$ 1.8 trillion in five areas. Actual returns depend on many factors, such as economic growth and demand, policy context, institutional capacities and the condition of assets. Also, these investments neither address all that may be needed within sectors (e.g. adaptation in the agricultural sector will consist of much more than dryland crop production) nor include all sectors (as health, education and industry sectors are not included). Data and methodological limitations mean that this graph does not imply full comparability of investments across sectors or countries.

Annex 45 bis

"Rising to the climate challenge: Coastal and marine resilience in the Caribbean", Canari Issue Paper, 2021, pages 1-3

CANARI ISSUE PAPER

No. 2

Rising to the climate challenge: Coastal and marine resilience in the Caribbean

Climate change poses a critical challenge for Caribbean small island developing states (SIDS). Rising sea levels and sea surface temperatures, ocean acidification and more intense hurricanes and storms, and the resulting impacts on coastal and marine ecosystems, pose significant threats to communities, livelihoods and key economic sectors that depend on these ecosystems. Building coastal and marine resilience is a priority for the region. While there have been significant strides to build resilience over the last decade, there remains a need for action 'on the ground' focused on the needs of the most vulnerable, including women, youth and key resource users such as fisherfolk. This issue paper highlights important lessons and innovations from work by the Caribbean Natural Resources Institute (CANARI) to build resilient coastal and marine ecosystems and livelihoods in Caribbean SIDS using a participatory and socially inclusive approach. It presents tools and methods that can be used by stakeholders responsible for or involved in management of coastal and marine resources – government agencies, civil society organisations (CSOs), including community and resource user groups, and the private sector. It further presents recommendations for funding agencies, policy makers and technical partners supporting management actions, including through the design and delivery of regional and national programmes, projects and initiatives.

This issues paper draws on ten years of work by CANARI and its partners across the Caribbean, particularly under the following projects:

- **Climate Change Adaptation in the Fisheries of Anguilla and Montserrat**, 2017-2020, funded by the United Kingdom Government under the Darwin Initiative
- **Climate ACTT: Action by Civil Society in Trinidad and Tobago to build resilience to climate change,** 2015-2016, funded by Conservational International and BHP Billiton.



Sargassum clogging the coastline, Tobago, January 2018. Credit: CANARI

- **Engaging Civil Society in Strategic Action Programme Implementation** under the Catalysing Implementation of the Strategic Action Programme for the Sustainable Management of Shared Living Marine Resources in the Caribbean and North Brazil Shelf Large Marine Ecosystems (CLME+) Project, 2017-2021, led by the United Nations Development Programme (UNDP) and funded by the Global Environment Facility (GEF) (32 countries and territories across Latin America and the Caribbean)
- **Powering Innovations in Civil Society and Enterprises for Sustainability in the Caribbean (PISCES)**, 2017-2020, funded by the European Union EuropeAid Programme (10 countries: Antigua and Barbuda, The Bahamas, Dominica, Grenada, Haiti, Jamaica, St. Kitts and Nevis, Saint Lucia, St. Vincent and the Grenadines, Trinidad and Tobago)
- **Regional Implementation of a Vulnerability and Capacity Assessment of Coastal and Fishing Communities** under the Climate Change Adaptation in the Eastern Caribbean Fisheries Sector Project (CC4FISH), 2017-2020, led by the Food and Agriculture Organization of the United Nations (FAO) and funded by GEF (5 countries: Grenada, St. Kitts and Nevis, Saint Lucia, St. Vincent and the Grenadines, Trinidad and Tobago)
- **Strengthening Caribbean Fisherfolk to Participate in Governance Project**, 2013-2016, funded by the European Union EuropeAid Programme (17 countries: Anguilla, Antigua and Barbuda, The Bahamas, Belize, Barbados, Dominica, Grenada, Guyana, Haiti, Jamaica, Montserrat, St. Kitts and Nevis, Saint Lucia, St. Vincent and the Grenadines, Suriname, Trinidad and Tobago, Turks and Caicos)

Why build coastal and marine resilience?

With 70% of the Caribbean population living and working in coastal areas, where most of the infrastructure (including roads, airports and seaports) is also located, the impacts of climate change on coastal and marine resources and the communities, livelihoods and economic sectors that depend on these resources are of particular concern[i]. Rising sea levels, increased air and sea surface temperatures, ocean acidification, rainfall variability and more intense hurricanes and storms are expected to trigger a series of interconnected and cascading biophysical and socio-economic impacts. The tourism and fisheries sectors, which are key contributors to employment, food security and gross domestic product (GDP) in Caribbean SIDS, will be affected by the erosion of beaches and loss of coral reefs and mangroves due to sea level rise, coral bleaching with rising sea surface temperatures, more intense storms and storm surges and ocean acidification. The cost to Caribbean SIDS from increased hurricane damage, infrastructure damage and loss of tourism revenue due to climate change is projected to reach $22 billion by 2050 or about 10% of the current regional economy[ii].

Climate change compounds existing challenges facing coastal and marine areas, including ecosystem loss and degradation from ad hoc development, pollution, invasive species, resource overexploitation, disease outbreaks and natural disasters such as earthquakes and volcanic eruptions. The combined effects threaten the long-term sustainability of coastal and marine resources and associated communities, livelihoods and economic sectors. Impacts are often hardest on vulnerable and marginalised groups, including poor coastal residents, community entrepreneurs, and subsistence and small-scale resource users such as fisherfolk.

Recognising these challenges, building coastal and marine resilience is a priority for Caribbean SIDS. **Resilience refers to the ability of a community, organisation or economic or natural system to resist, absorb and recover from the impacts of a hazard or shock while maintaining its structure and function[iii]**. Simply put, it is the capacity of a system to deal with change and continue to develop, or to 'survive and thrive.' Ensuring that coastal and marine resources, and the communities, livelihoods and economic sectors that depend on them, have



Coastal erosion in Guayaguayare, South Trinidad, May 2018.
Credit: Coastal Protection Unit, Trinidad & Tobago

the capacity to effectively withstand and recover from the impacts of climate change and other environmental and socio-economic changes is crucial for the region's development and long-term sustainability.

Building coastal and marine resilience requires:

- **recognising that humans and nature are closely interlinked, and that coastal and marine areas are integrated social-ecological systems**. Coastal and marine ecosystems provide critical goods and services for Caribbean communities and economies, which shape and alter these ecosystems. Attention must be paid to the multiple processes and impacts of climate change and other pressures on coastal and marine ecosystems, economies, livelihoods and well-being, and their interlinkages, to fully understand the impacts on the system and solutions for socio-economic and ecological resilience.
- **managing uncertainty** as climate change presents new and unexpected impacts and risks for Caribbean SIDS, including new infectious diseases, poor air quality (e.g. due to frequent Sahara dust plumes), mass sargassum strandings (e.g. due to increased soil erosion and nutrient inputs in the tropical North Atlantic Ocean) and unprecedented extreme weather events (e.g. the occurrence of back-to-back Category 5 Hurricanes in 2017). Robust climate information and monitoring systems are needed to enable planning for different scenarios and evidence-based decision-making.
- **innovation and shared learning** as new approaches, tools and practices are needed, which maintain socio-economic well-being and ecological integrity and build climate resilience. These approaches must draw on diverse experiences and interests, including of the most vulnerable and marginalised groups such as women, youth and the very poor. Further, enabling institutions, including policies, laws and governance structures, can facilitate integration, innovation and shared learning to build resilience.

Approaches to build coastal and marine resilience in the Caribbean

Caribbean governments have taken significant strides towards coastal and marine resilience over the last decade through climate modelling and information services, assessing coastal hazards and vulnerabilities, mainstreaming climate change into policies and plans and investing in large-scale physical infrastructure for coastal protection (e.g. sea walls and revetments) and addressing water and energy security (e.g. via desalination plants and solar powered plants). Regional agencies, including the Caribbean Community (CARICOM) and Organisation for the Eastern Caribbean States (OECS), have also enabled coordinated action and access to finance for climate change adaptation, mitigation and resilience building. These national and regional efforts are aligned with global commitments under the United Nations Framework Convention on Climate Change (UNFCCC) and its Paris Agreement, the 2030 Agenda and its 17 Sustainable Development Goals (SDGs) including Goal 13 Climate Action and the SIDS Accelerated Modalities of Action (SAMOA) Pathway.

However, there has been less attention and action 'on the ground' focused on the needs of the most vulnerable coastal communities and groups. These groups include small-scale farmers and fisherfolk, small and micro enterprise (SME) owners and members, women and youth whose livelihoods and well-being depend on coastal and marine resources, and who are already being impacted by climate change. CANARI has sought to engage and empower these vulnerable communities and groups, and wider civil society, to build resilient coastal and marine ecosystems and livelihoods using a participatory and inclusive approach. This work has included awareness raising and advocacy, assessing vulnerabilities and enhancing local capacity and action to adapt and build resilience to climate change.

Issues and proposed solutions to build resilience 'on the ground'

Although the importance of building resilience 'on the ground' is well recognised, there are several challenges that discourage a focus at the local level. One such challenge is effectively engaging a wide range of stakeholders and sectors in resilience building efforts for an integrated and comprehensive response across all levels. CANARI has used a variety of tools and approaches in its work to build resilience of coastal and marine ecosystems and livelihoods using a participatory and inclusive approach. The following sections highlight CANARI's experiences, lessons learnt, best practices and innovations across Caribbean SIDS focused on community-based and ecosystem-based approaches.

1. Integrating local and traditional knowledge and practices into decision-making

Climate change impacts are felt differently across communities and sectors in Caribbean SIDS. Understanding the local impacts and vulnerabilities of communities, their livelihoods and supporting coastal and marine ecosystems is critical to develop solutions that are culturally appropriate and viable. Yet, the most vulnerable groups are often under-represented in decision-making processes, including

Annex 46

"Summary for Policymakers. Climate Change 2021 – The Physical Science Basis", Cambridge University Press, *Intergovernmental Panel on Climate Change,* 2021, pages 3-6, 18-21

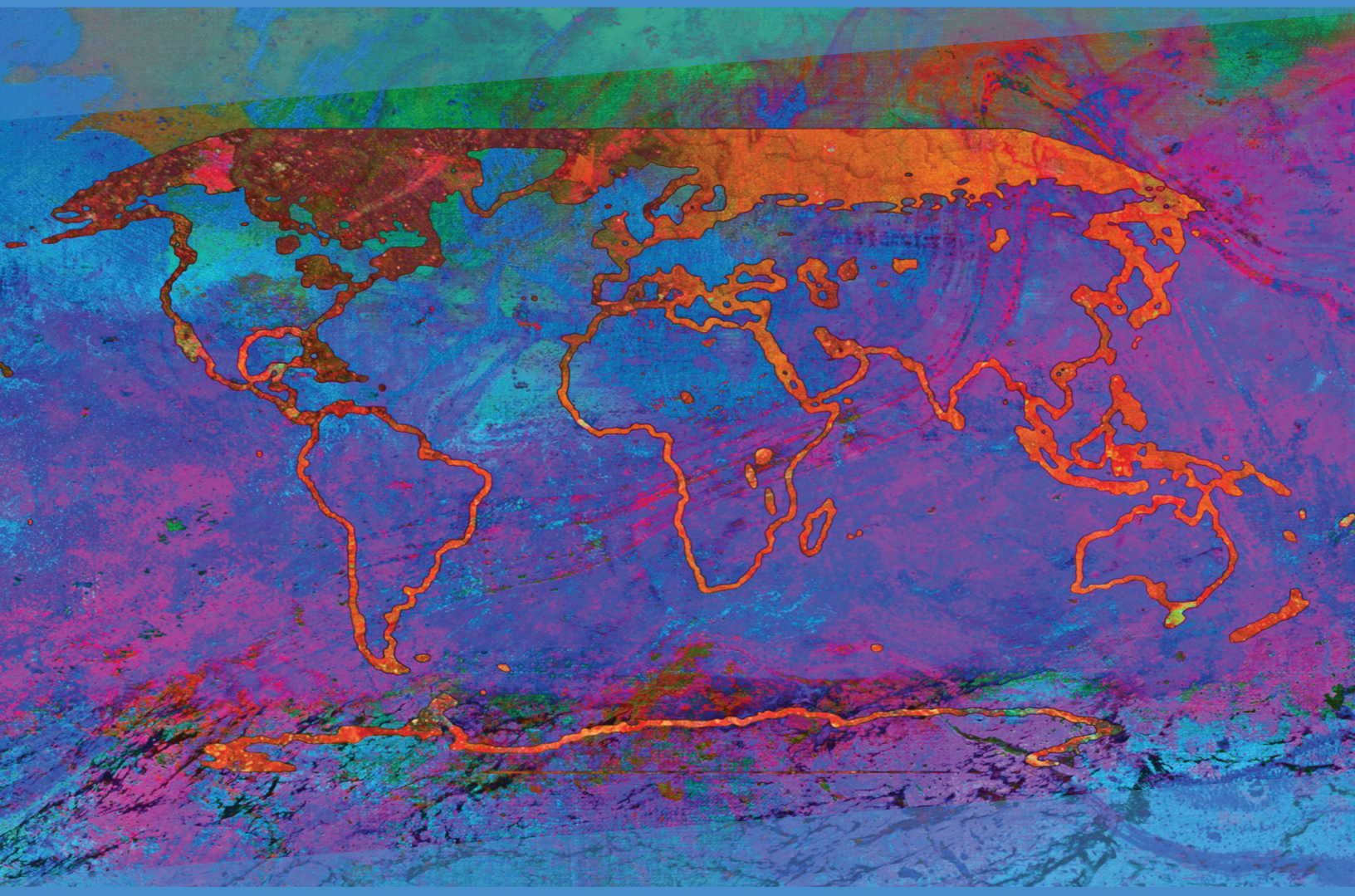
ipcc

INTERGOVERNMENTAL PANEL ON climate change

Climate Change 2021

The Physical Science Basis

Summary for Policymakers



WGI

Working Group I Contribution to the
Sixth Assessment Report of the
Intergovernmental Panel on Climate Change

WMO UNEP

Climate Change 2021
The Physical Science Basis

Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change

Edited by

Valérie Masson-Delmotte
Co-Chair Working Group I

Panmao Zhai
Co-Chair Working Group I

Anna Pirani
Head of TSU

Sarah L. Connors
Head of Science Team

Clotilde Péan
Head of Operations

Yang Chen
Senior Science officer

Leah Goldfarb
Senior Science officer

Melissa I. Gomis
Senior Science officer

J.B.Robin Matthews
Senior Science officer

Sophie Berger
Science Officer

Mengtian Huang
Science Officer

Ozge Yelekçi
Science Officer

Rong Yu
Science Officer

Baiquan Zhou
Science Officer

Elisabeth Lonnoy
Project Assistant

Thomas K. Maycock
Science Editor

Tim Waterfield
IT Officer

Katherine Leitzell
Communication Manager

Nada Caud
Outreach Manager

Working Group I Technical Support Unit

Front cover artwork: *Changing* by Alisa Singer, www.environmentalgraphiti.org © 2021 Alisa Singer.

© 2021 Intergovernmental Panel on Climate Change.
Printed October 2021 by the IPCC, Switzerland.
Electronic copies of this Summary for Policymakers are available from the IPCC website www.ipcc.ch

ISBN 978-92-9169-158-6

Summary for Policymakers

SPM

Summary for Policymakers

Drafting Authors:

Richard P. Allan (United Kingdom), Paola A. Arias (Colombia), Sophie Berger (France/Belgium), Josep G. Canadell (Australia), Christophe Cassou (France), Deliang Chen (Sweden), Annalisa Cherchi (Italy), Sarah L. Connors (France/United Kingdom), Erika Coppola (Italy), Faye Abigail Cruz (Philippines), Aïda Diongue-Niang (Senegal), Francisco J. Doblas-Reyes (Spain), Hervé Douville (France), Fatima Driouech (Morocco), Tamsin L. Edwards (United Kingdom), François Engelbrecht (South Africa), Veronika Eyring (Germany), Erich Fischer (Switzerland), Gregory M. Flato (Canada), Piers Forster (United Kingdom), Baylor Fox-Kemper (United States of America), Jan S. Fuglestvedt (Norway), John C. Fyfe (Canada), Nathan P. Gillett (Canada), Melissa I. Gomis (France/Switzerland), Sergey K. Gulev (Russian Federation), José Manuel Gutiérrez (Spain), Rafiq Hamdi (Belgium), Jordan Harold (United Kingdom), Mathias Hauser (Switzerland), Ed Hawkins (United Kingdom), Helene T. Hewitt (United Kingdom), Tom Gabriel Johansen (Norway), Christopher Jones (United Kingdom), Richard G. Jones (United Kingdom), Darrell S. Kaufman (United States of America), Zbigniew Klimont (Austria/Poland), Robert E. Kopp (United States of America), Charles Koven (United States of America), Gerhard Krinner (France/Germany, France), June-Yi Lee (Republic of Korea), Irene Lorenzoni (United Kingdom/Italy), Jochem Marotzke (Germany), Valérie Masson-Delmotte (France), Thomas K. Maycock (United States of America), Malte Meinshausen (Australia/Germany), Pedro M.S. Monteiro (South Africa), Angela Morelli (Norway/Italy), Vaishali Naik (United States of America), Dirk Notz (Germany), Friederike Otto (United Kingdom/Germany), Matthew D. Palmer (United Kingdom), Izidine Pinto (South Africa/Mozambique), Anna Pirani (Italy), Gian-Kasper Plattner (Switzerland), Krishnan Raghavan (India), Roshanka Ranasinghe (The Netherlands/Sri Lanka, Australia), Joeri Rogelj (United Kingdom/Belgium), Maisa Rojas (Chile), Alex C. Ruane (United States of America), Jean-Baptiste Sallée (France), Bjørn H. Samset (Norway), Sonia I. Seneviratne (Switzerland), Jana Sillmann (Norway/Germany), Anna A. Sörensson (Argentina), Tannecia S. Stephenson (Jamaica), Trude Storelvmo (Norway), Sophie Szopa (France), Peter W. Thorne (Ireland/United Kingdom), Blair Trewin (Australia), Robert Vautard (France), Carolina Vera (Argentina), Noureddine Yassaa (Algeria), Sönke Zaehle (Germany), Panmao Zhai (China), Xuebin Zhang (Canada), Kirsten Zickfeld (Canada/Germany)

Contributing Authors:

Krishna M. AchutaRao (India), Bhupesh Adhikary (Nepal), Edvin Aldrian (Indonesia), Kyle Armour (United States of America), Govindasamy Bala (India/United States of America), Rondrotiana Barimalala (South Africa/Madagascar), Nicolas Bellouin (United Kingdom/France), William Collins (United Kingdom), William D. Collins (United States of America), Susanna Corti (Italy), Peter M. Cox (United Kingdom), Frank J. Dentener (EU/The Netherlands), Claudine Dereczynski (Brazil), Alejandro Di Luca (Australia, Canada/Argentina), Alessandro Dosio (Italy), Leah Goldfarb (France/United States of America), Irina V. Gorodetskaya (Portugal/Belgium, Russian Federation), Pandora Hope (Australia), Mark Howden (Australia), A.K.M Saiful Islam (Bangladesh), Yu Kosaka (Japan), James Kossin (United States of America), Svitlana Krakovska (Ukraine), Chao Li (China), Jian Li (China), Thorsten Mauritsen (Germany/Denmark), Sebastian Milinski (Germany), Seung-Ki Min (Republic of Korea), Thanh Ngo Duc (Vietnam), Andy Reisinger (New Zealand), Lucas Ruiz (Argentina), Shubha Sathyendranath (United Kingdom/Canada, Overseas Citizen of India), Aimée B. A. Slangen (The Netherlands), Chris Smith (United Kingdom), Izuru Takayabu (Japan), Muhammad Irfan Tariq (Pakistan), Anne-Marie Treguier (France), Bart van den Hurk (The Netherlands), Karina von Schuckmann (France/Germany), Cunde Xiao (China)

This Summary for Policymakers should be cited as:

IPCC, 2021: Summary for Policymakers. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. In Press.

Introduction

This Summary for Policymakers (SPM) presents key findings of the Working Group I (WGI) contribution to the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6)[1] on the physical science basis of climate change. The report builds upon the 2013 Working Group I contribution to the IPCC's Fifth Assessment Report (AR5) and the 2018–2019 IPCC Special Reports[2] of the AR6 cycle and incorporates subsequent new evidence from climate science.[3]

This SPM provides a high-level summary of the understanding of the current state of the climate, including how it is changing and the role of human influence, the state of knowledge about possible climate futures, climate information relevant to regions and sectors, and limiting human-induced climate change.

Based on scientific understanding, key findings can be formulated as statements of fact or associated with an assessed level of confidence indicated using the IPCC calibrated language.[4]

The scientific basis for each key finding is found in chapter sections of the main Report and in the integrated synthesis presented in the Technical Summary (hereafter TS), and is indicated in curly brackets. The AR6 WGI Interactive Atlas facilitates exploration of these key synthesis findings, and supporting climate change information, across the WGI reference regions.[5]

A. The Current State of the Climate

Since AR5, improvements in observationally based estimates and information from paleoclimate archives provide a comprehensive view of each component of the climate system and its changes to date. New climate model simulations, new analyses, and methods combining multiple lines of evidence lead to improved understanding of human influence on a wider range of climate variables, including weather and climate extremes. The time periods considered throughout this section depend upon the availability of observational products, paleoclimate archives and peer-reviewed studies.

A.1 It is unequivocal that human influence has warmed the atmosphere, ocean and land. Widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred. {2.2, 2.3, Cross-Chapter Box 2.3, 3.3, 3.4, 3.5, 3.6, 3.8, 5.2, 5.3, 6.4, 7.3, 8.3, 9.2, 9.3, 9.5, 9.6, Cross-Chapter Box 9.1} (Figure SPM.1, Figure SPM.2)

A.1.1 Observed increases in well-mixed greenhouse gas (GHG) concentrations since around 1750 are unequivocally caused by human activities. Since 2011 (measurements reported in AR5), concentrations have continued to increase in the atmosphere, reaching annual averages of 410 parts per million (ppm) for carbon dioxide (CO_2), 1866 parts per billion (ppb) for methane (CH_4), and 332 ppb for nitrous oxide (N_2O) in 2019.[6] Land and ocean have taken up a near-constant proportion (globally about 56% per year) of CO_2 emissions from human activities over the past six decades, with regional differences (*high confidence*).[7]
{2.2, 5.2, 7.3, TS.2.2, Box TS.5}

---

1 Decision IPCC/XLVI-2.

2 The three Special Reports are: Global Warming of 1.5°C: An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty (SR1.5); Climate Change and Land: An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (SRCCL); IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC).

3 The assessment covers scientific literature accepted for publication by 31 January 2021.

4 Each finding is grounded in an evaluation of underlying evidence and agreement. A level of confidence is expressed using five qualifiers: very low, low, medium, high and very high, and typeset in italics, for example, *medium confidence*. The following terms have been used to indicate the assessed likelihood of an outcome or result: virtually certain 99–100% probability; very likely 90–100%; likely 66–100%; about as likely as not 33–66%; unlikely 0–33%; very unlikely 0–10%; and exceptionally unlikely 0–1%. Additional terms (extremely likely 95–100%; more likely than not >50–100%; and extremely unlikely 0–5%) are also used when appropriate. Assessed likelihood is typeset in italics, for example, *very likely*. This is consistent with AR5. In this Report, unless stated otherwise, square brackets [x to y] are used to provide the assessed *very likely* range, or 90% interval.

5 The Interactive Atlas is available at https://interactive-atlas.ipcc.ch

6 Other GHG concentrations in 2019 were: perfluorocarbons (PFCs) – 109 parts per trillion (ppt) CF_4 equivalent; sulphur hexafluoride (SF_6) – 10 ppt; nitrogen trifluoride (NF_3) – 2 ppt; hydrofluorocarbons (HFCs) – 237 ppt HFC-134a equivalent; other Montreal Protocol gases (mainly chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs)) – 1032 ppt CFC-12 equivalent). Increases from 2011 are 19 ppm for CO_2, 63 ppb for CH_4 and 8 ppb for N_2O.

7 Land and ocean are not substantial sinks for other GHGs.

A.1.2 Each of the last four decades has been successively warmer than any decade that preceded it since 1850. Global surface temperature[8] in the first two decades of the 21st century (2001–2020) was 0.99 [0.84 to 1.10] °C higher than 1850–1900.[9] Global surface temperature was 1.09 [0.95 to 1.20] °C higher in 2011–2020 than 1850–1900, with larger increases over land (1.59 [1.34 to 1.83] °C) than over the ocean (0.88 [0.68 to 1.01] °C). The estimated increase in global surface temperature since AR5 is principally due to further warming since 2003–2012 (+0.19 [0.16 to 0.22] °C). Additionally, methodological advances and new datasets contributed approximately 0.1°C to the updated estimate of warming in AR6.[10]
{2.3, Cross-Chapter Box 2.3} (Figure SPM.1)

A.1.3 The *likely* range of total human-caused global surface temperature increase from 1850–1900 to 2010–2019[11] is 0.8°C to 1.3°C, with a best estimate of 1.07°C. It is *likely* that well-mixed GHGs contributed a warming of 1.0°C to 2.0°C, other human drivers (principally aerosols) contributed a cooling of 0.0°C to 0.8°C, natural drivers changed global surface temperature by –0.1°C to +0.1°C, and internal variability changed it by –0.2°C to +0.2°C. It is *very likely* that well-mixed GHGs were the main driver[12] of tropospheric warming since 1979 and *extremely likely* that human-caused stratospheric ozone depletion was the main driver of cooling of the lower stratosphere between 1979 and the mid-1990s.
{3.3, 6.4, 7.3, TS.2.3, Cross-Section Box TS.1} (Figure SPM.2)

A.1.4 Globally averaged precipitation over land has *likely* increased since 1950, with a faster rate of increase since the 1980s (*medium confidence*). It is *likely* that human influence contributed to the pattern of observed precipitation changes since the mid-20th century and *extremely likely* that human influence contributed to the pattern of observed changes in near-surface ocean salinity. Mid-latitude storm tracks have *likely* shifted poleward in both hemispheres since the 1980s, with marked seasonality in trends (*medium confidence*). For the Southern Hemisphere, human influence *very likely* contributed to the poleward shift of the closely related extratropical jet in austral summer.
{2.3, 3.3, 8.3, 9.2, TS.2.3, TS.2.4, Box TS.6}

A.1.5 Human influence is *very likely* the main driver of the global retreat of glaciers since the 1990s and the decrease in Arctic sea ice area between 1979–1988 and 2010–2019 (decreases of about 40% in September and about 10% in March). There has been no significant trend in Antarctic sea ice area from 1979 to 2020 due to regionally opposing trends and large internal variability. Human influence *very likely* contributed to the decrease in Northern Hemisphere spring snow cover since 1950. It is *very likely* that human influence has contributed to the observed surface melting of the Greenland Ice Sheet over the past two decades, but there is only *limited evidence*, with *medium agreement*, of human influence on the Antarctic Ice Sheet mass loss.
{2.3, 3.4, 8.3, 9.3, 9.5, TS.2.5}

A.1.6 It is *virtually certain* that the global upper ocean (0–700 m) has warmed since the 1970s and *extremely likely* that human influence is the main driver. It is *virtually certain* that human-caused CO_2 emissions are the main driver of current global acidification of the surface open ocean. There is *high confidence* that oxygen levels have dropped in many upper ocean regions since the mid-20th century and *medium confidence* that human influence contributed to this drop.
{2.3, 3.5, 3.6, 5.3, 9.2, TS.2.4}

A.1.7 Global mean sea level increased by 0.20 [0.15 to 0.25] m between 1901 and 2018. The average rate of sea level rise was 1.3 [0.6 to 2.1] mm yr^{-1} between 1901 and 1971, increasing to 1.9 [0.8 to 2.9] mm yr^{-1} between 1971 and 2006, and further increasing to 3.7 [3.2 to 4.2] mm yr^{-1} between 2006 and 2018 (*high confidence*). Human influence was *very likely* the main driver of these increases since at least 1971.
{2.3, 3.5, 9.6, Cross-Chapter Box 9.1, Box TS.4}

---

8 The term 'global surface temperature' is used in reference to both global mean surface temperature and global surface air temperature throughout this SPM. Changes in these quantities are assessed with *high confidence* to differ by at most 10% from one another, but conflicting lines of evidence lead to *low confidence* in the sign (direction) of any difference in long-term trend. {Cross-Section Box TS.1}

9 The period 1850–1900 represents the earliest period of sufficiently globally complete observations to estimate global surface temperature and, consistent with AR5 and SR1.5, is used as an approximation for pre-industrial conditions.

10 Since AR5, methodological advances and new datasets have provided a more complete spatial representation of changes in surface temperature, including in the Arctic. These and other improvements have also increased the estimate of global surface temperature change by approximately 0.1°C, but this increase does not represent additional physical warming since AR5.

11 The period distinction with A.1.2 arises because the attribution studies consider this slightly earlier period. The observed warming to 2010–2019 is 1.06 [0.88 to 1.21] °C.

12 Throughout this SPM, 'main driver' means responsible for more than 50% of the change.

A.1.8 Changes in the land biosphere since 1970 are consistent with global warming: climate zones have shifted poleward in both hemispheres, and the growing season has on average lengthened by up to two days per decade since the 1950s in the Northern Hemisphere extratropics (*high confidence*). {2.3, TS.2.6}

Human influence has warmed the climate at a rate that is unprecedented in at least the last 2000 years

Changes in global surface temperature relative to 1850–1900

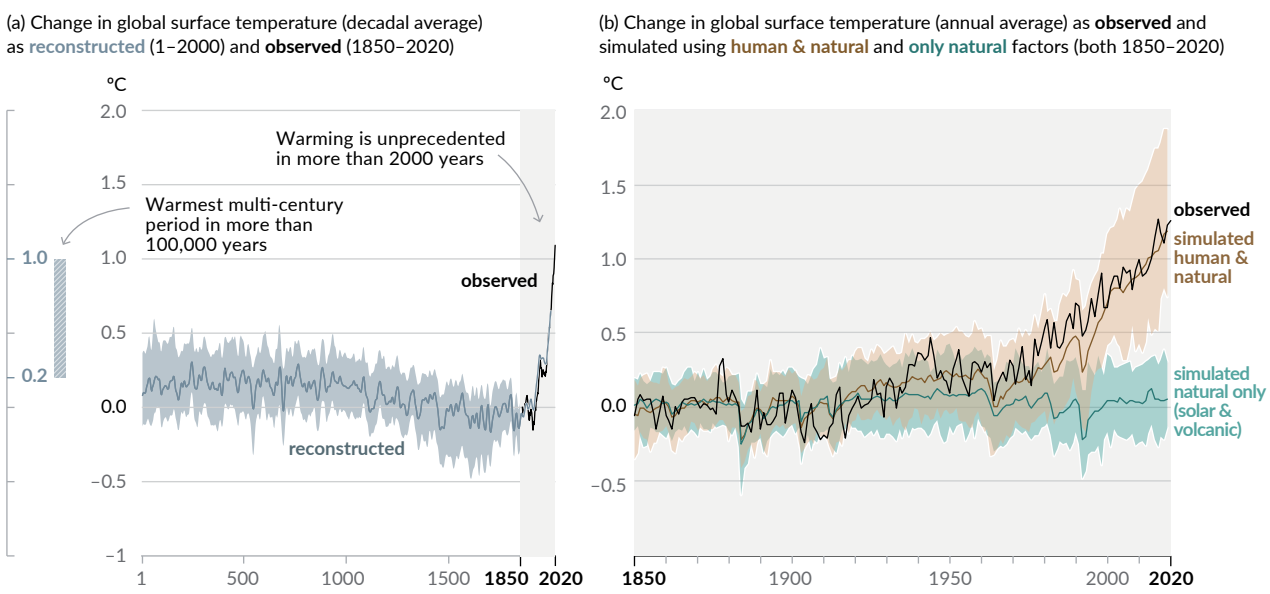


Figure SPM.1 | History of global temperature change and causes of recent warming

Panel (a) Changes in global surface temperature reconstructed from paleoclimate archives (solid grey line, years 1–2000) **and from direct observations** (solid black line, 1850–2020), both relative to 1850–1900 and decadally averaged. The vertical bar on the left shows the estimated temperature (*very likely* range) during the warmest multi-century period in at least the last 100,000 years, which occurred around 6500 years ago during the current interglacial period (Holocene). The Last Interglacial, around 125,000 years ago, is the next most recent candidate for a period of higher temperature. These past warm periods were caused by slow (multi-millennial) orbital variations. The grey shading with white diagonal lines shows the *very likely* ranges for the temperature reconstructions.

Panel (b) Changes in global surface temperature over the past 170 years (black line) relative to 1850–1900 and annually averaged, compared to Coupled Model Intercomparison Project Phase 6 (CMIP6) climate model simulations (see Box SPM.1) of the temperature response to both human and natural drivers (brown) and to only natural drivers (solar and volcanic activity, green). Solid coloured lines show the multi-model average, and coloured shades show the *very likely* range of simulations. (See Figure SPM.2 for the assessed contributions to warming).

{2.3.1; Cross-Chapter Box 2.3; 3.3; TS.2.2; Cross-Section Box TS.1, Figure 1a}

Projected changes in extremes are larger in frequency and intensity with every additional increment of global warming

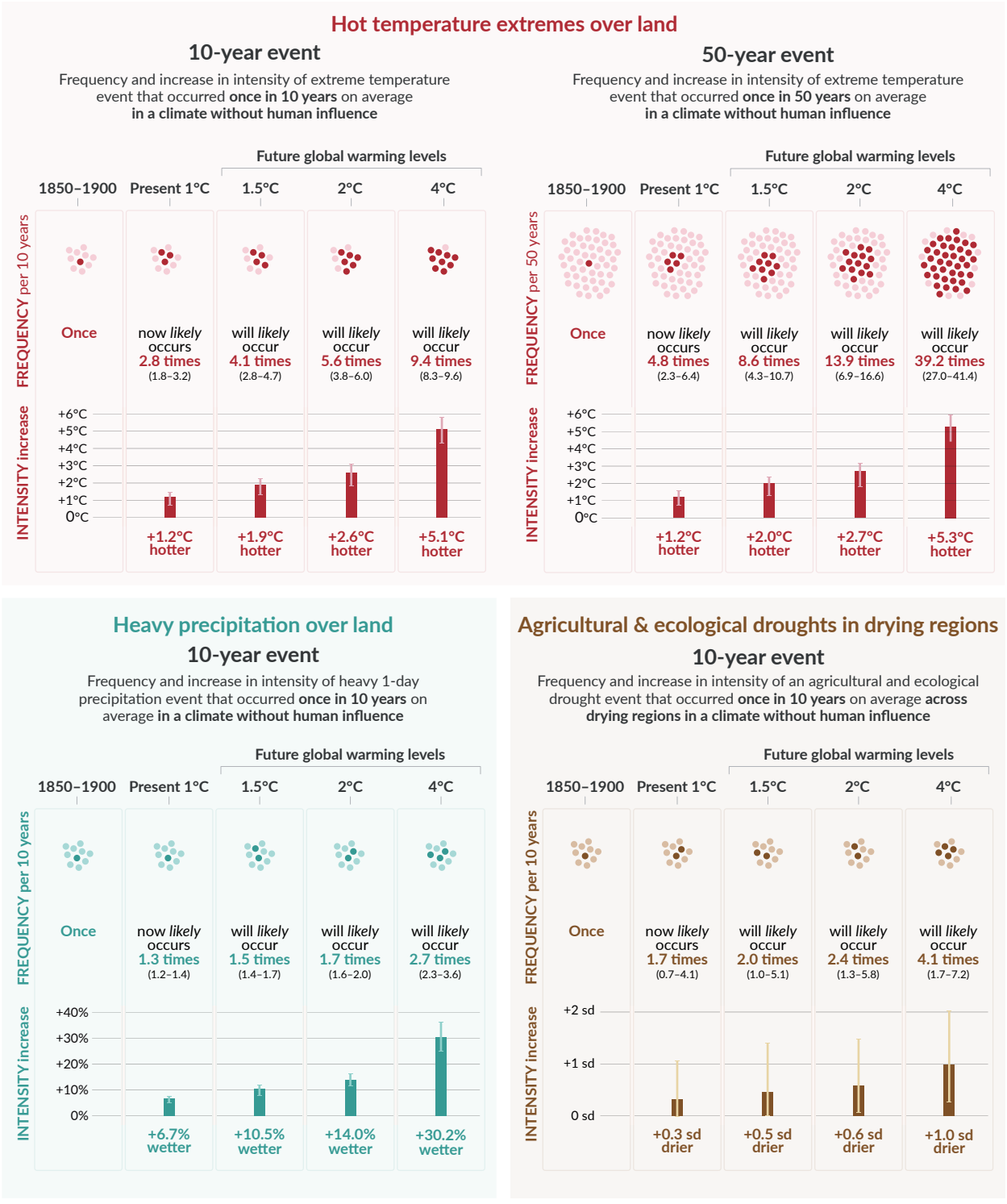


Figure SPM.6 | Projected changes in the intensity and frequency of hot temperature extremes over land, extreme precipitation over land, and agricultural and ecological droughts in drying regions

Projected changes are shown at global warming levels of 1°C, 1.5°C, 2°C, and 4°C and are relative to 1850–1900,[9] representing a climate without human influence. The figure depicts frequencies and increases in intensity of 10- or 50-year extreme events from the base period (1850–1900) under different global warming levels.

Hot temperature extremes are defined as the daily maximum temperatures over land that were exceeded on average once in a decade (10-year event) or once in 50 years (50-year event) during the 1850–1900 reference period. **Extreme precipitation events** are defined as the daily precipitation amount over land that

was exceeded on average once in a decade during the 1850–1900 reference period. **Agricultural and ecological drought events** are defined as the annual average of total column soil moisture below the 10th percentile of the 1850–1900 base period. These extremes are defined on model grid box scale. For hot temperature extremes and extreme precipitation, results are shown for the global land. For agricultural and ecological drought, results are shown for drying regions only, which correspond to the AR6 regions in which there is at least *medium confidence* in a projected increase in agricultural and ecological droughts at the 2°C warming level compared to the 1850–1900 base period in the Coupled Model Intercomparison Project Phase 6 (CMIP6). These regions include Western North America, Central North America, Northern Central America, Southern Central America, Caribbean, Northern South America, North-Eastern South America, South American Monsoon, South-Western South America, Southern South America, Western and Central Europe, Mediterranean, West Southern Africa, East Southern Africa, Madagascar, Eastern Australia, and Southern Australia (Caribbean is not included in the calculation of the figure because of the too-small number of full land grid cells). The non-drying regions do not show an overall increase or decrease in drought severity. Projections of changes in agricultural and ecological droughts in the CMIP Phase 5 (CMIP5) multi-model ensemble differ from those in CMIP6 in some regions, including in parts of Africa and Asia. Assessments of projected changes in meteorological and hydrological droughts are provided in Chapter 11.

In the **'frequency' section**, each year is represented by a dot. The dark dots indicate years in which the extreme threshold is exceeded, while light dots are years when the threshold is not exceeded. Values correspond to the medians (in bold) and their respective *likely* ranges based on the 5–95% range of the multi-model ensemble from simulations of CMIP6 under different Shared Socio-economic Pathway scenarios. For consistency, the number of dark dots is based on the rounded-up median. In the **'intensity' section**, medians and their *likely* ranges, also based on the 5–95% range of the multi-model ensemble from simulations of CMIP6, are displayed as dark and light bars, respectively. Changes in the intensity of hot temperature extremes and extreme precipitation are expressed as degree Celsius and percentage. As for agricultural and ecological drought, intensity changes are expressed as fractions of standard deviation of annual soil moisture.

{11.1; 11.3; 11.4; 11.6; 11.9; Figures 11.12, 11.15, 11.6, 11.7, and 11.18}

B.3 Continued global warming is projected to further intensify the global water cycle, including its variability, global monsoon precipitation and the severity of wet and dry events. {4.3, 4.4, 4.5, 4.6, 8.2, 8.3, 8.4, 8.5, Box 8.2, 11.4, 11.6, 11.9, 12.4, Atlas.3} (Figure SPM.5, Figure SPM.6)

B.3.1 There is strengthened evidence since AR5 that the global water cycle will continue to intensify as global temperatures rise (*high confidence*), with precipitation and surface water flows projected to become more variable over most land regions within seasons (*high confidence*) and from year to year (*medium confidence*). The average annual global land precipitation is projected to increase by 0–5% under the very low GHG emissions scenario (SSP1-1.9), 1.5–8% for the intermediate GHG emissions scenario (SSP2-4.5) and 1–13% under the very high GHG emissions scenario (SSP5-8.5) by 2081–2100 relative to 1995–2014 (*likely* ranges). Precipitation is projected to increase over high latitudes, the equatorial Pacific and parts of the monsoon regions, but decrease over parts of the subtropics and limited areas in the tropics in SSP2-4.5, SSP3-7.0 and SSP5-8.5 (*very likely*). The portion of the global land experiencing detectable increases or decreases in seasonal mean precipitation is projected to increase (*medium confidence*). There is *high confidence* in an earlier onset of spring snowmelt, with higher peak flows at the expense of summer flows in snow-dominated regions globally.
{4.3, 4.5, 4.6, 8.2, 8.4, Atlas.3, TS.2.6, TS.4.3, Box TS.6} (Figure SPM.5)

B.3.2 A warmer climate will intensify very wet and very dry weather and climate events and seasons, with implications for flooding or drought (*high confidence*), but the location and frequency of these events depend on projected changes in regional atmospheric circulation, including monsoons and mid-latitude storm tracks. It is *very likely* that rainfall variability related to the El Niño–Southern Oscillation is projected to be amplified by the second half of the 21st century in the SSP2-4.5, SSP3-7.0 and SSP5-8.5 scenarios.
{4.3, 4.5, 4.6, 8.2, 8.4, 8.5, 11.4, 11.6, 11.9, 12.4, TS.2.6, TS.4.2, Box TS.6} (Figure SPM.5, Figure SPM.6)

B.3.3 Monsoon precipitation is projected to increase in the mid- to long term at the global scale, particularly over South and South East Asia, East Asia and West Africa apart from the far west Sahel (*high confidence*). The monsoon season is projected to have a delayed onset over North and South America and West Africa (*high confidence*) and a delayed retreat over West Africa (*medium confidence*).
{4.4, 4.5, 8.2, 8.3, 8.4, Box 8.2, Box TS.13}

B.3.4 A projected southward shift and intensification of Southern Hemisphere summer mid-latitude storm tracks and associated precipitation is *likely* in the long term under high GHG emissions scenarios (SSP3-7.0, SSP5-8.5), but in the near term the effect of stratospheric ozone recovery counteracts these changes (*high confidence*). There is *medium confidence* in a continued poleward shift of storms and their precipitation in the North Pacific, while there is *low confidence* in projected changes in the North Atlantic storm tracks.
{4.4, 4.5, 8.4, TS.2.3, TS.4.2}

B.4 Under scenarios with increasing CO_2 emissions, the ocean and land carbon sinks are projected to be less effective at slowing the accumulation of CO_2 in the atmosphere. {4.3, 5.2, 5.4, 5.5, 5.6} (Figure SPM.7)

B.4.1 While natural land and ocean carbon sinks are projected to take up, in absolute terms, a progressively larger amount of CO_2 under higher compared to lower CO_2 emissions scenarios, they become less effective, that is, the proportion of emissions taken up by land and ocean decrease with increasing cumulative CO_2 emissions. This is projected to result in a higher proportion of emitted CO_2 remaining in the atmosphere (*high confidence*).
{5.2, 5.4, Box TS.5} (Figure SPM.7)

B.4.2 Based on model projections, under the intermediate GHG emissions scenario that stabilizes atmospheric CO_2 concentrations this century (SSP2-4.5), the rates of CO_2 taken up by the land and ocean are projected to decrease in the second half of the 21st century (*high confidence*). Under the very low and low GHG emissions scenarios (SSP1-1.9, SSP1-2.6), where CO_2 concentrations peak and decline during the 21st century, the land and ocean begin to take up less carbon in response to declining atmospheric CO_2 concentrations (*high confidence*) and turn into a weak net source by 2100 under SSP1-1.9 (*medium confidence*). It is *very unlikely* that the combined global land and ocean sink will turn into a source by 2100 under scenarios without net negative emissions (SSP2-4.5, SSP3-7.0, SSP5-8.5).[32]
{4.3, 5.4, 5.5, 5.6, Box TS.5, TS.3.3}

B.4.3 The magnitude of feedbacks between climate change and the carbon cycle becomes larger but also more uncertain in high CO_2 emissions scenarios (*very high confidence*). However, climate model projections show that the uncertainties in atmospheric CO_2 concentrations by 2100 are dominated by the differences between emissions scenarios (*high confidence*). Additional ecosystem responses to warming not yet fully included in climate models, such as CO_2 and CH_4 fluxes from wetlands, permafrost thaw and wildfires, would further increase concentrations of these gases in the atmosphere (*high confidence*).
{5.4, Box TS.5, TS.3.2}

The proportion of CO_2 emissions taken up by land and ocean carbon sinks is smaller in scenarios with higher cumulative CO_2 emissions

Total cumulative CO_2 emissions **taken up by land and ocean** (colours) and remaining in the atmosphere (grey) under the five illustrative scenarios from 1850 to 2100

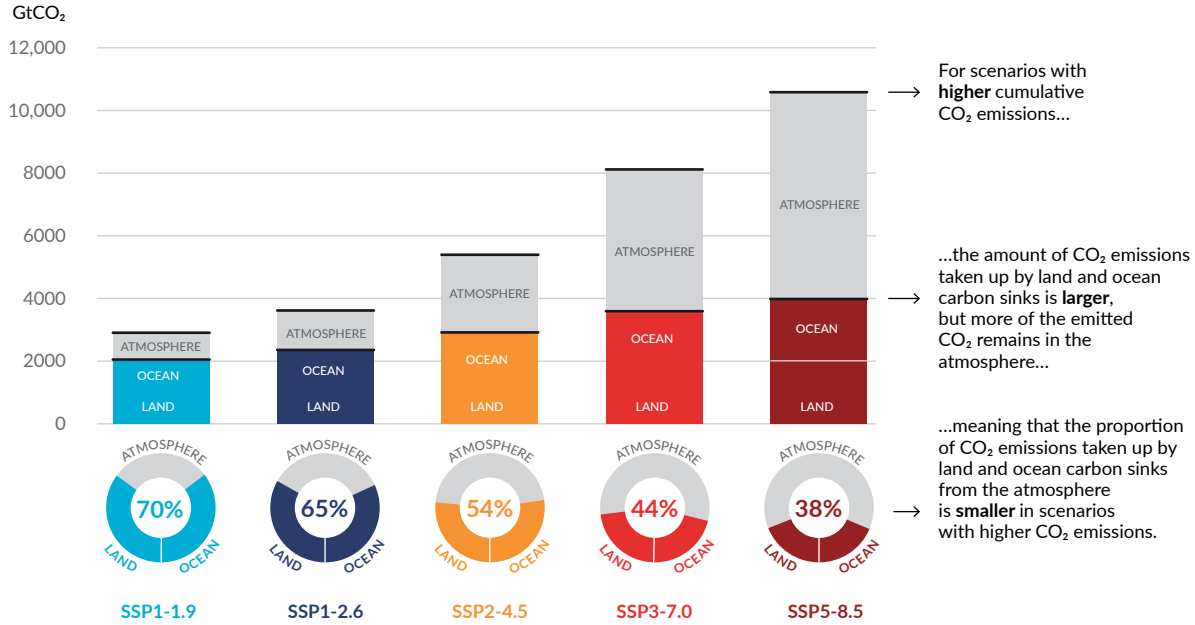


Figure SPM.7 | Cumulative anthropogenic CO_2 emissions taken up by land and ocean sinks by 2100 under the five illustrative scenarios

The cumulative anthropogenic (human-caused) carbon dioxide (CO_2) emissions taken up by the land and ocean sinks under the five illustrative scenarios (SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5) are simulated from 1850 to 2100 by Coupled Model Intercomparison Project Phase 6 (CMIP6) climate models in the concentration-driven simulations. Land and ocean carbon sinks respond to past, current and future emissions; therefore, cumulative sinks from 1850 to 2100 are presented here. During the historical period (1850–2019) the observed land and ocean sink took up 1430 $GtCO_2$ (59% of the emissions).

32 These projected adjustments of carbon sinks to stabilization or decline of atmospheric CO_2 are accounted for in calculations of remaining carbon budgets.

The bar chart illustrates the projected amount of cumulative anthropogenic CO_2 emissions ($GtCO_2$) between 1850 and 2100 remaining in the atmosphere (grey part) and taken up by the land and ocean (coloured part) in the year 2100. **The doughnut chart** illustrates the proportion of the cumulative anthropogenic CO_2 emissions taken up by the land and ocean sinks and remaining in the atmosphere in the year 2100. Values in % indicate the proportion of the cumulative anthropogenic CO_2 emissions taken up by the combined land and ocean sinks in the year 2100. The overall anthropogenic carbon emissions are calculated by adding the net global land-use emissions from the CMIP6 scenario database to the other sectoral emissions calculated from climate model runs with prescribed CO_2 concentrations.[33] Land and ocean CO_2 uptake since 1850 is calculated from the net biome productivity on land, corrected for CO_2 losses due to land-use change by adding the land-use change emissions, and net ocean CO_2 flux.

{5.2.1; Table 5.1; 5.4.5; Figure 5.25; Box TS.5; Box TS.5, Figure 1}

B.5 Many changes due to past and future greenhouse gas emissions are irreversible for centuries to millennia, especially changes in the ocean, ice sheets and global sea level. {2.3, Cross-Chapter Box 2.4, 4.3, 4.5, 4.7, 5.3, 9.2, 9.4, 9.5, 9.6, Box 9.4} (Figure SPM.8)

B.5.1 Past GHG emissions since 1750 have committed the global ocean to future warming (*high confidence*). Over the rest of the 21st century, *likely* ocean warming ranges from 2–4 (SSP1-2.6) to 4–8 times (SSP5-8.5) the 1971–2018 change. Based on multiple lines of evidence, upper ocean stratification (*virtually certain*), ocean acidification (*virtually certain*) and ocean deoxygenation (*high confidence*) will continue to increase in the 21st century, at rates dependent on future emissions. Changes are irreversible on centennial to millennial time scales in global ocean temperature (*very high confidence*), deep-ocean acidification (*very high confidence*) and deoxygenation (*medium confidence*).
{4.3, 4.5, 4.7, 5.3, 9.2, TS.2.4} (Figure SPM.8)

B.5.2 Mountain and polar glaciers are committed to continue melting for decades or centuries (*very high confidence*). Loss of permafrost carbon following permafrost thaw is irreversible at centennial time scales (*high confidence*). Continued ice loss over the 21st century is *virtually certain* for the Greenland Ice Sheet and *likely* for the Antarctic Ice Sheet. There is *high confidence* that total ice loss from the Greenland Ice Sheet will increase with cumulative emissions. There is *limited evidence* for low-likelihood, high-impact outcomes (resulting from ice-sheet instability processes characterized by deep uncertainty and in some cases involving tipping points) that would strongly increase ice loss from the Antarctic Ice Sheet for centuries under high GHG emissions scenarios.[34]
{4.3, 4.7, 5.4, 9.4, 9.5, Box 9.4, Box TS.1, TS.2.5}

B.5.3 It is *virtually certain* that global mean sea level will continue to rise over the 21st century. Relative to 1995–2014, the *likely* global mean sea level rise by 2100 is 0.28–0.55 m under the very low GHG emissions scenario (SSP1-1.9); 0.32–0.62 m under the low GHG emissions scenario (SSP1-2.6); 0.44–0.76 m under the intermediate GHG emissions scenario (SSP2-4.5); and 0.63–1.01 m under the very high GHG emissions scenario (SSP5-8.5); and by 2150 is 0.37–0.86 m under the very low scenario (SSP1-1.9); 0.46–0.99 m under the low scenario (SSP1-2.6); 0.66–1.33 m under the intermediate scenario (SSP2-4.5); and 0.98–1.88 m under the very high scenario (SSP5-8.5) (*medium confidence*).[35] Global mean sea level rise above the *likely* range – approaching 2 m by 2100 and 5 m by 2150 under a very high GHG emissions scenario (SSP5-8.5) (*low confidence*) – cannot be ruled out due to deep uncertainty in ice-sheet processes.
{4.3, 9.6, Box 9.4, Box TS.4} (Figure SPM.8)

B.5.4 In the longer term, sea level is committed to rise for centuries to millennia due to continuing deep-ocean warming and ice-sheet melt and will remain elevated for thousands of years (*high confidence*). Over the next 2000 years, global mean sea level will rise by about 2 to 3 m if warming is limited to 1.5°C, 2 to 6 m if limited to 2°C and 19 to 22 m with 5°C of warming, and it will continue to rise over subsequent millennia (*low confidence*). Projections of multi-millennial global mean sea level rise are consistent with reconstructed levels during past warm climate periods: *likely* 5–10 m higher than today around 125,000 years ago, when global temperatures were *very likely* 0.5°C–1.5°C higher than 1850–1900; and *very likely* 5–25 m higher roughly 3 million years ago, when global temperatures were 2.5°C–4°C higher (*medium confidence*).
{2.3, Cross-Chapter Box 2.4, 9.6, Box TS.2, Box TS.4, Box TS.9}

---

33 The other sectoral emissions are calculated as the residual of the net land and ocean CO_2 uptake and the prescribed atmospheric CO_2 concentration changes in the CMIP6 simulations. These calculated emissions are net emissions and do not separate gross anthropogenic emissions from removals, which are included implicitly.

34 Low-likelihood, high-impact outcomes are those whose probability of occurrence is low or not well known (as in the context of deep uncertainty) but whose potential impacts on society and ecosystems could be high. A tipping point is a critical threshold beyond which a system reorganizes, often abruptly and/or irreversibly. (Glossary) {1.4, Cross-Chapter Box 1.3, 4.7}

35 To compare to the 1986–2005 baseline period used in AR5 and SROCC, add 0.03 m to the global mean sea level rise estimates. To compare to the 1900 baseline period used in Figure SPM.8, add 0.16 m.

Annex 46 bis

"Barbados Resilience Profile" USAID, May 2021



USAID
FROM THE AMERICAN PEOPLE

BARBADOS RESILIENCE PROFILE

MAY 2021

Photo by Cedric Frixon on Unsplash

The Eastern and Southern Caribbean (ESC) region is highly vulnerable to natural hazards. In recent years, extreme hurricanes have devastated communities and infrastructure in the region and left thousands of people without shelter, livelihoods, and services. Caribbean countries incurred an estimated $27 billion in losses and damages from natural hazards between 2000 and 2017 (Friar, 2019), and averaged as much as 5.7 percent loss of GDP annually due to such disasters (Acevedo, 2016). The economic impact is staggering, making resilience an imperative for the region.

The United States Agency for International Development (USAID) Eastern and Southern Caribbean Mission (USAID/ESC) partners with regional and national institutions to support long-term resilience to natural hazards. In 2020, USAID/ESC conducted a Resilience Assessment for the ESC region to better understand the interplay of the region's socioeconomic, environmental, and institutional context, the natural hazard and human-induced stressors that impact its communities and development sectors, and the spectrum of resilience capacities already in place, as shown here (Hellmuth et al. 2020).



The [ESC Resilience Assessment] finds USAID/ESC can invest in strengthening the region's resilience ecosystem most effectively by:

- Taking systems- and sector-level approaches
- Focusing on core capabilities and sustainable programming
- Supporting and strengthening coordination at all levels
- Balancing regional and country-specific programming

The assessment includes country resilience profiles for Antigua and Barbuda, Grenada, Guyana, Saint Lucia, Trinidad and Tobago, and this one for Barbados.

BARBADOS

Barbados is one of the most populated and prosperous Caribbean nations, scoring high on many United Nations Human Development Index indicators. However, the country is challenged by youth poverty and impacts from natural disasters. Tourism is the primary source of income for the country, which has suffered from the impacts of travel moratoriums during the COVID-19 pandemic. Being a mostly low-lying country, Barbados experiences flash floods, droughts, small-scale landslides, earthquakes, and fires. The country's disaster and emergency management legislation and structure is strong, as is its data collection, but implementation of policy and deployment of these data resources are still lacking.

COUNTRY CONTEXT

ENVIRONMENTAL, SOCIAL AND ECONOMIC CONTEXT

Environmental	The island of Barbados is bordered by the Caribbean Sea to the west and the Atlantic Ocean to the east. The area of the country is 430 square kilometers with 97 kilometers of coastline. Its terrain is mainly flat with a hilly interior. The climate consists of a wet season from June to November and a dry season from December to May. The island has no major rivers or surface streams, and therefore relies on groundwater as the nation's primary water source. The historical (1901–2016) mean annual temperature is 26°C and historical mean annual precipitation is 2067.8 mm. Projections indicate that mean annual temperature will rise by 1.3°C (0.9°C to 1.97°C) and annual precipitation will decrease by 47.8 mm (-290.1 mm to 153.1 mm) by 2040 to 2059.[1] The island is also subject to sea level rise, increasing storm intensity, earthquakes, landslides, and tsunamis (UNDP 2020a; World Bank 2020b).
Social	Barbados is one of the most populated and prosperous Caribbean nations. The country is among the most densely populated nations in the world with a density of 637 people per km^2. Barbados sits in the high human development category of the UNDP Human Development Index, and mean life expectancy and years of school are high compared to other Caribbean nations. Globally, Barbados has one of the highest literacy rates in the world (98 percent). The country has achieved universal access to education and health services, free access to HIV/AIDS treatment, and almost 100 percent access to clean drinking water and sanitation. Although Barbados has one of the narrowest gender gaps in the region, the country lags behind other nations in the high human development category in regard to gender equality. n 2019, the global gender gap index (GGI) for Barbados was 0.75 (World Economic Forum 2020). GGI is a compass to track progress on relative gaps between women and men on health, education, economy, and politics. There is also a high poverty rate among youth (15–24 years) in Barbados (23 percent) compared to individuals over 24 years of age (15 percent). Natural disasters and environmental degradation have been found to impact youth access to adequate healthcare, education, and protection from violence. Barbados also has a considerable aging population (UNDP 2019b; Evanson 2014).
Economic	The majority of the workforce in Barbados is employed by the tourism, government, manufacturing, construction, mining, agriculture, and fishing sectors. Tourism is a significant economic driver in the country. An offshore financial services sector has become the second largest source of financial exchange after tourism. Sugar production was formerly a large contributor to the nation's GDP; however, economic diversification coupled with recent drought and declines in soil fertility have diminished the importance of this crop to the national economy (UNDP 2020a).

INSTITUTIONAL CONTEXT AND LEGAL FRAMEWORK AFFECTING RESILIENCE

Since 2003, Barbados has developed policies, strategies, and legislation aligned with comprehensive disaster management. The Emergency Management Act of 2007 established the Department of

1 Projections represent the model ensemble median under the high emissions scenario (RCP 8.5) and the range of values in parentheses represent the 10th to 90th percentile.

Emergency Management. The Department of Emergency Management oversees the country's National Disaster Management Program, which seeks to educate citizens about the various elements of disaster management, create appropriate mechanisms to promote and advance disaster management activities, promote and institutionalize the practice of appropriate preventive and mitigation measures, and promote the development and maintenance of warning, response, and recovery plans for all sectors. The Department developed a 2019–2023 Strategic Plan, which outlines its programs and mechanisms. These include the National Emergency Management System, a multi-sector mechanism that brings together human resources elements, technical expertise, and other resources to ensure effective readiness and to address disaster risk reduction. The Department also chairs the Emergency Management Advisory Council, established in 2006 by emergency management legislation, which includes public and private sector representation. The Department works heavily with 30 District Emergency Organizations, a community volunteer mechanism and the primary vehicle for organizing preparedness at the local scale. Barbados serves as the Central Sub-Regional Disaster Emergency Response Focal Point for Caribbean Disaster Emergency Management Agency (CDEMA) which supports emergency response to Dominica, Saint Lucia, and Saint Vincent and the Grenadines (CDEMA 2016).

Barbados created a National Climate Change Policy in 2012. This policy outlines plans to further institutional, administrative, and legislative work in both climate adaptation and mitigation in Barbados. The Green Economy Scoping Study and Coastal Risk Assessment and Management Program, among other programs, were developed to help achieve this goal.

RISK AND RESILIENCE ASSESSMENT

RISK AND RESILIENCE PROFILE

Priority Risks

As a small and densely populated nation with a low-lying coastal zone, Barbados is vulnerable to a range of natural hazards. The tourism-dependent economy also presents significant risk to financial stability, in the event of impacts from natural shocks or stressors on the tourism industry.

Barbados experiences flooding caused by tropical storms and hurricanes and by extreme rainfall during the rainy season. The country's low-lying coastal zone also makes it vulnerable to sea level rise and storm surge. Poor drainage and inadequate storm water infrastructure in many areas result in common flash floods. Intense rainfall and wave action in coastal areas also results in small-scale landslides, particularly in the Scotland District. These landslides result in adverse impacts to agriculture, transportation, and housing infrastructure. Coastal activities are threatened by sargassum seaweed.

Barbados is also particularly vulnerable to hydrological drought because the country has limited above and below ground water storage capacity. Barbados is classified as a water-scarce country and droughts have severe implications for water resources users, including the agriculture and tourism industries. Barbados experiences earthquakes frequently and is ranked in the top 10 countries in the world in terms of probable maximum loss from earthquakes. Wildfires are common during the dry season and pose a risk to human health, crops, property, and water resources. Finally, the country is at risk from changing instances of pests due to climate change, including the introduction of non-native invasive pests.

Resilience Capacity

Institutional capacity:

- **Strengths:** The enactment of disaster management legislation and the structure of the national disaster management mechanism in Barbados allows for interdisciplinary, inter-sector partnerships and the mainstreaming of risk management into national planning processes. The National Emergency Management System houses a Vulnerable Persons Committee that has been successful in representing this group in disaster management decision-making.

- **Weaknesses:** A lack of capacity results in weak enforcement of the existing legislative framework. Additionally, the special needs of vulnerable communities in awareness and preparedness, emergency shelter situations, post-disaster recovery, and access to education and employment appear to be overlooked within the policy and planning framework.

Knowledge and technical capacity:

- **Strengths:** Barbados benefits from having decades of local data that can be used to inform resilience and disaster management planning and programming. The government invested data and information into geographic information system platforms to support decision-making.
- **Weaknesses:** Fragmentation of data and lack of centralization and integration across agencies presents issues for analysis and planning efforts. Furthermore, databases may be developed, but without sufficient personnel, equipment, or technical skill for maintenance.

Human and community capacity:

- **Strengths:** The country has heavy regional engagement from volunteers through the Department of Emergency Management's District Emergency Organizations. Barbados designed a disaster drill training course to be used at national and regional levels and designated a group of trainers to conduct the courses.
- **Weaknesses:** In the public sector, a lack of human resource capacities has resulted in a lack of interagency coordination for environmental management and disaster risk reduction.

Financial capacity:

- **Strengths:** The Department of Emergency Management and 30 District Emergency Organizations receives budgetary support from the Government of Barbados.
- **Weaknesses:** Agencies across the government often lack the necessary funding to maintain data collection and management programs effectively.



Photo by Anson Aswat on Unsplash

CURRENT STATUS OF THE COUNTRY'S RESILIENCE MEASURES

The table provides a snapshot of illustrative ongoing resilience measures in the country and is not meant to be comprehensive.

Program Name	Entity	Status: Year(s) and Size ($)	Description
Roofs to Reef Program (R2RP)	Government of Barbados	2019 $624,527	R2RP is the Government's sustainable development model for the next decade. The primary focus is on improving the social and environmental circumstances of the people in Barbados. R2RP will enhance the country's ability to recover from climatic events. R2RP is hinged on six thematic areas: Shelter, Water, Energy, Waste, Land use, and Ecosystems Management
Water Resource Management and Flood Resilience Program	Government of Barbados and USAID	2013-2020 Joint funding from USAID and Government of Barbados totalling $7 million	USAID recently celebrated the completion of this task, which sought to improve Barbados' water resource management and flood resilience. Activities were split into two phases. The first phase included the following studies: (i) An updated Stormwater Management Plan; (ii) Flood Reduction Measures in the Trents/Holetown Area; (iii) Report on the management of the Holetown lagoon; (iv) Stormwater and Groundwater Quality Study; and an education, awareness, outreach and training program. The second phase involved upgrading drains and culverts to alleviate incidences of frequent flooding in the Holetown and Trents area on the west coast of Barbados.
National Coastal Risk Information and Planning Platform (NCRIPP)	Inter-American Development Bank	N/A	The NCRIPP study assessed coastal and island-wide hazards in Barbados and developed a software platform to investigate hazards, vulnerability, and risk. The study produced a Coastal Risk Atlas, an enterprise-level geographic information system and GeoDatabase used by the Barbados Government to increase resilience in vulnerable areas.
Water Sector Resilience Nexus for Sustainability in Barbados	Implementer: Caribbean Community Climate Change Centre (CCCCC), Government of Barbados Sponsor: Green Climate Fund (GCF)	2018–2024	This is the CCCCC's first country project and is designed to strengthen the resilience of Barbados to the impacts of climate change, support adaptation measures in the water sector, and reduce the carbon footprint of the Barbados Water Authority.

SOURCES FOR ADDITIONAL INFORMATION

- Country Document for Disaster Risk Reduction: Barbados, 2014.
- Indicators of Disaster Risk and Risk Management: Barbados.
- Barbados Second National Communication to the UNFCCC.

REFERENCES

Acevedo, S. 2016. Gone with the wind: Estimating hurricane and climate change costs in the Caribbean. IMF Working Paper WP/16/199. International Monetary Fund, Western Hemisphere Department. Accessed March 2021, https://www.imf.org/en/Publications/WP/Issues/2016/12/31/Gone-with-the-Wind-Estimating-Hurricane-and-Climate-Change-Costs-in-the-Caribbean-44333 Caribbean Development Bank. 2020. Annual Report 2019. St. Michael, Barbados: Caribbean Development Bank.

Caribbean Disaster Emergency Management Agency. 2016. The Regional Response Mechanism. Information booklet. St. Michael, Barbados: Caribbean Disaster Emergency Management Agency.

Evanson, Danielle. 2014. Country document for disaster risk reduction: Barbados. Bridgetown, Barbados: Barbados Department of Emergency Management.

Friar, Tayler, Ed. 2019. "Understanding Risk Caribbean Conference: Proceedings from the 2019 UR Caribbean Conference." Washington, D.C.: The International Bank for Reconstruction and Development/The World Bank.

Hellmuth, Molly, et al. Resilience Assessment: Eastern and Southern Caribbean. November 2020. United States Agency for International Development.

United Nations Development Programme. 2019b. Briefing note for countries on the 2019 Human Development Report: Barbados.

United Nations Development Programme. 2020a. "Climate Change Adaptation: Barbados". UNDP Climate Change Adaptation. Accessed October 2020. https://www.adaptation-undp.org/explore/caribbean/ barbados.

World Bank. 2020b. "Barbados Climate Data - Projections." Climate Change Knowledge Portal. Accessed October 2020. https://climateknowledgeportal.worldbank.org/country/barbados/climate-data-projections.

World Economic Forum. 2020. Global Gender Gap Report 2020. Insight Report, Geneva: World Economic Forum.



Photo by Anthony Ingham on Unsplash

This document was produced for review by the United States Agency for International Development. It was prepared by Environmental Incentives and ICF for the LAC Environment Support Contract.

Annex 47

"Global Carbon and other Biogeochemical Cycles and Feedbacks. Climate Change 2021 – The Physical Science Basis", Cambridge University Press, *Intergovernmental Panel on Climate Change,* 2021, pages 673-679, 687-690, 739-741, 777-778

5 Global Carbon and Other Biogeochemical Cycles and Feedbacks

Coordinating Lead Authors:
Josep G. Canadell (Australia), Pedro M.S. Monteiro (South Africa)

Lead Authors:
Marcos H. Costa (Brazil), Leticia Cotrim da Cunha (Brazil), Peter M. Cox (United Kingdom), Alexey V. Eliseev (Russian Federation), Stephanie Henson (United Kingdom), Masao Ishii (Japan), Samuel Jaccard (Switzerland), Charles Koven (United States of America), Annalea Lohila (Finland), Prabir K. Patra (Japan/India), Shilong Piao (China), Joeri Rogelj (United Kingdom/Belgium), Stephen Syampungani (Zambia), Sönke Zaehle (Germany), Kirsten Zickfeld (Canada/Germany)

Contributing Authors:
Georgii A. Alexandrov (Russian Federation), Govindasamy Bala (India/United States of America), Laurent Bopp (France), Lena Boysen (Germany), Long Cao (China), Naveen Chandra (Japan/India), Philippe Ciais (France), Sergey N. Denisov (Russian Federation), Frank J. Dentener (EU, The Netherlands), Hervé Douville (France), Amanda Fay (United States of America), Piers Forster (United Kingdom), Baylor Fox-Kemper (United States of America), Pierre Friedlingstein (United Kingdom), Weiwei Fu (United States of America/China), Sabine Fuss (Germany), Véronique Garçon (France), Bettina Gier (Germany), Nathan P. Gillett (Canada), Luke Gregor (Switzerland/South Africa), Karsten Haustein (United Kingdom/Germany), Vanessa Haverd (Australia), Jian He (United States of America/China), Helene T. Hewitt (United Kingdom), Forrest M. Hoffman (United States of America), Tatiana Ilyina (Germany), Robert B. Jackson (United States of America), Christopher Jones (United Kingdom), David P. Keller (Germany/United States of America), Lester Kwiatkowski (France/United Kingdom), Robin D. Lamboll (United Kingdom/United States of America, United Kingdom), Xin Lan (United States of America/China), Charlotte Laufkötter (Switzerland/Germany), Corinne Le Quéré (United Kingdom), Andrew Lenton (Australia), Jared Lewis (Australia/New Zealand), Spencer Liddicoat (United Kingdom), Laura Lorenzoni (United States of America/Venezuela), Nicole Lovenduski (United States of America), Andrew H. MacDougall (Canada), Sabine Mathesius (Canada/Germany), H. Damon Matthews (Canada), Malte Meinshausen (Australia/Germany), Igor I. Mokhov (Russian Federation), Vaishali Naik (United States of America), Zebedee R. J. Nicholls (Australia), Intan Suci Nurhati (Indonesia), Michael O'Sullivan (United Kingdom), Glen Peters (Norway), Julia Pongratz (Germany), Benjamin Poulter (United States of America),

Jean-Baptiste Sallée (France), Marielle Saunois (France), Edward A.G. Schuur (United States of America), Sonia I. Seneviratne (Switzerland), Ann Stavert (Australia), Parvadha Suntharalingam (United Kingdom/United States of America), Kaoru Tachiiri (Japan), Jens Terhaar (Switzerland/Germany), Rona Thompson (Norway, Luxembourg/New Zealand), Hanqin Tian (United States of America), Jocelyn Turnbull (New Zealand), Sergio M. Vicente-Serrano (Spain), Xuhui Wang (China), Rik Wanninkhof (United States of America), Philip Williamson (United Kingdom)

Review Editors:
Victor Brovkin (Germany/Russian Federation), Richard A. Feely (United States of America)

Chapter Scientist:
Alice D. Lebehot (South Africa/France)

This chapter should be cited as:
Canadell, J.G., P.M.S. Monteiro, M.H. Costa, L. Cotrim da Cunha, P.M. Cox, A.V. Eliseev, S. Henson, M. Ishii, S. Jaccard, C. Koven, A. Lohila, P.K. Patra, S. Piao, J. Rogelj, S. Syampungani, S. Zaehle, and K. Zickfeld, 2021: Global Carbon and other Biogeochemical Cycles and Feedbacks. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 673–816, doi:10.1017/9781009157896.007.

Table of Contents

Executive Summary 676

5.1 Introduction 680

5.1.1 The Physical and Biogeochemical Processes in Carbon–Climate Feedbacks 681

5.1.2 Paleo Trends and Feedbacks 683

5.2 Historical Trends, Variability and Budgets of CO_2, CH_4 and N_2O 687

5.2.1 CO_2: Trends, Variability and Budget 687

Cross-Chapter Box 5.1 | Interactions Between the Carbon and Water Cycles, Particularly Under Drought Conditions 697

5.2.2 Methane (CH_4): Trends, Variability and Budget 700

Cross-Chapter Box 5.2 | Drivers of Atmospheric Methane Changes During 1980–2019 706

5.2.3 N_2O: Trends, Variability and Budget 708

5.2.4 The Relative Importance of CO_2, CH_4, and N_2O 712

5.3 Ocean Acidification and Deoxygenation 714

5.3.1 Paleoclimate Context 714

5.3.2 Historical Trends and Spatial Characteristics in the Upper Ocean 715

5.3.3 Ocean Interior Change 717

5.3.4 Future Projections for Ocean Acidification 719

5.3.5 Coastal Ocean Acidification and Deoxygenation 720

5.4 Biogeochemical Feedbacks on Climate Change 722

5.4.1 Direct CO_2 Effect on Land Carbon Uptake 722

5.4.2 Direct CO_2 Effects on Projected Ocean Carbon Uptake 723

5.4.3 Climate Effect on Land Carbon Uptake 724

Box 5.1 | Permafrost Carbon and Feedbacks to Climate 726

5.4.4 Climate Effects on Future Ocean Carbon Uptake 728

5.4.5 Carbon Cycle Projections in Earth System Models 730

5.4.6 Emergent Constraints to Reduce Uncertainties in Projections 736

5.4.7 Climate Feedbacks from CH_4 and N_2O 737

5.4.8 Combined Biogeochemical Climate Feedback . 737

5.4.9 Abrupt Changes and Tipping Points 739

5.4.10 Long-term Response Past 2100 741

5.4.11 Near-term Prediction of Ocean and Land Carbon Sinks 742

5.5 Remaining Carbon Budgets 742

5.5.1 Transient Climate Response to Cumulative Emissions of Carbon Dioxide (TCRE) 742

Cross-Chapter Box 5.3 | The Ocean Carbon–Heat Nexus and Climate Change Commitment 743

5.5.2 Remaining Carbon Budget Assessment 749

Box 5.2 | Implications of Methodological Advancements in Estimating the Remaining Carbon Budget since the IPCC's Fifth Assessment Report (AR5) 754

5.6 Biogeochemical Implications of Carbon Dioxide Removal and Solar Radiation Modification 755

5.6.1 Introduction 755

5.6.2 Biogeochemical Responses to Carbon Dioxide Removal (CDR) 755

Box 5.3 | Carbon Cycle Response to CO_2 Removal from the Atmosphere 758

5.6.3 Biogeochemical Responses to Solar Radiation Modification (SRM) 767

5.7 Final Remarks 769

Frequently Asked Questions

FAQ 5.1 | Is the Natural Removal of Carbon From the Atmosphere Weakening? 771

FAQ 5.2 | Can Thawing Permafrost Substantially Increase Global Warming? 773

FAQ 5.3 | Could Climate Change Be Reversed By Removing Carbon Dioxide From the Atmosphere? 775

FAQ 5.4 | What Are Carbon Budgets? 777

References 779

Executive Summary

It is unequivocal that the increases in atmospheric carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) since the pre-industrial period are caused by human activities. The accumulation of GHGs in the atmosphere is determined by the balance between anthropogenic emissions, anthropogenic removals, and physical-biogeochemical source and sink dynamics on land and in the ocean. This chapter assesses how physical and biogeochemical processes of the carbon and nitrogen cycles affect the variability and trends of GHGs in the atmosphere as well as ocean acidification and deoxygenation. It identifies physical and biogeochemical feedbacks that have affected (or could affect) future rates of GHG accumulation in the atmosphere, and therefore, influence climate change and its impacts. This chapter also assesses the remaining carbon budget to limit global warming within various goals, as well as the large-scale consequences of carbon dioxide removal (CDR) and solar radiation modification (SRM) on biogeochemical cycles. {Figures 5.1, 5.2}.

The Human Perturbation of the Carbon and Biogeochemical Cycles

Global mean concentrations for well-mixed GHGs (CO_2, CH_4 and N_2O) in 2019 correspond to increases of about 47%, 156%, and 23%, respectively, above the levels in 1750 (representative of the pre-industrial era) (*high confidence*). Current atmospheric concentrations of the three GHGs are higher than at any point in the last 800,000 years, and in 2019 reached 409.9 parts per million (ppm) of CO_2, 1866.3 parts per billion (ppb) of CH_4, and 332.1 ppb of N_2O (*very high confidence*). Current CO_2 concentrations in the atmosphere are also unprecedented in the last 2 million years (*high confidence*). In the past 60 million years, there have been periods in Earth's history when CO_2 concentrations were significantly higher than at present, but multiple lines of evidence show that the rate at which CO_2 has increased in the atmosphere during 1900–2019 is at least 10 times faster than at any other time during the last 800,000 years (*high confidence*), and 4–5 times faster than during the last 56 million years (*low confidence*). {5.1.1, 2.2.3; Figures 5.3, 5.4; Cross-Chapter Box 2.1}

Contemporary Trends of Greenhouse Gases

It is unequivocal that the increase of CO_2, CH_4, and N_2O in the atmosphere over the industrial era is the result of human activities (*very high confidence*). This assessment is based on multiple lines of evidence including atmospheric gradients, isotopes, and inventory data. During the last measured decade, global average annual anthropogenic emissions of CO_2, CH_4, and N_2O, reached the highest levels in human history at 10.9 ± 0.9 petagrams of carbon per year (PgC yr^{-1}, 2010–2019), 335–383 teragrams of methane per year ($TgCH_4$ yr^{-1}, 2008–2017), and 4.2–11.4 teragrams of nitrogen per year (TgN yr^{-1}, 2007–2016), respectively (*high confidence*). {5.2.1, 5.2.2, 5.2.3, 5.2.4; Figures 5.6, 5.13, 5.15}.

The CO_2 emitted from human activities during the decade of 2010–2019 (decadal average 10.9 ± 0.9 PgC yr^{-1}) was distributed between three Earth system components: 46% accumulated in the atmosphere (5.1 ± 0.02 PgC yr^{-1}), 23% was taken up by the ocean (2.5 ± 0.6 PgC yr^{-1}) and 31% was stored by vegetation in terrestrial ecosystems (3.4 ± 0.9 PgC yr^{-1}) (*high confidence*). Of the total anthropogenic CO_2 emissions, the combustion of fossil fuels was responsible for 81–91%, with the remainder being the net CO_2 flux from land-use change and land management (e.g., deforestation, degradation, regrowth after agricultural abandonment, and peat drainage). {5.2.1.2, 5.2.1.5; Table 5.1; Figures 5.5, 5.7, 5.12}

Over the past six decades, the average fraction of anthropogenic CO_2 emissions that has accumulated in the atmosphere (referred to as the airborne fraction) has remained nearly constant at approximately 44%. The ocean and land sinks of CO_2 have continued to grow over the past six decades in response to increasing anthropogenic CO_2 emissions (*high confidence)*. Interannual and decadal variability of the regional and global ocean and land sinks indicate that these sinks are sensitive to climate conditions and therefore to climate change (*high confidence*). {5.2.1.1, 5.2.1.2, 5.2.1.3, 5.2.1.4; Figures 5.7, 5.8, 5.10}

Recent observations show that ocean carbon processes are starting to change in response to the growing ocean sink, and these changes are expected to contribute significantly to future weakening of the ocean sink under medium- to high-emissions scenarios. However, the effects of these changes are not yet reflected in a weakening trend of the contemporary (1960–2019) ocean sink (*high confidence*). {5.1.2, 5.2.1.3, 5.3.2.1; Figures 5.8, 5.20; Cross-Chapter Box 5.3}

Atmospheric concentration of CH_4 grew at an average rate of 7.6 ± 2.7 ppb yr^{-1} for the last decade (2010–2019), with a faster growth of 9.3 ± 2.4 ppb yr^{-1} over the last six years (2014–2019) (*high confidence*). The multi-decadal growth trend in atmospheric CH_4 is dominated by anthropogenic activities (*high confidence*), and the growth since 2007 is largely driven by emissions from both fossil fuels and agriculture (dominated by livestock) (*medium confidence)*. The interannual variability is dominated by El Niño–Southern Oscillation cycles, during which biomass burning and wetland emissions, as well as loss by reaction with tropospheric hydroxyl radical (OH) play an important role. {5.2.2; Figures 5.13, 5.14; Table 5.2; Cross-Chapter Box 5.2}

Atmospheric concentration of N_2O grew at an average rate of 0.85 ± 0.03 ppb yr^{-1} between 1995 and 2019, with a further increase to 0.95 ± 0.04 ppb yr^{-1} in the most recent decade (2010–2019). This increase is dominated by anthropogenic emissions, which have increased by 30% between the 1980s and the most recent observational decade (2007–2016) (*high confidence*). Increased use of nitrogen fertilizer and manure contributed to about two-thirds of the increase during the 1980–2016 period, with the fossil fuels/industry, biomass burning, and wastewater accounting for much of the rest (*high confidence*). {5.2.3; Figures 5.15, 5.16, 5.17}

Ocean Acidification and Ocean Deoxygenation

Ocean acidification is strengthening as a result of the ocean continuing to take up CO_2 from human-caused emissions (*very high confidence*). This CO_2 uptake is driving changes in seawater chemistry that result in the decrease of pH and associated reductions in the saturation state of calcium carbonate, which is a constituent of skeletons or shells of a variety of marine organisms. These trends of ocean acidification are becoming clearer globally, with a *very likely* rate of decrease in pH in the ocean surface layer of 0.016 to 0.020 per decade in the subtropics and 0.002 to 0.026 per decade in subpolar and polar zones since the 1980s. Ocean acidification has spread deeper in the ocean, surpassing 2000 m depth in the northern North Atlantic and in the Southern Ocean. The greater projected pH declines in Coupled Model Intercomparison Project Phase 6 (CMIP6) models are primarily a consequence of higher atmospheric CO_2 concentrations in the Shared Socio-economic Pathways (SSPs) scenarios than their Coupled Model Intercomparison Project Phase 5 (CMIP5) Representative Concentration Pathway (RCP) analogues. {5.3.2.2, 5.3.3.1; 5.3.4.1; Figures 5.20, 5.21}

Ocean deoxygenation is projected to continue to increase with ocean warming (*high confidence*). Earth system models (ESMs) project a 32–71% greater subsurface (100–600 m) oxygen decline, depending on the scenario, than reported in the Special Report on the Ocean and Cryosphere (SROCC) for the period 2080–2099. This is attributed to the effect of larger surface warming in CMIP6 models, which increases ocean stratification and reduces ventilation (*medium confidence*). There is *low confidence* in the projected reduction of oceanic N_2O emissions under high-emissions scenarios because of greater oxygen losses simulated in ESMs in CMIP6, uncertainties in the process of oceanic N_2O emissions, and a limited number of modelling studies available. {5.3.3.2; 7.5}

Future Projections of Carbon Feedbacks on Climate Change

Oceanic and terrestrial carbon sinks are projected to continue to grow with increasing atmospheric concentrations of CO_2, but the fraction of emissions taken up by land and ocean is expected to decline as the CO_2 concentration increases (*high confidence*). ESMs suggest approximately equal global land and ocean carbon uptake for each of the SSP scenarios. However, the range of model projections is much larger for the land carbon sink. Despite the wide range of model responses, uncertainty in atmospheric CO_2 by 2100 is dominated by future anthropogenic emissions rather than uncertainties related to carbon–climate feedbacks (*high confidence*). {5.4.5; Figure 5.25, 5.26}

Increases in atmospheric CO_2 lead to increases in land carbon storage through CO_2 fertilization of photosynthesis and increased water use efficiency (*high confidence*). However, the overall change in land carbon also depends on land-use change and on the response of vegetation and soil to continued warming and changes in the water cycle, including increased droughts in some regions that will diminish the sink capacity. Climate change alone is expected to increase land carbon accumulation in the high latitudes (not including permafrost) and also to lead to a counteracting loss of land carbon in the tropics (*medium confidence*, Figure 5.25). More than half of the latest CMIP6 ESMs include nutrient limitations on the carbon cycle, but these models still project increasing tropical land carbon (*medium confidence*) and increasing global land carbon (*high confidence*) through the 21st century. {5.4.1, 5.4.3, 5.4.5; Figure 5.27; Cross-Chapter Box 5.1}

Future trajectories of the ocean CO_2 sink are strongly emissions-scenario dependent (*high confidence*). Emissions scenarios SSP4-6.0 and SSP5-8.5 lead to warming of the surface ocean and large reductions of the buffering capacity, which will slow the growth of the ocean sink after 2050. Scenario SSP1-2.6 limits further reductions in buffering capacity and warming, and the ocean sink weakens in response to the declining rate of increasing atmospheric CO_2. There is *low confidence* in how changes in the biological pump will influence the magnitude and direction of the ocean carbon feedback. {5.4.2, 5.4.4, Cross-Chapter Box 5.3}

Beyond 2100, land and ocean may transition from being a carbon sink to a source under either very high emissions or net negative emissions scenarios, but for different reasons. Under very high emissions scenarios such as SSP5-8.5, ecosystem carbon losses due to warming lead the land to transition from a carbon sink to a source (*medium confidence*), while the ocean is expected to remain a sink (*high confidence*). For scenarios in which CO_2 concentration stabilizes, land and ocean carbon sinks gradually take up less carbon as the increase in atmospheric CO_2 slows down. In scenarios with moderate net negative CO_2 emissions, and CO_2 concentrations declining during the 21st century (e.g., SSP1-2.6), the land sink transitions to a net source in decades to a few centuries after CO_2 emissions become net negative, while the ocean remains a sink (*low confidence*). Under scenarios with large net negative CO_2 emissions and rapidly declining CO_2 concentrations (e.g., SSP5-3.4-OS (overshoot)), both land and ocean switch from a sink to a transient source during the overshoot period (*medium confidence*). {5.4.10, 5.6.2.1.2; Figures 5.30, 5.33}

Thawing terrestrial permafrost will lead to carbon release (*high confidence*), but there is *low confidence* in the timing, magnitude and the relative roles of CO_2 versus CH_4 as feedback processes. CO_2 release from permafrost is projected to be 3–41 PgC per 1°C of global warming by 2100, based on an ensemble of models. However, the incomplete representation of important processes such as abrupt thaw, combined with weak observational constraints, only allow *low confidence* in both the magnitude of these estimates and in how linearly proportional this feedback is to the amount of global warming. It is *very unlikely* that gas clathrates in terrestrial and subsea permafrost will lead to a detectable departure from the emissions trajectory during this century. {5.4.9; Box 5.1}

The net response of natural CH_4 and N_2O sources to future warming will be increased emissions (*medium confidence*). Key processes include increased CH_4 emissions from wetlands and permafrost thaw, as well as increased soil N_2O emissions in a warmer climate, while ocean N_2O emissions are projected to decline at

centennial time scale. The magnitude of the responses of each individual process and how linearly proportional these feedbacks are to the amount of global warming is known with *low confidence* due to incomplete representation of important processes in models combined with weak observational constraints. Models project that, over the 21st century, the combined feedback of 0.02–0.09 W m^{-2} $°C^{-1}$ is comparable to the effect of a CO_2 release of 5–18 petagrams of carbon equivalent per °C (PgCeq $°C^{-1}$) (*low confidence*). {5.4.7, 5.4.8; Figure 5.29}

The response of biogeochemical cycles to the anthropogenic perturbation can be abrupt at regional scales, and irreversible on decadal to century time scales (*high confidence*). The probability of crossing uncertain regional thresholds (e.g., high severity fires, forest dieback) increases with climate change (*high confidence*). Possible abrupt changes and tipping points in biogeochemical cycles lead to additional uncertainty in 21st century GHG concentrations, but these are *very likely* to be smaller than the uncertainty associated with future anthropogenic emissions (*high confidence*). {5.4.9}

Remaining Carbon Budgets to Climate Stabilization

There is a near-linear relationship between cumulative CO_2 emissions and the increase in global mean surface air temperature (GSAT) caused by CO_2 over the course of this century for global warming levels up to at least 2°C relative to pre-industrial (*high confidence*). Halting global warming would thus require global net anthropogenic CO_2 emissions to become zero. The ratio between cumulative CO_2 emissions and the consequent GSAT increase, which is called the transient climate response to cumulative emissions of CO_2 (TCRE), *likely* falls in the 1.0°C–2.3°C per 1000 PgC range. The narrower range compared to the IPCC Fifth Assessment Report (AR5) is due to a better integration of evidence across the science in this assessment. Beyond this century, there is *low confidence* that the TCRE remains an accurate predictor of temperature changes in scenarios of very low or net negative CO_2 emissions because of uncertain Earth system feedbacks that can result in further warming or a path-dependency of warming as a function of cumulative CO_2 emissions. {5.4, 5.5.1}

Mitigation requirements over this century for limiting maximum warming to specific levels can be quantified using a carbon budget that relates cumulative CO_2 emissions to global mean temperature increase (*high confidence*). For the period 1850–2019, a total of 655 ± 65 PgC (2390 ± 240 $GtCO_2$, *likely* range) of anthropogenic CO_2 has been emitted. Remaining carbon budgets (starting from 1 January 2020) for limiting warming to 1.5°C, 1.7°C, and 2.0°C are 140 PgC (500 $GtCO_2$), 230 PgC (850 $GtCO_2$) and 370 PgC (1350 $GtCO_2$), respectively, based on the 50th percentile of TCRE. For the 67th percentile, the respective values are 110 PgC (400 $GtCO_2$), 190 PgC (700 $GtCO_2$) and 310 PgC (1150 $GtCO_2$). These remaining carbon budgets may vary by an estimated ± 60 PgC (220 $GtCO_2$) depending on how successfully future non-CO_2 emissions can be reduced. Since AR5 and the Special Report on Global Warming of 1.5°C (SR1.5), estimates have undergone methodological improvements, resulting in larger, yet consistent estimates. {5.5.2, 5.6; Figure 5.31; Table 5.8}

Several factors affect the precise value of remaining carbon budgets, including estimates of historical warming, future emissions from thawing permafrost, and variations in projected non-CO_2 warming. Remaining carbon budget estimates can increase or decrease by 150 PgC (*likely* range; 150 PgC equals 550 $GtCO_2$) due to uncertainties in the level of historical warming, and by an additional ± 60 PgC (±220 GtCO, *likely* range) due to geophysical uncertainties surrounding the climate response to non-CO_2 emissions such as CH_4, N_2O, and aerosols. Permafrost thaw is included in the estimates, together with other feedbacks that are often not captured by models. Despite the large uncertainties surrounding the quantification of the effects of additional Earth system feedback processes, such as emissions from wetlands and permafrost thaw, these feedbacks represent identified additional amplifying risk factors that scale with additional warming and mostly increase the challenge of limiting warming to specific temperature thresholds. These uncertainties do not change the basic conclusion that global CO_2 emissions would need to decline to at least net zero to halt global warming. {5.4, 5.5.2}

Biogeochemical Implications of Carbon Dioxide Removal and Solar Radiation Modification

Land- and ocean-based carbon dioxide removal (CDR) methods have the potential to sequester CO_2 from the atmosphere, but the benefits of this removal would be partially offset by CO_2 release from land and ocean carbon stores (*very high confidence*). The fraction of CO_2 removed that remains out of the atmosphere, a measure of CDR effectiveness, decreases slightly with increasing amount of removal (*medium confidence*) and decreases strongly if CDR is applied at lower CO_2 concentrations (*medium confidence*). {5.6.2.1; Figures 5.32, 5.33, 5.34}

The century-scale climate–carbon cycle response to a CO_2 removal from the atmosphere is not always equal and opposite to the response to a CO_2 emission (*medium confidence*). For simultaneously cumulative CO_2 emissions and removals of greater than or equal to 100 PgC, CO_2 emissions are 4 ± 3% more effective at raising atmospheric CO_2 than CO_2 removals are at lowering atmospheric CO_2. The asymmetry originates from state-dependencies and non-linearities in carbon cycle processes and implies that an extra amount of CDR is required to compensate for a positive emission of a given magnitude to attain the same change in atmospheric CO_2. The net effect of this asymmetry on the global surface temperature is poorly constrained due to *low agreement* between models (*low confidence*). {5.6.2.1; Figure 5.35}

Wide-ranging side effects of CDR methods have been identified that can either weaken or strengthen the carbon sequestration and cooling potential of these methods and affect the achievement of sustainable development goals (*high confidence*). Biophysical and biogeochemical side effects of CDR methods are associated with changes in surface albedo,

the water cycle, emissions of CH_4 and N_2O, ocean acidification and marine ecosystem productivity (*high confidence*). These side effects and associated Earth system feedbacks can decrease carbon uptake and/or change local and regional climate, and in turn limit the CO_2 sequestration and cooling potential of specific CDR methods (*medium confidence*). Deployment of CDR, particularly on land, can also affect water quality and quantity, food production and biodiversity, with consequences for the achievement of related sustainable development goals (*high confidence*). These effects are often highly dependent on local context, management regime, prior land use, and scale of deployment (*high confidence*). A wide range of co-benefits are obtained with methods that seek to restore natural ecosystems or improve soil carbon (*high confidence*). The biogeochemical effects of terminating CDR are expected to be small for most CDR methods (*medium confidence*). {5.6.2.2; Figure 5.36; Cross-Chapter Box 5.1}

Solar radiation modification (SRM) would increase the global land and ocean CO_2 sinks (*medium confidence*) but would not stop CO_2 from increasing in the atmosphere, thus exacerbating ocean acidification under continued anthropogenic emissions (*high confidence*). SRM acts to cool the planet relative to unmitigated climate change, which would increase the land sink by reducing plant and soil respiration and slow the reduction of ocean carbon uptake due to warming (*medium confidence*). SRM would not counteract or stop ocean acidification (*high confidence*). The sudden and sustained termination of SRM would rapidly increase global warming, with the return of positive and negative effects on the carbon sinks (*very high confidence*). {4.6.3; 5.6.3}

times faster, respectively, than the maximum centennial growth rate averages of those gases during the last 800 kyr (Fig. 5.4).

5.1.2.3 Holocene Changes

Atmospheric GHG concentrations were much less variable during the pre-industrial Holocene (from 11.7 ka to 1750 CE). Atmospheric CH_4 concentrations decreased at the beginning of the Holocene, consistent with a general weakening of boreal sources (Yang et al., 2017; Beck et al., 2018) and further decline during the mid-Holocene owing to a reduction in Southern Hemisphere emissions concomitant with a southward shift of the ITCZ (Singarayer et al., 2011; Beck et al., 2018). Atmospheric CH_4 concentrations increased about 5 ka, which prompted the hypothesis of an early anthropogenic influence related to land-use changes in South East Asia (Ruddiman et al., 2016). However, stable isotope compositions on CH_4 extracted from Greenland and Antarctic ice (Beck et al., 2018) reveal that natural emissions located in the southern tropics were responsible for the rise in atmospheric CH_4 concentrations, in line with model simulations (Singarayer et al., 2011) thus disputing the early anthropogenic influence on the global CH_4 budget. Atmospheric N_2O concentrations increased slightly (20 ppb) across the Holocene, associated with a gradual decline in its nitrogen stable isotope composition (H. Fischer et al., 2019). The combined signal is consistent with a small increase in terrestrial emissions, offset by a reduction in marine emissions (Schilt et al., 2010b; H. Fischer et al., 2019).

The early Holocene decrease in CO_2 concentration by about 5 ppm (Schmitt et al., 2012) has been attributed to post-glacial regrowth in terrestrial biomass and a gradual increase in peat reservoirs over the Holocene, resulting in the sequestration of several hundred PgC (Yu et al., 2010; Nichols and Peteet, 2019). Peat accumulation rates in boreal and temperate regions were higher under warmer summer conditions in the early to mid-Holocene (Loisel et al., 2014; Stocker et al., 2017). The 20 ppm gradual increase of atmospheric CO_2 starting 7 ka has been attributed to a decrease in natural terrestrial biomass due to climate change, carbonate compensation and enhanced shallow water carbonate deposition (Menviel and Joos, 2012; Brovkin et al., 2016), consistent with stable carbon isotope measurements on CO_2 extracted from Antarctic ice (Elsig et al., 2009; Schmitt et al., 2012). These isotopic measurements do not support an early anthropogenic influence on atmospheric CO_2 due to land-use change and forest clearing (Ruddiman et al., 2016). Recent paleoceanographic evidence suggests that remineralized carbon outgassing associated with increased Southern Ocean circulation and upwelling (Studer et al., 2018), possibly promoted by stronger Southern Hemisphere westerly winds (Saunders et al., 2018), could have additionally contributed to the late Holocene increase in atmospheric CO_2 concentrations. However, the role of these mechanisms remained insignificant in transient Holocene ESM simulations (Brovkin et al., 2019). Overall, as in AR5 (WGI, Chapter 5), there is *medium confidence* in the key drivers of the CO_2 increase between the early Holocene and the beginning of the industrial era, yet there is *low confidence* in the relative contributions of these drivers due to insufficient quantitative constraints on particular processes.

5.2 Historical Trends, Variability and Budgets of CO_2, CH_4 and N_2O

This section assesses the trends and variability in atmospheric accumulation of the three main greenhouse gases (GHGs) – CO_2, CH_4 and N_2O – their ocean and terrestrial sources and sinks as well as their budgets during the Industrial Era (1750–2019). Emphasis is placed on the more recent contemporary period (1959–2019) where understanding is increasingly better constrained by atmospheric, ocean and land observations. The section also assesses our increased understanding of the anthropogenic forcing and processes driving the trends, as well as how variability at the seasonal to decadal scales provide insights on the mechanism governing long-term trends and emerging biogeochemical–climate feedbacks with their regional characteristics.

5.2.1 CO_2: Trends, Variability and Budget

5.2.1.1 Anthropogenic CO_2 Emissions

There are two anthropogenic sources of carbon dioxide (CO_2): fossil emissions and net emissions (including removals) resulting from land-use change and land management (also shown in this chapter as LULUCF: land use, land-use change, and forestry; in previous IPCC reports it has been termed forestry and other land use, FOLU). Fossil CO_2 emissions include the combustion of the fossil fuels coal, oil and gas, covering all sectors of the economy (electricity, transport, industrial, and buildings), fossil carbonates such as in cement manufacturing, and other industrial processes such as the production of chemicals and fertilizers (Figure 5.5a). Fossil CO_2 emissions are estimated by combining economic activity data and emissions factors, with different levels of methodological complexity (tiers) or approaches (e.g., IPCC Guidelines for National Greenhouse Gas Inventories). Several organizations or groups provide estimates of fossil CO_2 emissions, with each dataset having slightly different system boundaries, methods, activity data, and emissions factors (Andrew, 2020). Datasets cover different time periods, which can dictate the datasets and methods that are used for a particular application. The data reported here is from an annually updated data source that combines multiple sources to maximise temporal coverage (Friedlingstein et al., 2020). The uncertainty in global fossil CO_2 emissions is estimated to be ±5% (1 standard deviation).

Fossil CO_2 emissions have grown continuously since the beginning of the industrial era (Figure 5.5) with short intermissions due to global economic crises or social instability (Peters et al., 2012; Friedlingstein et al., 2020). In the most recent decade (2010–2019), fossil CO_2 emissions reached an average 9.6 ± 0.5 PgC yr^{-1} and were responsible for 86% of all anthropogenic CO_2 emissions. In 2019, fossil CO_2 emissions were estimated to be 9.9 ± 0.5 PgC yr^{-1} excluding carbonation (Friedlingstein et al., 2020), the highest on record. These estimates exclude the cement carbonation sink of around 0.2 PgC yr^{-1}. Fossil CO_2 emissions grew at 0.9% yr^{-1} in the 1990s, increasing to 3.0% yr^{-1} in the 2000s, and reduced to 1.2% from 2010 to 2019. The slower growth in fossil CO_2 emissions in the last decade is due to a slowdown in growth from coal use.

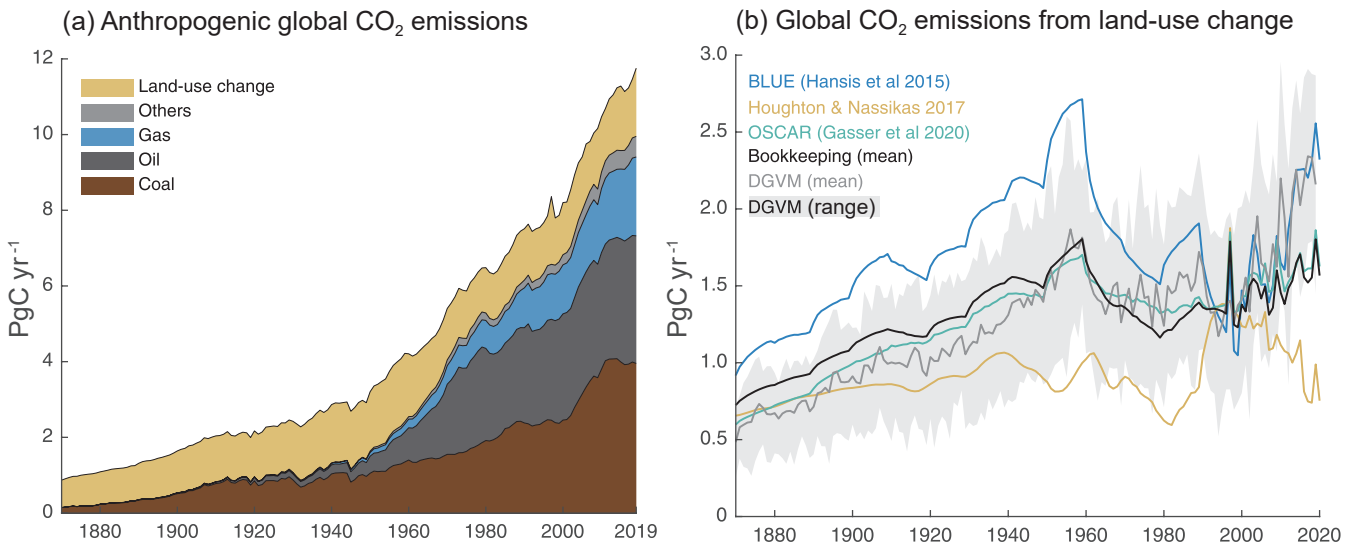


Figure 5.5 | Global anthropogenic CO_2 emissions. (a) Historical trends of anthropogenic CO_2 emissions (fossil fuels and net land-use change, including land management, called LULUCF flux in the main text) for the period 1870 to 2019, with 'others' representing flaring, emissions from carbonates during cement manufacture. Data sources: (Boden et al., 2017; IEA, 2017; Andrew, 2018; BP, 2018; Le Quéré et al., 2018a; Friedlingstein et al., 2020). **(b)** The net land-use change CO_2 flux (PgC yr^{-1}) as estimated by three bookkeeping models and 16 Dynamic Global Vegetation Models (DGVMs) for the global annual carbon budget 2019 (Friedlingstein et al., 2020). The three bookkeeping models are from Hansis et al., 2015; Houghton and Nassikas, 2017; Gasser et al., 2020 and are all updated to 2019. Their average is used to determine the net land-use change flux in the annual global carbon budget (black line). The DGVM estimates are the result of differencing a simulation with and without land-use changes run under observed historical climate and CO_2, following the Trendy v9 protocol (https://sites.exeter.ac.uk/trendy/protocol/); they are used to provide an uncertainty range to the bookkeeping estimates (Friedlingstein et al., 2020). All estimates are unsmoothed annual data. Estimates differ in process comprehensiveness of the models and in definition of flux components included in the net land use change flux. Further details on data sources and processing are available in the chapter data table (Table 5.SM.6).

CO_2 emissions from coal use grew at 4.8% yr^{-1} in the 2000s, but slowed to 0.4% yr^{-1} in the 2010s. CO_2 emissions from oil use grew steadily at 1.1% yr^{-1} in both the 2000s and 2010s. CO_2 emissions from gas use grew at 2.5% yr^{-1} in the 2000s and 2.4% yr^{-1} in 2010s, but has shown signs of accelerated growth of 3% yr^{-1} since 2015 (G.P. Peters et al., 2020). Direct CO_2 emissions from carbonates in cement production are around 4% of total fossil CO_2 emissions, and grew at 5.8% yr^{-1} in the 2000s but a slower 2.4% yr^{-1} in the 2010s. The uptake of CO_2 in cement infrastructure (carbonation) offsets about one half of the carbonate emissions from current cement production (Friedlingstein et al., 2020). These results are robust across the different fossil CO_2 emissions datasets, despite minor differences in levels and rates, as expected given the reported uncertainties (Andrew, 2020). During 2020, the COVID-19 pandemic led to a rapid, temporary decline in fossil CO_2 emissions, estimated to be around 7% based on a synthesis of four estimates. (Cross-Chapter Box 6.1; Forster et al., 2020; Friedlingstein et al., 2020; Le Quéré et al., 2020; Z. Liu et al., 2020).

The global net flux from land-use change and land management is composed of carbon fluxes from land-use conversions, land management and changes therein (Pongratz et al., 2018) and is equivalent to the LULUCF fluxes from the agriculture, forestry and other land use (AFOLU) sector (Jia et al., 2019). It consists of gross emissions (loss of biomass and soil carbon in clearing or logging, harvested product decay, emissions from peat drainage and burning, degradation) and gross removals (CO_2 uptake in natural vegetation regrowing after harvesting or agricultural abandonment, afforestation). The LULUCF flux relates to direct human interference with terrestrial vegetation, as opposed to the natural carbon fluxes occurring due to interannual variability or trends in environmental conditions (in particular, climate, CO_2, and nutrient deposition) (Houghton, 2013).

Progress since AR5 and SRCCL (IPCC, 2019a) allows more accurate estimates of gross and net fluxes due to the availability of more models, model advancement in terms of inclusiveness of land-use practices, and advanced land-use forcings (Ciais et al., 2013; Klein Goldewijk et al., 2017; Hurtt et al., 2020). In addition, important terminological discrepancies were resolved. First, synergistic effects of land-use change and environmental changes have been identified as a key reason for the large discrepancies between model estimates of the LULUCF flux, explaining up to 50% of differences (Pongratz et al., 2014; Stocker and Joos, 2015; Gasser et al., 2020). Another reason for discrepancies relates to natural fluxes being considered as part of the LULUCF flux when occurring on managed land in the United Nations Framework Convention on Climate Change (UNFCCC) national GHG inventories; these fluxes are considered part of the natural terrestrial sink in global vegetation models and excluded in bookkeeping models (Grassi et al., 2018). LULUCF fluxes following national GHG inventories or Food and Agriculture Organization of the United Nations (FAO) datasets, including recent estimates (Tubiello et al., 2021), are thus excluded from our global assessment, but their comparison against the academic approach is available elsewhere – at the global scale (Jia et al., 2019) and European level (Petrescu et al., 2020).

Land-use-related component fluxes can be verified by the growing databases of global satellite-based biomass observations in combination with information on remotely sensed land cover change.

However, they differ from bookkeeping and modelling with Dynamic Global Vegetation Models (DGVMs) in excluding legacy emissions from pre-satellite-era land-use change and land management, and neglecting soil carbon changes, often focusing on gross deforestation, not regrowth (Jia et al., 2019).

For the decade 2010–2019, average emissions were estimated at 1.6 ± 0.7 PgC yr^{-1} (mean ± standard deviation, 1 sigma; Friedlingstein et al., 2020). A *likely* general upward trend since 1850 is reversed during the second part of the 20th century (Figure 5.5b). Trends since the 1980s have *low confidence* because they differ between estimates, which is related, among other things, to Houghton and Nassikas (2017) using a different land-use forcing than Hansis et al. (2015) and the DGVMs. Higher emissions estimates are expected from DGVMs run under transient environmental conditions compared to bookkeeping estimates, because the DGVM estimate includes the loss of additional sink capacity. Because the transient setup requires a reference simulation without land-use change to separate anthropogenic fluxes from natural land fluxes, LULUCF estimates by DGVMs include the sink forests that would have developed in response to environmental changes on areas that in reality have been cleared (Pongratz et al., 2014). The agricultural areas that replaced these forests have a reduced residence time of carbon, lacking woody material, and thus provide a substantially smaller additional sink over time (Gitz and Ciais, 2003). The loss of additional sink capacity is growing in particular with atmospheric CO_2 and increases DGVM-based LULUCF flux estimates relative to bookkeeping estimates over time (Figure 5.5).

Gross emissions are on average two to three times larger than the net flux from LULUCF, increasing from an average of 3.5 ± 1.2 PgC yr^{-1} for the decade of the 1960s to an average of 4.4 ± 1.6 PgC yr^{-1} during 2010–2019 (Friedlingstein et al., 2020). Gross removals partly balance these gross emissions to yield the net flux from LULUCF and increase from –2.0 ± 0.7 PgC yr^{-1} for the 1960s to –2.9 ± 1.2 PgC yr^{-1} during 2010–2019. These large gross fluxes show the relevance of land management, such as harvesting or rotational agriculture, and the large potential to reduce emissions by halting deforestation and degradation.

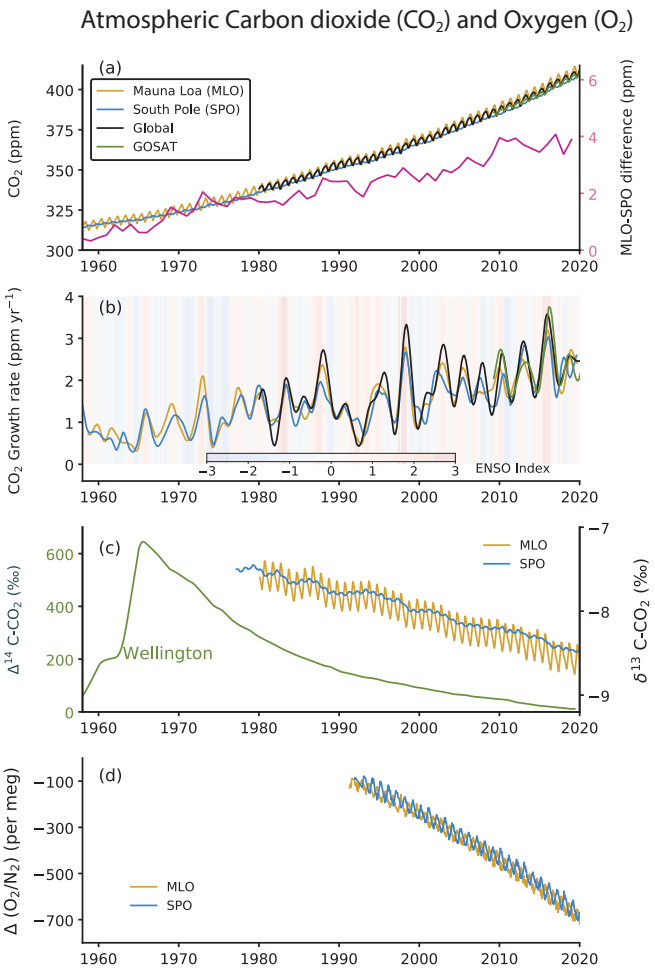
More evidence on the pre-industrial LULUCF flux has emerged since AR5 in the form of new estimates of cumulative carbon losses until today, and of a better understanding of natural carbon cycle processes over the Holocene (Ciais et al., 2013). Cumulative carbon losses by land-use activities since the start of agriculture and forestry (pre-industrial and industrial era) have been estimated at 116 PgC based on global compilations of carbon stocks for soils (Sanderman et al., 2017) with about 70 PgC of this occurring prior to 1750, and for vegetation as 447 PgC (inner quartiles of 42 calculations: 375–525 PgC) (Erb et al., 2018). Emissions prior to 1750 can be estimated by subtracting the post-1750 LULUCF flux from Table 5.1 from the combined soil and vegetation losses until today; they would then amount to 328 (161–501) PgC assuming error ranges are independent. A share of 353 (310–395) PgC from prior to 1800 has indirectly been suggested as the difference between net biosphere flux and terrestrial sink estimates, which is compatible with ice-core records due to a low airborne fraction of anthropogenic emissions in pre-industrial times (Erb et al., 2018; see also Section 5.1.2.3). *Low confidence* is assigned to pre-industrial emissions estimates.

Since AR5, evidence emerged that the LULUCF flux might have been underestimated as DGVMs include anthropogenic land cover change, but often ignore land management practices not associated with a change in land cover; land management is more widely captured by bookkeeping models through use of observation-based carbon densities (Ciais et al., 2013; Pongratz et al., 2018). Sensitivity studies show that practices such as wood and crop harvesting increase global net LULUCF emissions (Arneth et al., 2017) and explain about half of the cumulative loss in biomass (Erb et al., 2018).

5.2.1.2 Atmosphere

Atmospheric CO_2 concentration measurements in remote locations began in 1957 at the South Pole Observatory (SPO) and in 1958 at Mauna Loa Observatory (MLO), Hawaii, USA (Keeling, 1960) (Figure 5.6a). Since then, measurements have been extended to multiple locations around the world (Bacastow et al., 1980; Conway et al., 1994; Nakazawa et al., 1997). In addition, high-density global observations of total column CO_2 measurements by dedicated GHG-observing satellites began in 2009 (Yoshida et al., 2013; O'Dell et al., 2018). Annual mean CO_2 growth rates are observed to be 1.56 ± 0.18 ppm yr^{-1} (average and range from 1 standard deviation of annual values) over the 61 years of atmospheric measurements (1959–2019), with the rate of CO_2 accumulation almost tripling from an average of 0.82 ± 0.29 ppm yr^{-1} during the decade of 1960–1969 to 2.39 ± 0.37 ppm yr^{-1} during the decade of 2010–2019 (Chapter 2). The latter agrees well with that derived for total column (XCO_2) measurements by the Greenhouse Gases Observing Satellite (GOSAT; Figure 5.6b). The interannual oscillations in monthly mean CO_2 growth rates (Figure 5.6b) show a close relationship with the El Niño–Southern Oscillation (ENSO) cycle (Figure 5.6b) due to the ENSO-driven changes in terrestrial and ocean CO_2 sources and sinks on the Earth's surface (Section 5.2.1.4).

Multiple lines of evidence unequivocally establish the dominant role of human activities in the growth of atmospheric CO_2. First, the systematic increase in the difference between the MLO and SPO records (Figure 5.6a) is caused primarily by the increase in emissions from fossil fuel combustion in industrialized regions that are situated predominantly in the Northern Hemisphere (Ciais et al., 2019). Second, measurements of the stable carbon isotope in the atmosphere ($d^{13}C$–CO_2) are more negative over time because CO_2 from fossil fuels extracted from geological storage is depleted in ^{13}C (Figure 5.6c; Rubino et al., 2013; Keeling et al., 2017). Third, measurements of the $d(O_2/N_2)$ ratio show a declining trend because for every molecule of carbon burned, 1.17 to 1.98 molecules of oxygen (O_2) is consumed (Figure 5.6d; Ishidoya et al., 2012; Keeling and Manning, 2014). These three lines of evidence confirm unambiguously that the atmospheric increase of CO_2 is due to an oxidative process (i.e., combustion). Fourth, measurements of radiocarbon (^{14}C–CO_2) at sites around the world (Levin et al., 2010; Graven et al., 2017; Turnbull et al., 2017) show a continued long-term decrease in the $^{14}C/^{12}C$ ratio. Fossil fuels are devoid of ^{14}C and therefore fossil fuel-derived CO_2 additions decrease the atmospheric $^{14}C/^{12}C$ ratio (Suess, 1955).



Over the past six decades, the fraction of anthropogenic CO_2 emissions that has accumulated in the atmosphere (referred to as airborne fraction) has remained near constant at approximately 44% (Figure 5.7) (Ballantyne et al., 2012; Ciais et al., 2019; Gruber et al., 2019b; Friedlingstein et al., 2020). This suggests that the land and ocean CO_2 sinks have continued to grow at a rate consistent with the growth rate of anthropogenic CO_2 emissions, albeit with large interannual and sub-decadal variability dominated by the land sinks (Figure 5.7).

Since AR5, an alternative observable diagnostic to the airborne fraction has been proposed to understand the trends in land and ocean sinks in response to its driving atmospheric CO_2 concentrations (Raupach et al., 2014; Bennedsen et al., 2019). It is the sink rate that is defined as the combined ocean and land sink flux per unit of atmospheric excess of CO_2 above pre-industrial levels (Raupach et al.,

Figure 5.6 | Time series of CO_2 concentrations and related measurements in ambient air. (a) Concentration time series and MLO-SPO difference, **(b)** growth rates, **(c)** ^{14}C and ^{13}C isotopes, and **(d)** O_2/N_2 ratio. The data for Mauna Loa Observatory (MLO) and South Pole Observatory (SPO) are taken from the Scripps Institution of Oceanography (SIO)/University of California, San Diego (Keeling et al., 2001). The global mean CO_2 are taken from National Oceanic and Atmospheric Administration (NOAA) cooperative network (as in Chapter 2), and Greenhouse Gases Observing Satellite (GOSAT) monthly mean XCO_2 (mixing ratio) time series are taken from National Institute for Environmental Studies (Yoshida et al., 2013). CO_2 growth rates are calculated as the time derivative of deseasonalized time series (Nakazawa et al., 1997). The $D(O_2/N_2)$ are expressed in per meg units (= (FF/M) × 10^6, where FF = moles of O_2 consumed by fossil-fuel burning, M = 3.706 × 10^{19}, total number of O_2 molecules in the atmosphere (Keeling and Manning, 2014). The $^{14}CO_2$ time series at Barring Head, Wellington, New Zealand (BHD) is taken from GNS Science and NIWA (Turnbull et al., 2017). The multivariate ENSO index (MEI) is shown as the shaded background in panel (b); (warmer shade indicates El Niño). Further details on data sources and processing are available in the chapter data table (Table 5.SM.6).

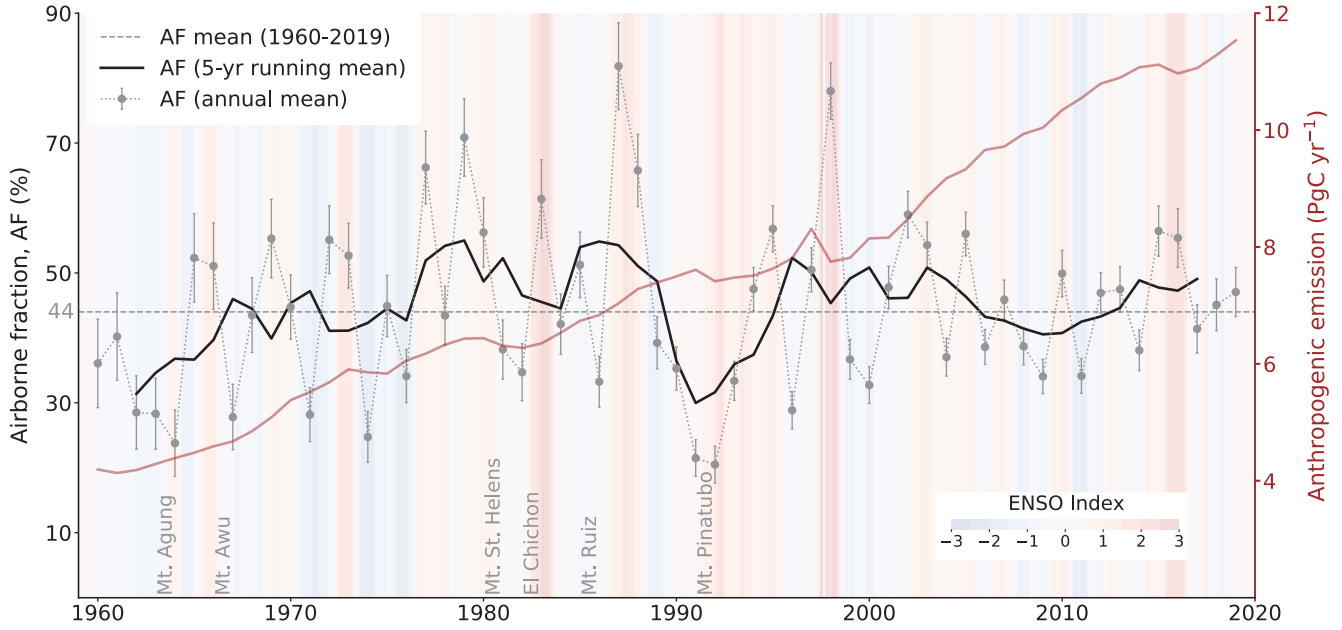


Figure 5.7 | Airborne fraction and anthropogenic (fossil fuel and land-use change) CO_2 emissions. Data as in Section 5.2.1.1. The multivariate El Niño–Southern Oscillation (ENSO) index (shaded) and the major volcanic eruptions are marked along the x-axis. Further details on data sources and processing are available in the chapter data table (Table 5.SM.6).

permafrost thaw (Box 5.1) and fire (Section 5.4.3.2), natural CH_4 and N_2O emissions (Section 5.4.7), and aerosol and atmospheric chemistry (Section 6.3.6). We derive a physical climate feedback parameter α, as defined in Section 7.4.1.1, for CO_2-based feedbacks using the linear framework proposed by Gregory et al. (2009), using the radiative forcing equations for CO_2 (Etminan et al., 2016).

The climate feedback parameter for CO_2 (–1.13 ± 0.45 W m^{-2} °C^{-1}, mean and 1 standard-deviation range) is dominated by the contribution of the CO_2-induced increase of ocean and land carbon storage (–1.46 ± 0.41 W m^{-2} °C^{-1}, corresponding to a β_{L+O} of 1.66 ± 0.31 PgC ppm^{-1}), with smaller contributions from the carbon cycle's response to climate (0.24 ± 0.17 W m^{-2} °C^{-1}, corresponding to γ_{L+O} of –50 ± 34 PgC °C^{-1}), and emissions from permafrost thaw (0.09 [0.02 to 0.20] W m^{-2} °C^{-1}, corresponding to γ of –18 [3 to 41] PgC °C^{-1}, mean and 5–95% range) (Figure 5.29a). This estimate does not include an estimate of the fire-related CO_2 feedback (range: 0.01–0.06 W m^{-2} °C^{-1}), as only *limited evidence* was available to inform its assessment. The sum (mean and 5–95th percentile range) of feedbacks from natural emissions of CH_4 including permafrost thaw, and N_2O (0.05 [0.02 to 0.09] W m^{-2} °C^{-1}), and feedbacks from aerosol and atmospheric chemistry (–0.20 [–0.41 to 0.01] W m^{-2} °C^{-1}) leads to an estimate of the non-CO_2 biogeochemical feedback parameter of –0.15 [–0.36 to +0.06] W m^{-2} °C^{-1}. There is *low confidence* in the estimate of the non-CO_2 biogeochemical feedbacks, due to the large range in the estimates of α for some individual feedbacks (Figure 5.29c), which can be attributed to the diversity in how models account for these feedbacks, limited process-level understanding, and the existence of known feedbacks where there is insufficient evidence to assess the feedback strength.

CO_2 and non-CO_2 biogeochemical feedbacks are an important component of the assessment of TCRE and the remaining carbon budget (Section 5.5). The feedbacks of the carbon cycle of CO_2 and climate are implicitly taken account in the TCRE assessment, because they are represented in the various underlying lines of evidence. Other feedback contributions, such as the non-CO_2 biogeochemical feedback, can be converted into a carbon-equivalent feedback term (γ; Section 5.4.5.5, 7.6) by reverse application of the linear feedback approximation (Gregory et al., 2009). The contributions of non-CO_2 biogeochemical feedbacks combine to a linear feedback term of 30 ± 27 PgCeq °C^{-1} (1 standard deviation range, 111 ± 98 Gt CO_2.eq °C^{-1}), including a feedback term of –11 [–18 to –5] PgCeq °C^{-1} (5–95% range, –40 [–62 to –18] Gt CO_2.eq °C^{-1}) from natural CH_4 and N_2O sources. The biogeochemical feedback from permafrost thaw leads to a combined linear feedback term of –21 ± 12 PgCeq °C^{-1} (1 standard deviation range –77 ± 44 Gt CO_2-eq °C^{-1}). For the integration of these feedbacks in the assessment of the remaining carbon budget (Section 5.5.2), two individual non-CO_2 feedbacks (tropospheric ozone, and methane lifetime) are captured in the AR6-calibrated emulators (Box 7.1). Excluding those two contributions, the resulting combined linear feedback term for application in Section 5.5.2 is assessed at a reduction of 7 ± 27 PgCeq °C^{-1} (1 standard deviation range, –26 ± 97 PgCeq °C^{-1}). For the same reasons as for the feedback terms expressed in W m^{-2} °C^{-1} (see above), there is overall *low confidence* in the magnitude of these feedbacks.

5.4.9 Abrupt Changes and Tipping Points

The applicability of the linear feedback framework (Section 5.4.5.5) suggests that large-scale biogeochemical feedbacks are approximately linear in the forcing from changes in CO_2 and climate. Nevertheless, regionally the biosphere is known to be capable of producing abrupt changes or even 'tipping points' (Higgins and Scheiter, 2012; Lasslop et al., 2016). Abrupt change is defined as a change in the system that is substantially faster than the typical rate of the changes in its history (Section 1.4.5). A related matter is a tipping point: a critical threshold beyond which a system reorganizes, often abruptly and/or irreversibly. Possible abrupt changes in the Earth system include those related to ecosystems and biogeochemistry (Lenton et al., 2008; Steffen et al., 2018): tropical and boreal forest

Table 5.6 | Examples of possible biogeochemical abrupt changes and tipping points in the Earth system. The fourth and sixth columns provide upper estimates of the impact of each example on the evolution of atmospheric GHGs in the 21st century. These upper estimates are therefore *very unlikely* but provide a useful comparison to the impact of direct anthropogenic emissions (currently 2.5 ppm yr^{-1}).

Abrupt Change/ Tipping Point	Key Region(s)	Probability to Occur in the 21st Century	Maximum CO_2 or CH_4 Release in the 21st Century	Principal Development Time Scale	Maximum CO_2 or CH_4 Rate of Change Over the 21st Century	(Ir)reversibility
Tropical forests dieback (Section 5.4.9.1.1)	Amazon watershed	Low	<200 PgC as CO_2 (Section 5.4.9.1.1; *medium confidence*)	Multi-decadal	CO_2: <0.5 ppm yr^{-1}	Irreversible at multi-decadal scale (*medium confidence*)
Boreal forests dieback (Sections 5.4.9.1.1, 5.4.3.2)	Boreal Eurasia and North America	Low	<27 Pg (Section 5.4.9.1.2; *medium confidence*)	Multi-decadal	Small (*low confidence*)	Irreversible at multi-decadal scale (*medium confidence*)
Biogenic emissions from permafrost thaw (Section 5.4.9.1.2)	Pan-Arctic	High	up to 240 PgC of CO_2 and up to 5300 Tg of CH_4 (Section 5.4.8.1.2; *low confidence*)	Multi-decadal	CO_2: ≤1 ppm yr^{-1} CH_4: ≤10 ppb yr^{-1}	Irreversible at centennial time scales (*high confidence*)
Methane release from clathrates (Section 5.4.9.1.3)	Oceanic shelf	Very low	*very likely* small (Section 5.4.9.1.3)	Multi-millennium	CH_4: ≤0.2 ppb yr^{-1}	Irreversible at multi-millennium time scales (*medium confidence*)

dieback; and release of greenhouse gases (GHGs) from permafrost and methane clathrates (Table 5.6). In this section we therefore focus on estimating upper limits on the possible impact of abrupt changes on the evolution of atmospheric GHGs out to 2100, for comparison to the impact of direct anthropogenic emissions.

5.4.9.1 Assessment of Biogeochemical Tipping Points

5.4.9.1.1 Forest dieback

Published examples of abrupt biogeochemical changes in models include tropical rain forest dieback (Cox et al., 2004; Jones et al., 2009; Brando et al., 2014; Le Page et al., 2017; Zemp et al., 2017), and temperate and boreal forest dieback (Joos et al., 2001; Lucht et al., 2006; Scheffer et al., 2012; Lasslop et al., 2016; Section 5.4.3). Such transitions may be related to: (i) large-scale changes in mean climate conditions crossing particular climate thresholds (Joos et al., 2001; Cox et al., 2004; Lucht et al., 2006; Hirota et al., 2011; Scheffer et al., 2012; Le Page et al., 2017; Zemp et al., 2017); (ii) temperature and precipitation extremes (Staver et al., 2011; Higgins and Scheiter, 2012; Scheffer et al., 2012; Pavlov, 2015; Zemp et al., 2017); or (iii) possible enhancement and intermittency in fire activity (Staver et al., 2011; Higgins and Scheiter, 2012; Lasslop et al., 2016; Brando et al., 2020). Simulated changes in forest cover are a combination of the effects of CO_2 on photosynthesis and water-use efficiency (Section 5.4.1), and the effects of climate change on photosynthesis, respiration and disturbance (Section 5.4.3). In ESMs, direct CO_2 effects tend to enhance forest growth, but the impacts of climate change vary between being predominantly negative in the tropics and predominantly positive in the boreal zone (Figure 5.27).

Most ESMs project continuing carbon accumulation in tropical forests as a result of direct CO_2 effects overwhelming the negative effects of climate change (Huntingford et al., 2013; Drijfhout et al., 2015; Boulton et al., 2017). In the real world, forests may be less vulnerable to climate changes than those modelled in ESMs because of the greater plant trait diversity, which confers additional resilience (Reyer et al., 2015; Levine et al., 2016; Sakschewski et al., 2016), and because of possible acclimation of vegetation to warming (Good et al., 2011, 2013; Lloret et al., 2012; Mercado et al., 2018). On the contrary, forests may be more vulnerable in the real world due to indirect climate change effects such as insect outbreaks and diseases not considered here (Section 5.4.3.2) or model limitations in representing the effects disturbances such as wildfire and droughts. In general, forests are most vulnerable when climate change is combined with increased rates of direct deforestation (Nobre et al., 2016; Le Page et al., 2017).

To estimate an upper limit on the impact of Amazon forest dieback on atmospheric CO_2, we consider the *very unlikely* limiting case of negligible direct-CO_2 effects (Section 5.4.1). Emergent constraint approaches (Section 5.4.6) may be used to estimate an overall loss of tropical land carbon due to climate change alone, of around 50 PgC per °C of tropical warming (Cox et al., 2013; Wenzel et al., 2014). This implies an upper limit to the release of tropical land carbon of <200 PgC over the 21st century (assuming tropical warming of <4°C, and no CO_2-fertilization), which translates to dCO_2/dt <0.5 ppm yr^{-1}.

Boreal forest dieback is not expected to change the atmospheric CO_2 concentration substantially because forest loss at the south is partly compensated by: (i) temperate forest invasion into previously boreal areas; and (ii) boreal forest gain at the north (Friend et al., 2014; Kicklighter et al., 2014; Schaphoff et al., 2016) (*medium confidence*). An upper estimate of this magnitude, based on statistical modelling of climate change alone, is of 27 Pg vegetation carbon loss in the southern boreal forest, which is roughly balanced by gains in the northern zone (Koven, 2013). Carbon release from vegetation and soil due to wildfires in boreal regions (Eliseev et al., 2014b; Turetsky et al., 2015; X.J. Walker et al., 2019) is also not expected to change this estimate substantially because of its small present-day value of about 0.2 PgC yr^{-1} (van der Werf et al., 2017), and because of *likely* increases in precipitation in boreal regions (Section 4.5.1).

5.4.9.1.2 Biogenic emissions following permafrost thaw

There is large uncertainty in release of GHGs from permafrost in the 21st century. The largest of these estimates implies tens to hundreds of gigatons of carbon released in the form of CO_2 (Box 5.1) and CH_4 emissions up to 100 $TgCH_4$ yr^{-1} (Box 5.1). A carbon dioxide release of such magnitude would lead to an increase in the CO_2 accumulation rate in the atmosphere of ≤1 ppm yr^{-1}. These emissions develop at a multi-decadal time scale. Assuming a CH_4 lifetime in the atmosphere of the order of 10 years and the associated feedback parameter of 1.34 ± 0.04 (Section 6.2.2.1), this would increase the atmospheric CH_4 content by about 500 ppb over the century, corresponding to a rate of ≤10 ppb yr^{-1}. Irrespective of its origin, additional CH_4 accumulation of such a magnitude is not expected to modify the temperature response to anthropogenic emissions by more than a few tenths of a °C (Gedney et al., 2004; Eliseev et al., 2008; Denisov et al., 2013). Emissions from permafrost thawing are assessed in Box 5.1.

5.4.9.1.3 Methane release from clathrates

The total global clathrate reservoir is estimated to contain 1500–2000 PgC (Archer et al., 2009; Ruppel and Kessler, 2017), held predominantly in ocean sediments, with only an estimated 20 PgC in and under permafrost (Ruppel, 2015). The present-day CH_4 release from shelf clathrates is <10 $TgCH_4$ yr^{-1} (Kretschmer et al., 2015; Saunois et al., 2020). Despite polar amplification (Chapter 7), substantial releases from the permafrost-embedded subsea clathrates is *very unlikely* (Minshull et al., 2016; Malakhova and Eliseev, 2017, 2020). This is consistent with an overall small release of CH_4 from the shelf clathrates during the last deglacial transition, despite large reorganizations in climate state (Bock et al., 2017; Petrenko et al., 2017; Dyonisius et al., 2020). The long time scales associated with clathrate destabilization makes it *unlikely* that CH_4 release from the ocean to the atmosphere will deviate markedly from the present-day value through the 21st century (Hunter et al., 2013), corresponding to no more than additional 20 ppb of atmospheric CH_4 (i.e., <0.2 ppb yr^{-1}). Another possible source of CH_4 is gas clathrates in deeper terrestrial permafrost and below it (Buldovicz et al., 2018; Chuvilin et al., 2018), which may have caused recent craters in the north of Russia (Arzhanov et al., 2016, 2020; Arzhanov and Mokhov, 2017; Kizyakov et al., 2017, 2018). Land clathrates are formed at depths greater than 200 m (Ruppel and Kessler, 2017; Malakhova

and Eliseev, 2020), which precludes a substantial response to global warming over the next few centuries and associated emissions.

Thus, it is *very unlikely* that CH_4 emissions from clathrates will substantially warm the climate system over the next few centuries.

5.4.9.2 Abrupt Changes Detected in Earth System Model Projections

Projecting abrupt changes is intrinsically difficult, because by definition abrupt changes occur in a small region of the parameter and/or forcing space. At the time of AR5 there was no available systematic study of abrupt changes or tipping points in ESMs. An analysis of ESMs since AR5 has identified a number of abrupt changes in the CMIP5 ensemble (Drijfhout et al., 2015; Bathiany et al., 2020). These include abrupt changes in tropical forests and high-latitude greening, permafrost thaw, and vegetation composition change (Bathiany et al., 2020). Most modelled abrupt changes were detected in boreal and tundra regions, with few models showing Amazon forest dieback (Bathiany et al., 2020).

Based on the evidence presented in this section, we conclude that abrupt changes and tipping points in the biogeochemical cycles lead to additional uncertainty in 21st century GHG concentrations changes. However, these are *very likely* to be small compared to the uncertainty associated with future anthropogenic emissions (*high confidence*).

5.4.10 Long-term Response Past 2100

The AR5 assessed with *very high confidence* that the carbon cycle in the ocean and on land will continue to respond to climate change and rising atmospheric CO_2 concentrations created during the 21st century (WGI, Chapter 6, Executive Summary). Since AR5, experiments with the Community Earth System Model version 1 (CESM1) under the RCP8.5 extension scenario to 2300, suggest that both land and ocean carbon–climate feedbacks strengthen in time, land and ocean carbon-concentration feedbacks weaken, and the relative importance of ocean sinks versus land sinks increases (Randerson et al., 2015). Under high emissions scenarios, this relative strengthening of land carbon–climate feedbacks leads the terrestrial biosphere to shift from sink to source at some point after 2100 in all of the CMIP5 ESMs and CMIP5-era Earth system models of intermediate complexity (EMICs) (Tokarska et al., 2016). The strengthening of land and ocean carbon–climate feedbacks projected beyond 2100 under high emissions scenarios offsets the declining climate sensitivity to incremental increases of CO_2, leading to a net strengthening of carbon cycle feedbacks, as measured by the gain parameter, from one century to the next (Randerson et al., 2015).

Figure 5.30 shows carbon cycle changes to 2300 under three SSP scenarios with long-term extensions: SSP5-8.5, SSP5-3.4-overshoot, and SSP1-2.6, for four CMIP6 ESMs and one EMIC. Under all three scenarios, all five models project a reversal of the terrestrial carbon cycle from a sink to a source. However, the reasons for these reversals under very high emissions and low/negative emissions are very different. Under the SSP5-8.5 scenario, the terrestrial carbon–climate feedback is projected to strengthen, while the carbon-concentration feedbacks weaken after emissions peak at 2100, which together drives the land to become a net carbon source after 2100 (Tokarska et al., 2016). The difference in both timing and magnitude of this transition across the ensemble, leads to an assessment of *medium confidence* in the likelihood and *low confidence* in the timing and strength, of the land transitioning from a net sink to a net source under such a scenario. Based on *high agreement* across all available models, we assess with *high confidence* that the ocean sink strength would weaken but not reverse under a long-term high emissions scenario. In the SSP5-3.4-overshoot scenario, both the terrestrial and ocean reservoirs act as transient carbon sources during the overshoot period, when net anthropogenic CO_2 emissions are negative and CO_2 concentrations are falling, and then revert to near-zero (land) or weak sink (ocean) fluxes after stabilization of atmospheric CO_2. The SSP1-2.6 scenario, characterized by lower peak CO_2 concentrations, a smaller overshoot, and much less carbon loss from land-use change, shows instead a relaxation towards a neutral biosphere on land, and a sustained weak sink in the ocean (see also Section 5.6.2.2.1.2).

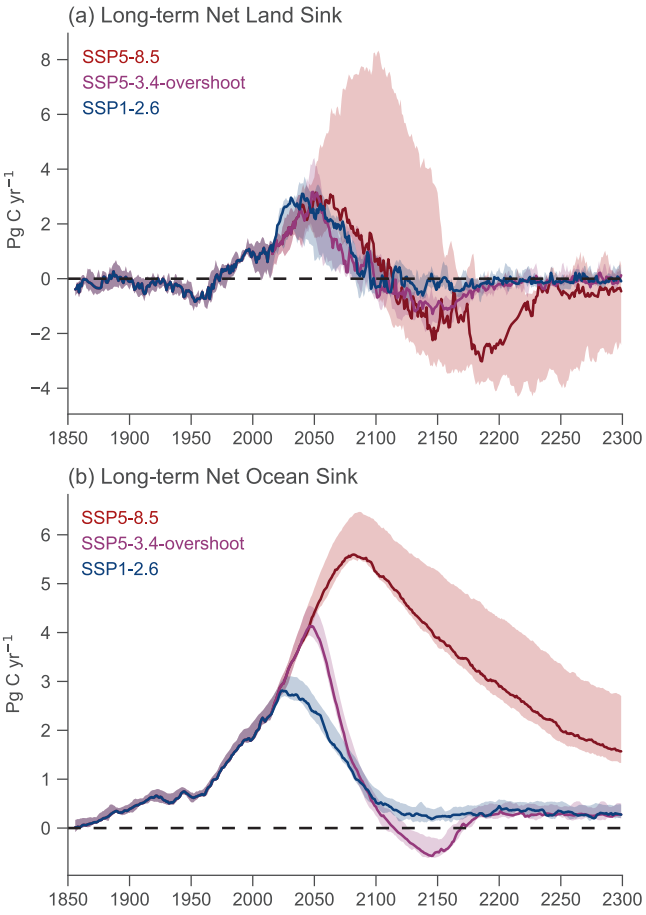


Figure 5.30 | Trajectories of carbon cycle dynamics for models beyond 2100. Shown are three scenarios: SSP5-8.5; SSP5-3.4-overshoot; and SSP1-2.6, from four ESMs (CanESM5, UKESM1, CESM2-WACCM, IPSL-CM6a-LR) and one EMIC (UVIC-ESCM, Mengis et al., 2020) for which extensions beyond 2100 are available. Solid lines represent the median flux value across the ensemble, and shading represents 15th–85th percentiles across the ensemble. Further details on data sources and processing are available in the chapter data table (Table 5.SM.6).

Frequently Asked Questions

FAQ 5.4 | What Are Carbon Budgets?

There are several types of carbon budgets. Most often, the term refers to the total net amount of carbon dioxide (CO_2) that can still be emitted by human activities while limiting global warming to a specified level (e.g., 1.5°C or 2°C above pre-industrial levels). This is referred to as the 'remaining carbon budget'. Several choices and value judgements have to be made before it can be unambiguously estimated. When the remaining carbon budget is combined with all past CO_2 emissions to date, a 'total carbon budget' compatible with a specific global warming limit can also be defined. A third type of carbon budget is the 'historical carbon budget', which is a scientific way to describe all past and present sources and sinks of CO_2.

The term *remaining carbon budget* is used to describe the total net amount of CO_2 that human activities can still release into the atmosphere while keeping global warming to a specified level, like 1.5°C or 2°C relative to pre-industrial temperatures. Emissions of CO_2 from human activities are the main cause of global warming. A remaining carbon budget can be defined because of the specific way CO_2 behaves in the Earth system. That is, global warming is roughly linearly proportional to the total net amount of CO_2 emissions that are released into the atmosphere by human activities – also referred to as cumulative anthropogenic CO_2 emissions. Other greenhouse gases behave differently and have to be accounted for separately.

The concept of a remaining carbon budget implies that, to stabilize global warming at any particular level, global emissions of CO_2 need to be reduced to net zero levels at some point. 'Net zero CO_2 emissions' describes a situation where all the anthropogenic emissions of CO_2 are counterbalanced by deliberate anthropogenic removals so that, on average, no CO_2 is added or removed from the atmosphere by human activities. Atmospheric CO_2 concentrations in such a situation would gradually decline to a long-term stable level as excess CO_2 in the atmosphere is taken up by ocean and land sinks (see FAQ 5.1). The concept of a remaining carbon budget also means that, if CO_2 emissions reductions are delayed, deeper and faster reductions are needed later to stay within the same budget. If the remaining carbon budget is exceeded, this will result in either higher global warming or a need to actively remove CO_2 from the atmosphere to reduce global temperatures back down to the desired level (see FAQ 5.3).

Estimating the size of remaining carbon budgets depends on a set of choices. These choices include: (1) the global warming level that is chosen as a limit (for example, 1.5°C or 2°C relative to pre-industrial levels); (2) the probability with which we want to ensure that warming is held below that limit (for example, a one-in-two, two-in-three, or higher chance), and (3) how successful we are in limiting emissions of other greenhouse gases that affect the climate, such as methane or nitrous oxide. These choices can be informed by science, but ultimately represent subjective choices. Once these choices have been made, to estimate the remaining carbon budget for a given temperature goal, we can combine knowledge about: how much our planet has warmed already; the amount of warming per cumulative tonne of CO_2; and the amount of warming that is still expected once global net CO_2 emissions are brought down to zero. For example, to limit global warming to 1.5°C above pre-industrial levels with either a one-in-two (50%) or two-in-three (67%) chance, the remaining carbon budgets amount to 500 and 400 billion tonnes of CO_2, respectively, from 1 January 2020 onward (FAQ 5.4, Figure 1). Currently, human activities are emitting around 40 billion tonnes of CO_2 into the atmosphere in a single year.

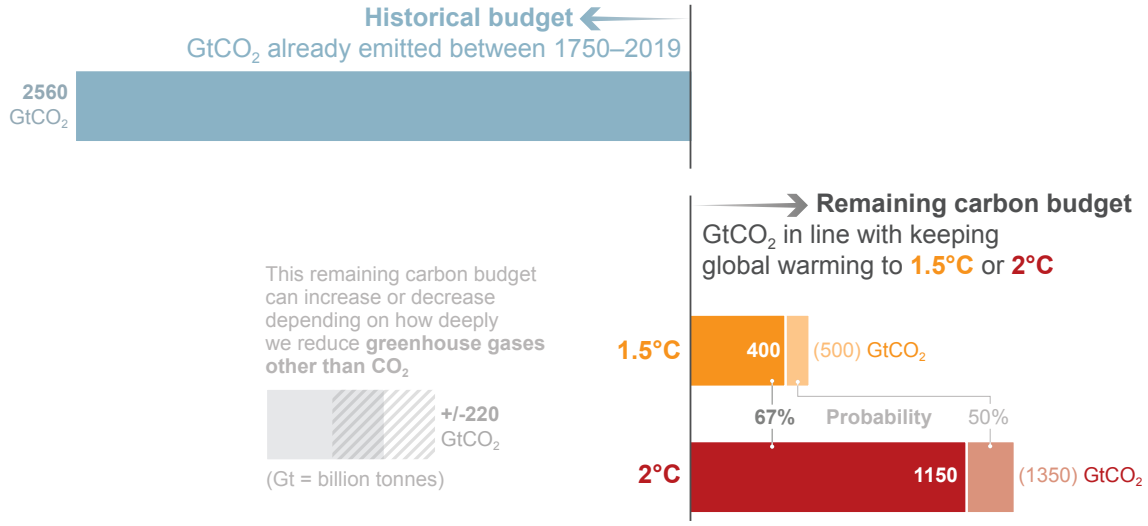
The remaining carbon budget depends on how much the world has already warmed to date. This past warming is caused by historical emissions, which are estimated by looking at the *historical carbon budget* – a scientific way to describe all past and present sources and sinks of CO_2. It describes how the CO_2 emissions from human activities have redistributed across the various CO_2 reservoirs of the Earth system. These reservoirs are the ocean, the land vegetation, and the atmosphere (into which CO_2 was emitted). The share of CO_2 that is not taken up by the ocean or the land, and that thus increases the concentration of CO_2 in the atmosphere, causes global warming. The historical carbon budget tells us that, of the about 2560 billion tonnes of CO_2 that were released into the atmosphere by human activities between the years 1750 and 2019, about a quarter were absorbed by the ocean (causing ocean acidification) and about a third by the land vegetation. About 45% of these emissions remain in the atmosphere (see FAQ 5.1). Adding these historical CO_2 emissions to estimates of remaining carbon budgets allows an estimate of the *total carbon budget* consistent with a specific global warming level.

FAQ 5.4 (continued)

In summary, determining a remaining carbon budget – that is, how much CO_2 can be released into the atmosphere while stabilizing global temperature below a chosen level – is well understood but relies on a set of choices. However, it is clear that, for limiting warming below 1.5°C or 2°C, the remaining carbon budget from 2020 onwards is much smaller than the total CO_2 emissions released to date.

FAQ 5.4: **What are Carbon Budgets?**

The term carbon budget is used in several ways. Most often the term refers to the total net amount of carbon dioxide (CO_2) that can still be emitted by human activities while limiting global warming to a specified level.



FAQ 5.4, Figure 1 | Various types of carbon budgets. Historical cumulative carbon dioxide (CO_2) emissions determine to a large degree how much the world has warmed to date, while the remaining carbon budget indicates how much CO_2 could still be emitted while keeping warming below specific temperature thresholds. Several factors limit the precision with which the remaining carbon budget can be estimated. Therefore, estimates need to specify the probability with which they aim at limiting warming to the intended target level (e.g., limiting warming to 1.5°C with a 67% probability).

Annex 48

"Weather and Climate Extreme Events in a Changing Climate. Climate Change 2021: The Physical Science Basis", Cambridge University Press, *Intergovernmental Panel on Climate Change,* 2021, pages 1513-1520

11

Weather and Climate Extreme Events in a Changing Climate

Coordinating Lead Authors:
Sonia I. Seneviratne (Switzerland), Xuebin Zhang (Canada)

Lead Authors:
Muhammad Adnan (Pakistan), Wafae Badi (Morocco), Claudine Dereczynski (Brazil), Alejandro Di Luca (Australia/Canada/Argentina), Subimal Ghosh (India), Iskhaq Iskandar (Indonesia), James Kossin (United States of America), Sophie Lewis (Australia), Friederike Otto (United Kingdom/Germany), Izidine Pinto (South Africa/Mozambique), Masaki Satoh (Japan), Sergio M. Vicente-Serrano (Spain), Michael Wehner (United States of America), Botao Zhou (China)

Contributing Authors:
Mathias Hauser (Switzerland), Megan Kirchmeier-Young (Canada/United States of America), Lisa V. Alexander (Australia), Richard P. Allan (United Kingdom), Mansour Almazroui (Saudi Arabia), Lincoln M. Alvez (Brazil), Margot Bador (France, Australia/France), Rondrotiana Barimalala (South Africa/Madagascar), Richard A. Betts (United Kingdom), Suzana J. Camargo (United States of America/Brazil, United States of America), Pep G. Canadell (Australia), Erika Coppola (Italy), Markus G. Donat (Spain/Germany, Australia), Hervé Douville (France), Robert J. H. Dunn (United Kingdom/Germany,United Kingdom), Erich Fischer (Switzerland), Hayley J. Fowler (United Kingdom), Nathan P. Gillett (Canada), Peter Greve (Austria/Germany), Michael Grose (Australia), Lukas Gudmundsson (Switzerland/Germany, Iceland), José Manuel Guttiérez (Spain), Lofti Halimi (Algeria), Zhenyu Han (China), Kevin Hennessy (Australia), Richard G. Jones (United Kingdom), Yeon-Hee Kim (Republic of Korea), Thomas Knutson (United States of America), June-Yi Lee (Republic of Korea), Chao Li (China), Georges-Noel T. Longandjo (South Africa/Democratic Republic of the Congo), Kathleen L. McInnes (Australia), Tim R. McVicar (Australia), Malte Meinshausen (Australia/Germany), Seung-Ki Min (Republic of Korea), Ryan S. Padron Flasher (Switzerland/Ecuador, United States of America), Christina M. Patricola (United States of America), Roshanka Ranasinghe (The Netherlands/Sri Lanka, Australia), Johan Reyns (The Netherlands/Belgium), Joeri Rogelj (United Kingdom/Belgium), Alex C. Ruane (United States of America), Daniel Ruiz Carrascal (United States of America/Colombia), Bjørn H. Samset (Norway), Jonathan Spinoni (Italy),

Qiaohong Sun (Canada/China), Ying Sun (China), Mouhamadou Bamba Sylla (Rwanda/Senegal), Claudia Tebaldi (United States of America), Laurent Terray (France), Wim Thiery (Belgium), Jessica Tierney (United States of America), Maarten K. van Aalst (The Netherlands), Bart van den Hurk (The Netherlands), Robert Vautard (France), Wen Wang (China), Seth Westra (Australia), Jakob Zscheischler (Germany)

Review Editors:
Johnny Chan (China), Asgeir Sorteberg (Norway), Carolina Vera (Argentina)

Chapter Scientists:
Mathias Hauser (Switzerland), Megan Kirchmeier-Young (Canada/United States of America), Hui Wan (Canada)

This Chapter should be cited as:
Seneviratne, S.I., X. Zhang, M. Adnan, W. Badi, C. Dereczynski, A. Di Luca, S. Ghosh, I. Iskandar, J. Kossin, S. Lewis, F. Otto, I. Pinto, M. Satoh, S.M. Vicente-Serrano, M. Wehner, and B. Zhou, 2021: Weather and Climate Extreme Events in a Changing Climate. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1513–1766, doi:10.1017/9781009157896.013.

Table of Contents

Executive Summary 1517

11.1 Introduction 1521
11.1.1 Scope of the Chapter 1521
11.1.2 What Are Extreme Events and How are Their Changes Studied? 1522
11.1.3 Types of Extremes Assessed in this Chapter 1522
11.1.4 Effects of Greenhouse Gas and Other External Forcings on Extremes 1522
Box 11.1 | Thermodynamic and Dynamic Changes in Extremes Across Scales 1526
11.1.5 Effects of Large-scale Circulation on Changes in Extremes 1528
11.1.6 Effects of Regional-scale Processes and Forcings and Feedbacks on Changes in Extremes 1528
11.1.7 Global-scale Synthesis 1529
Box 11.2 | Changes in Low-likelihood, High-impact Extremes 1534

11.2 Data and Methods 1536
11.2.1 Definition of Extremes 1536
11.2.2 Data 1537
Box 11.3 | Extremes in Paleoclimate Archives Compared to Instrumental Records 1538
11.2.3 Attribution of Extremes 1540
11.2.4 Projecting Changes in Extremes as a Function of Global Warming Levels 1541
Cross-Chapter Box 11.1 | Translating Between Regional Information at Global Warming Levels Versus Scenarios for End Users 1542

11.3 Temperature Extremes 1546
11.3.1 Mechanisms and Drivers 1546
11.3.2 Observed Trends 1548
11.3.3 Model Evaluation 1550
11.3.4 Detection and Attribution, Event Attribution 1552
11.3.5 Projections 1553

11.4 Heavy Precipitation 1557
11.4.1 Mechanisms and Drivers 1557
11.4.2 Observed Trends 1557
11.4.3 Model Evaluation 1561
11.4.4 Detection and Attribution, Event Attribution 1562
11.4.5 Projections 1563

11.5 Floods 1567
11.5.1 Mechanisms and Drivers 1567
11.5.2 Observed Trends 1568
11.5.3 Model Evaluation 1568
11.5.4 Detection and Attribution, Event Attribution 1569
11.5.5 Future Projections 1569

11.6 Droughts 1570
11.6.1 Mechanisms and Drivers 1570
11.6.2 Observed Trends 1573
11.6.3 Model Evaluation 1575
11.6.4 Detection and Attribution, Event Attribution 1577
11.6.5 Projections 1579

11.7 Extreme Storms 1583
11.7.1 Tropical Cyclones 1585
11.7.2 Extratropical Storms 1592
11.7.3 Severe Convective Storms 1594
11.7.4 Extreme Winds 1597

11.8 Compound Events 1598
11.8.1 Overview 1598
11.8.2 Concurrent Extremes in Coastal and Estuarine Regions 1599
11.8.3 Concurrent Droughts and Heatwaves 1600
Box 11.4 | Case Study: Global-scale Concurrent Climate Anomalies – the 2015–2016 Extreme El Niño and 2018 Boreal Spring–Summer 1601

11.9 Regional Information on Extremes 1604
11.9.1 Overview 1604
11.9.2 Temperature Extremes 1605
11.9.3 Heavy Precipitation 1605
11.9.4 Droughts 1605

Acknowledgements 1607

Frequently Asked Questions

FAQ 11.1 | How Do Changes In Climate Extremes Compare With Changes In Climate Averages? 1608

FAQ 11.2 | Will Unprecedented Extremes Occur As a Result Of Human-Induced Climate Change? 1610

FAQ 11.3 | Did Climate Change Cause That Recent Extreme Event In My Country? 1611

Large Tables 1613

References 1706

Appendix 11.A 1759

Executive Summary

This chapter assesses changes in weather and climate extremes on regional and global scales, including observed changes and their attribution, as well as projected changes. The extremes considered include temperature extremes, heavy precipitation and pluvial floods, river floods, droughts, storms (including tropical cyclones), as well as compound events (multivariate and concurrent extremes). The assessment focuses on land regions excluding Antarctica. Changes in marine extremes are addressed in Chapter 9 and Cross-Chapter Box 9.1. Assessments of past changes and their drivers are from 1950 onward, unless indicated otherwise. Projections for changes in extremes are presented for different levels of global warming, supplemented with information for the conversion to emissions scenario-based projections (Cross-Chapter Box 11.1 and Table 4.2). Since the IPCC Fifth Assessment Report (AR5), there have been important new developments and knowledge advances on changes in weather and climate extremes, in particular regarding human influence on individual extreme events, on changes in droughts, tropical cyclones, and compound events, and on projections at different global warming levels (1.5°C–4°C). These, together with new evidence at regional scales, provide a stronger basis and more regional information for the AR6 assessment on weather and climate extremes.

It is an established fact that human-induced greenhouse gas emissions have led to an increased frequency and/or intensity of some weather and climate extremes since pre-industrial time, in particular for temperature extremes. Evidence of observed changes in extremes and their attribution to human influence (including greenhouse gas and aerosol emissions and land-use changes) has strengthened since AR5, in particular for extreme precipitation, droughts, tropical cyclones and compound extremes (including dry/hot events and fire weather). Some recent hot extreme events would have been *extremely unlikely* to occur without human influence on the climate system. {11.2, 11.3, 11.4, 11.6, 11.7, 11.8}

Regional changes in the intensity and frequency of climate extremes generally scale with global warming. New evidence strengthens the conclusion from the IPCC Special Report on Global Warming of 1.5°C (SR1.5) that even relatively small incremental increases in global warming (+0.5°C) cause statistically significant changes in extremes on the global scale and for large regions (*high confidence*). In particular, this is the case for temperature extremes (*very likely*), the intensification of heavy precipitation (*high confidence*) including that associated with tropical cyclones (*medium confidence*), and the worsening of droughts in some regions (*high confidence*). The occurrence of extreme events unprecedented in the observed record will rise with increasing global warming, even at 1.5°C of global warming. Projected percentage changes in frequency are higher for the rarer extreme events (*high confidence*). {11.1, 11.2, 11.3, 11.4, 11.6, 11.9, Cross-Chapter Box 11.1}

Methods and Data for Extremes

Since AR5, the confidence about past and future changes in weather and climate extremes has increased due to better physical understanding of processes, an increasing proportion of the scientific literature combining different lines of evidence, and improved accessibility to different types of climate models (*high confidence*). There have been improvements in some observation-based datasets, including reanalysis data (*high confidence*). Climate models can reproduce the sign (direction) of changes in temperature extremes observed globally and in most regions, although the magnitude of the trends may differ (*high confidence*). Models are able to capture the large-scale spatial distribution of precipitation extremes over land (*high confidence*). The intensity and frequency of extreme precipitation simulated by Coupled Model Intercomparison Project Phase 6 (CMIP6) models are similar to those simulated by CMIP5 models (*high confidence*). Higher horizontal model resolution improves the spatial representation of some extreme events (e.g., heavy precipitation events), in particular in regions with highly varying topography (*high confidence*). {11.2, 11.3, 11.4}

Temperature Extremes

The frequency and intensity of hot extremes (including heatwaves) have increased, and those of cold extremes have decreased on the global scale since 1950 (*virtually certain*). This also applies at regional scale, with more than 80% of AR6 regions[1] showing similar changes assessed to be at least *likely*. In a few regions, *limited evidence* (data or literature) prevents the reliable estimation of trends. {11.3, 11.9}

Human-induced greenhouse gas forcing is the main driver of the observed changes in hot and cold extremes on the global scale (*virtually certain*) and on most continents (*very likely*). The effect of enhanced greenhouse gas concentrations on extreme temperatures is moderated or amplified at the regional scale by regional processes such as soil moisture or snow/ice-albedo feedbacks, by regional forcing from land-use and land-cover changes, or aerosol concentrations, and decadal and multi-decadal natural variability. Changes in anthropogenic aerosol concentrations have *likely* affected trends in hot extremes in some regions. Irrigation and crop expansion have attenuated increases in summer hot extremes in some regions, such as the Midwestern USA (*medium confidence*).

1 See Figure 1.18 for definition of AR6 regions. Acronyms for inhabited regions: ARP: Arabian Peninsula; CAF: Central Africa; CAR: Caribbean; CAU: Central Australia; CNA: Central North America; EAS: East Asia; EAU: Eastern Australia; ECA: East Central Asia; EEU: Eastern Europe; ENA: Eastern North America; ESAF: East Southern Africa; ESB: East Siberia; GIC: Greenland/Iceland; MDG: Madagascar; MED: Mediterranean; NAU: Northern Australia; NCA: Northern Central America; NEAF: North Eastern Africa; NEN: North-Eastern North America; NES: North-Eastern South America; NEU: Northern Europe; NSA: Northern South America; NWN: North-Western North America; NWS: North-Western South America; NZ: New Zealand; RAR: Russian Arctic; RFE: Russian Far East; SAH: Sahara; SAM: South American Monsoon; SAS: South Asia; SAU: Southern Australia; SCA: Southern Central America; SEA: Southeast Asia; SEAF: South Eastern Africa; SES: South-Eastern South America; SSA: Southern South America; SWS: South-Western South America; TIB: Tibetan Plateau; WAF: Western Africa; WCA: West Central Asia; WCE: Western and Central Europe; WNA: Western North America; WSAF: West Southern Africa; WSB: West Siberia.

Urbanization has *likely* exacerbated changes in temperature extremes in cities, in particular for nighttime extremes. {11.1, 11.2, 11.3}

The frequency and intensity of hot extremes will continue to increase and those of cold extremes will continue to decrease, at global and continental scales and in nearly all inhabited regions[1] with increasing global warming levels. This will be the case even if global warming is stabilized at 1.5°C. Relative to present-day conditions, changes in the intensity of extremes would be at least double at 2°C, and quadruple at 3°C of global warming, compared to changes at 1.5°C of global warming. The number of hot days and hot nights and the length, frequency, and/or intensity of warm spells or heatwaves will increase over most land areas (*virtually certain*). In most regions, future changes in the intensity of temperature extremes will *very likely* be proportional to changes in global warming, and up to two to three times larger (*high confidence*). The highest increase of temperature of hottest days is projected in some mid-latitude and semi-arid regions and in the South American Monsoon region, at about 1.5 times to twice the rate of global warming (*high confidence*). The highest increase of temperature of coldest days is projected in Arctic regions, at about three times the rate of global warming (*high confidence*). The frequency of hot temperature extreme events will *very likely* increase nonlinearly with increasing global warming, with larger percentage increases for rarer events. {11.2, 11.3, 11.9; Table 11.1; Figure 11.3}

Heavy Precipitation and Pluvial Floods

The frequency and intensity of heavy precipitation events have *likely* increased at the global scale over a majority of land regions with good observational coverage. Heavy precipitation has *likely* increased on the continental scale over three continents: North America, Europe, and Asia. Regional increases in the frequency and/or intensity of heavy precipitation have been observed with at least *medium confidence* for nearly half of AR6 regions, including WSAF, ESAF, WSB, SAS, ESB, RFE, WCA, ECA, TIB, EAS, SEA, NAU, NEU, EEU, GIC, WCE, SES, CNA, and ENA. {11.4, 11.9}

Human influence, in particular greenhouse gas emissions, is *likely* the main driver of the observed global-scale intensification of heavy precipitation over land regions. It is *likely* that human-induced climate change has contributed to the observed intensification of heavy precipitation at the continental scale in North America, Europe and Asia. Evidence of a human influence on heavy precipitation has emerged in some regions (*high confidence*). {11.4, 11.9, Table 11.1}

Heavy precipitation will generally become more frequent and more intense with additional global warming. At a global warming level of 4°C relative to the pre-industrial level, very rare (e.g., one in 10 or more years) heavy precipitation events would become more frequent and more intense than in the recent past, on the global scale (*virtually certain*) and in all continents and AR6 regions. The increase in frequency and intensity is *extremely likely* for most continents and *very likely* for most AR6 regions. At the global scale, the intensification of heavy precipitation will follow the rate of increase in the maximum amount of moisture that the atmosphere can hold as it warms (*high confidence*), of about 7% per 1°C of global warming. The increase in the frequency of heavy precipitation events will be non-linear with more warming and will be higher for rarer events (*high confidence*), with a *likely* doubling and tripling in the frequency of 10-year and 50-year events, respectively, compared to the recent past at 4°C of global warming. Increases in the intensity of extreme precipitation at regional scales will vary, depending on the amount of regional warming, changes in atmospheric circulation and storm dynamics (*high confidence*). {11.4, Box 11.1}

The projected increase in the intensity of extreme precipitation translates to an increase in the frequency and magnitude of pluvial floods – surface water and flash floods – (*high confidence*), as pluvial flooding results from precipitation intensity exceeding the capacity of natural and artificial drainage systems. {11.4}

River Floods

Significant trends in peak streamflow have been observed in some regions over the past decades (*high confidence*). The seasonality of river floods has changed in cold regions where snow-melt is involved, with an earlier occurrence of peak streamflow (*high confidence*). {11.5}

Global hydrological models project a larger fraction of land areas to be affected by an increase in river floods than by a decrease in river floods (*medium confidence*). Regional changes in river floods are more uncertain than changes in pluvial floods because complex hydrological processes and forcings, including land cover change and human water management, are involved. {11.5}

Droughts

Different drought types exist, and they are associated with different impacts and respond differently to increasing greenhouse gas concentrations. Precipitation deficits and changes in evapotranspiration govern net water availability. A lack of sufficient soil moisture, sometimes amplified by increased atmospheric evaporative demand, results in agricultural and ecological drought. Lack of runoff and surface water result in hydrological drought. {11.6}

Human-induced climate change has contributed to increases in agricultural and ecological droughts in some regions due to evapotranspiration increases (*medium confidence*). Increases in evapotranspiration have been driven by increases in atmospheric evaporative demand induced by increased temperature, decreased relative humidity and increased net radiation (*high confidence*). Trends in precipitation are not a main driver in affecting global-scale trends in drought (*medium confidence*), but have induced increases in meteorological droughts in a few AR6 regions (NES: *high confidence*; WAF, CAF, ESAF, SAM, SWS, SSA, SAS: *medium confidence*). Increasing

trends in agricultural and ecological droughts have been observed on all continents (WAF, CAF, WSAF, ESAF, WCA, ECA, EAS, SAU, MED, WCE, WNA, NES: *medium confidence*), but decreases only in one AR6 region (NAU: *medium confidence*). Increasing trends in hydrological droughts have been observed in a few AR6 regions (MED: *high confidence*; WAF, EAS, SAU: *medium confidence*). Regional-scale attribution shows that human-induced climate change has contributed to increased agricultural and ecological droughts (MED, WNA), and increased hydrological drought (MED) in some regions (*medium confidence*). {11.6, 11.9}

More regions are affected by increases in agricultural and ecological droughts with increasing global warming (*high confidence*). Several regions will be affected by more severe agricultural and ecological droughts even if global warming is stabilised at 2°C, including MED, WSAF, SAM and SSA (*high confidence*), and ESAF, MDG, EAU, SAU, SCA, CAR, NSA, NES, SWS, WCE, NCA, WNA and CNA (*medium confidence*). Some regions are also projected to be affected by more severe agricultural and ecological droughts at 1.5°C (MED, WSAF, ESAF, SAU, NSA, SAM, SSA, CNA, *medium confidence*). At 4°C of global warming, about 50% of all inhabited AR6 regions would be affected by increases in agricultural and ecological droughts (WCE, MED, CAU, EAU, SAU, WCA, EAS, SCA, CAR, NSA, NES, SAM, SWS, SSA, NCA, CNA, ENA, WNA, WSAF, ESAF, MDG: *medium confidence* or higher), and only two regions (NEAF, SAS) would experience decreases in agricultural and ecological drought (*medium confidence*). There is *high confidence* that the projected increases in agricultural and ecological droughts are strongly affected by evapotranspiration increases associated with enhanced atmospheric evaporative demand. Several regions are projected to be more strongly affected by hydrological droughts with increasing global warming (at 4°C of global warming: NEU, WCE, EEU, MED, SAU, WCA, SCA, NSA, SAM, SWS, SSA, WNA, WSAF, ESAF, MDG: *medium confidence* or higher). There is *low confidence* that effects of enhanced atmospheric carbon dioxide (CO_2) concentrations on plant water-use efficiency alleviate extreme agricultural and ecological droughts in conditions characterized by limited soil moisture and enhanced atmospheric evaporative demand. There is also *low confidence* that these effects will substantially reduce global plant transpiration and the severity of hydrological droughts. There is *high confidence* that the land carbon sink will become less efficient due to soil moisture limitations and associated drought conditions in some regions in higher-emissions scenarios, in particular under global warming levels above 4°C. {11.6, 11.9, Cross-Chapter Box 5.1}

Extreme Storms, Including Tropical Cyclones

The average and maximum rain rates associated with tropical cyclones (TCs), extratropical cyclones and atmospheric rivers across the globe, and severe convective storms in some regions, increase in a warming world (*high confidence*). Available event attribution studies of observed strong TCs provide *medium confidence* for a human contribution to extreme TC rainfall. Peak TC rain rates increase with local warming at least at the rate of mean water vapour increase over oceans (about 7% per 1°C of warming) and in some cases exceeding this rate due to increased low-level moisture convergence caused by increases in TC wind intensity (*medium confidence*). {11.7, 11.4, Box 11.1}

It is *likely* that the global proportion of Category 3–5 tropical cyclone instances[2] has increased over the past four decades. The average location where TCs reach their peak wind intensity has *very likely* migrated poleward in the western North Pacific Ocean since the 1940s, and TC translation speed has *likely* slowed over the conterminous USA since 1900. Evidence of similar trends in other regions is not robust. The global frequency of TC rapid intensification events has *likely* increased over the past four decades. None of these changes can be explained by natural variability alone (*medium confidence*).

The proportion of intense TCs, average peak TC wind speeds, and peak wind speeds of the most intense TCs will increase on the global scale with increasing global warming (*high confidence*). The total global frequency of TC formation will decrease or remain unchanged with increasing global warming (*medium confidence*). {11.7.1}

There is *low confidence* in past changes of maximum wind speeds and other measures of dynamical intensity of extratropical cyclones. Future wind speed changes are expected to be small, although poleward shifts in the storm tracks could lead to substantial changes in extreme wind speeds in some regions (*medium confidence*). There is *low confidence* in past trends in characteristics of severe convective storms, such as hail and severe winds, beyond an increase in precipitation rates. The frequency of spring severe convective storms is projected to increase in the USA, leading to a lengthening of the severe convective storm season (*medium confidence*); evidence in other regions is limited. {11.7.2, 11.7.3}.

Compound Events, Including Dry/Hot Events, Fire Weather, Compound Flooding, and Concurrent Extremes

The probability of compound events has *likely* increased in the past due to human-induced climate change and will *likely* continue to increase with further global warming. Concurrent heatwaves and droughts have become more frequent, and this trend will continue with higher global warming (*high confidence*). Fire weather conditions (compound hot, dry and windy events) have become more probable in some regions (*medium confidence*) and there is *high confidence* that they will become more frequent in some regions at higher levels of global warming. The probability of compound flooding (storm surge, extreme rainfall and/or river flow) has increased in some locations (*medium confidence*), and will continue to increase due to sea level rise and increases in heavy precipitation, including changes in precipitation intensity associated with tropical cyclones (*high confidence*). The land area affected by concurrent extremes has increased (*high confidence*). Concurrent

2 Six-hourly intensity estimates during the lifetime of each TC.

extreme events at different locations, but possibly affecting similar sectors (e.g., critical crop-producing areas for global food supply) in different regions, will become more frequent with increasing global warming, in particular above 2°C of global warming (*high confidence*). {11.8, Box 11.2, Box 11.4}.

Low-likelihood, High-impact Events Associated With Climate Extremes

The future occurrence of low-likelihood, high-impact events linked to climate extremes is generally associated with *low confidence*, but cannot be excluded, especially at global warming levels above 4°C. Compound events, including concurrent extremes, are a factor increasing the probability of low-likelihood, high-impact events (*high confidence*). With increasing global warming, some compound events with low likelihood in past and current climates will become more frequent, and there is a higher chance of occurrence of historically unprecedented events and surprises (*high confidence*). However, even extreme events that do not have a particularly low probability in the present climate (at more than 1°C of global warming) can be perceived as surprises because of the pace of global warming (*high confidence*). {Box 11.2}

Annex 49

"Frequently Asked Questions. Climate Change 2021: The Physical Science Basis", Cambridge University Press, *Intergovernmental Panel on Climate Change,* 2021, pages 3-4, 28-29

Frequently Asked Questions

FAQ

Frequently Asked Questions

Coordinating Editors:
Sophie Berger (France/Belgium), Sarah L. Connors (France/United Kingdom)

Drafting Authors:
Richard P. Allan (United Kingdom), Paola A. Arias (Colombia), Kyle Armour (United States of America), Terje Berntsen (Norway), Lisa Bock (Germany), Ruth Cerezo-Mota (Mexico), Kim Cobb (United States of America), Alejandro Di Luca (Australia, Canada/Argentina), Paul Edwards (United States of America), Tamsin L. Edwards (United Kingdom), Seita Emori (Japan), François Engelbrecht (South Africa), Veronika Eyring (Germany), Piers Forster (United Kingdom), Baylor Fox- Kemper (United States of America), Sandro Fuzzi (Italy), John C. Fyfe (Canada), Nathan P. Gillett (Canada), Nicholas R. Golledge (New Zealand/United Kingdom), Melissa I. Gomis (France/Switzerland), William J. Gutowski (United States of America), Rafiq Hamdi (Belgium), Mathias Hauser (Switzerland), Ed Hawkins (United Kingdom), Nigel Hawtin (United Kingdom), Darrell S. Kaufman (United States of America), Megan Kirchmeier-Young (Canada/ United States of America), Charles Koven (United States of America), June-Yi Lee (Republic of Korea), Sophie Lewis (Australia), Jochem Marotzke (Germany), Valérie Masson-Delmotte (France), Thorsten Mauritsen (Sweden/Denmark), Thomas K. Maycock (United States of America), Shayne McGregor (Australia), Sebastian Milinski (Germany), Olaf Morgenstern (New Zealand/ Germany), Swapna Panickal (India), Joeri Rogelj (United Kingdom/Belgium), Maisa Rojas (Chile), Alex C. Ruane (United States of America), Bjørn H. Samset (Norway), Trude Storelvmo (Norway), Sophie Szopa (France), Jessica Tierney (United States of America), Russell S. Vose (United States of America), Masahiro Watanabe (Japan), Sönke Zaehle (Germany), Xuebin Zhang (Canada), Kirsten Zickfeld (Canada/Germany)

These Frequently Asked Questions have been extracted from the chapters of the underlying report and are compiled here. When referencing specific FAQs, please reference the corresponding chapter in the report from where the FAQ originated (e.g., FAQ 3.1 is part of Chapter 3).

Table of Contents

Frequently Asked Questions

FAQ 1.1 Do We Understand Climate Change Better Now Compared to When the IPCC Started? 6

FAQ 1.2 Where Is Climate Change Most Apparent? 8

FAQ 1.3 What Can Past Climate Teach Us About the Future? 10

FAQ 2.1 The Earth's Temperature Has Varied Before. How Is the Current Warming Any Different? 12

FAQ 2.2 What Is the Evidence for Climate Change? 14

FAQ 3.1 How Do We Know Humans Are Responsible for Climate Change? .. 16

FAQ 3.2 What is Natural Variability and How Has it Influenced Recent Climate Changes? 18

FAQ 3.3 Are Climate Models Improving? 20

FAQ 4.1 How Will the Climate Change Over the Next Twenty Years? 22

FAQ 4.2 How Quickly Would We See the Effects of Reducing Carbon Dioxide Emissions? 24

FAQ 4.3 At a Given Level of Global Warming, What Are the Spatial Patterns of Climate Change? 26

FAQ 5.1 Is the Natural Removal of Carbon From the Atmosphere Weakening? 28

FAQ 5.2 Can Thawing Permafrost Substantially Increase Global Warming? 30

FAQ 5.3 Could Climate Change Be Reversed By Removing Carbon Dioxide From the Atmosphere? 32

FAQ 5.4 What Are Carbon Budgets? 34

FAQ 6.1 What Are Short-lived Climate Forcers and How Do They Affect the Climate? .. 36

FAQ 6.2 What Are the Links Between Limiting Climate Change and Improving Air Quality? 38

FAQ 7.1 What Is the Earth's Energy Budget, and What Does It Tell Us About Climate Change? 40

FAQ 7.2 What Is the Role of Clouds in a Warming Climate? 42

FAQ 7.3 What Is Equilibrium Climate Sensitivity and How Does It Relate to Future Warming? 44

FAQ 8.1 How Does Land Use Change Alter the Water Cycle? 46

FAQ 8.2 Will Floods Become More Severe or More Frequent as a Result of Climate Change? 48

FAQ 8.3 What Causes Droughts, and Will Climate Change Make Them Worse? 50

FAQ 9.1 Can Continued Melting of the Greenland and Antarctic Ice Sheets Be Reversed? How Long Would It Take for Them to Grow Back? 52

FAQ 9.2 How Much Will Sea Level Rise in the Next Few Decades? 54

FAQ 9.3 Will the Gulf Stream Shut Down? 56

FAQ 10.1 How Can We Provide Useful Climate Information for Regional Stakeholders? 58

FAQ 10.2 Why Are Cities Hotspots of Global Warming? 60

FAQ 11.1 How Do Changes In Climate Extremes Compare With Changes In Climate Averages? 62

FAQ 11.2 Will Unprecedented Extremes Occur As a Result Of Human-Induced Climate Change? 64

FAQ 11.3 Did Climate Change Cause That Recent Extreme Event In My Country? 65

FAQ 12.1 What Is a Climatic Impact-driver (CID)? 67

FAQ 12.2 What Are Climatic Thresholds and Why Are They Important? 69

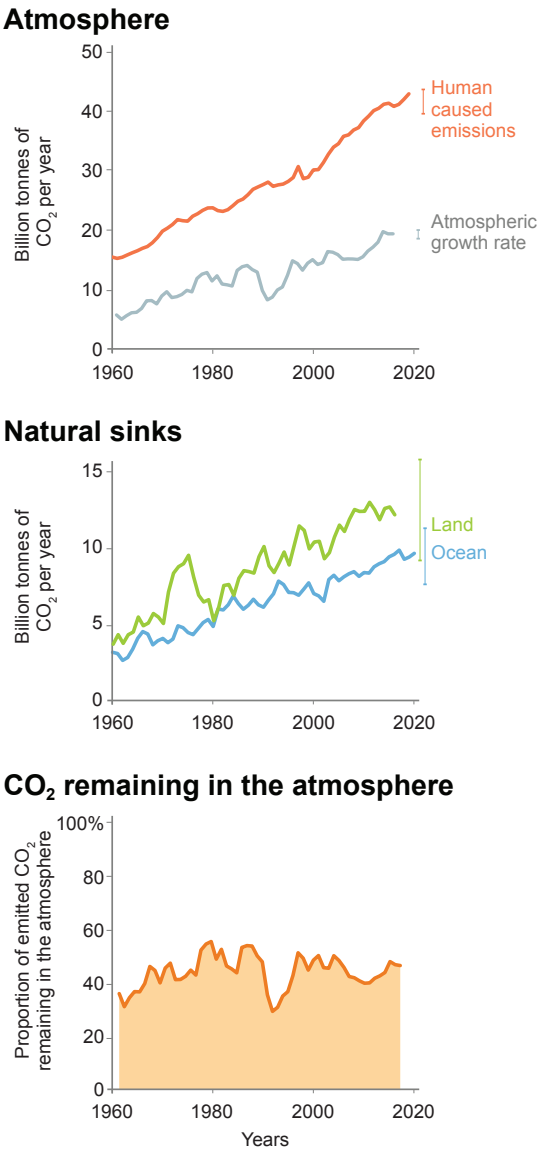
FAQ 12.3 How Will Climate Change Affect the Regional Characteristics of a Climate Hazard? 71

FAQ 5.1 | Is the Natural Removal of Carbon From the Atmosphere Weakening?

For decades, about half of the carbon dioxide (CO_2) that human activities have emitted to the atmosphere has been taken up by natural carbon sinks in vegetation, soils and oceans. These natural sinks of CO_2 have thus roughly halved the rate at which atmospheric CO_2 concentrations have increased, and therefore slowed down global warming. However, observations show that the processes underlying this uptake are beginning to respond to increasing CO_2 in the atmosphere and climate change in a way that will weaken nature's capacity to take up CO_2 in the future. Understanding of the magnitude of this change is essential for projecting how the climate system will respond to future emissions and emissions reduction efforts.

FAQ 5.1: **Is natural removal of carbon from the atmosphere weakening?**

No, natural carbon sinks have taken up a near constant fraction of our carbon dioxide (CO_2) emissions over the last six decades. However, this fraction is expected to decline in the future if CO_2 emissions continue to increase.



Direct observations of CO_2 concentrations in the atmosphere, which began in 1958, show that the atmosphere has only retained roughly half of the CO_2 emitted by human activities, due to the combustion of fossil fuels and land-use change such as deforestation (FAQ 5.1, Figure 1). Natural carbon cycle processes on land and in the oceans have taken up the remainder of these emissions. These land and ocean removals or 'sinks' have grown largely in proportion to the increase in CO_2 emissions, taking up 31% (land) and 23% (ocean) of the emissions in 2010–2019, respectively (FAQ 5.1, Figure 1). Therefore, the average proportion of yearly CO_2 emissions staying in the atmosphere has remained roughly stable at 44% over the last six decades, despite continuously increasing CO_2 emissions from human activities.

On land, it is mainly the vegetation that captures CO_2 from the atmosphere through *plant photosynthesis*, which ultimately accumulates both in vegetation and soils. As more CO_2 accumulates in the atmosphere, plant carbon capture increases through the *CO_2 fertilization effect* in regions where plant growth is not limited by, for instance, nutrient availability. Climate change affects the processes responsible for the uptake and release of CO_2 on land in multiple ways. Land CO_2 uptake is generally increased by longer growing seasons due to global warming in cold regions and by nitrogen deposition in nitrogen-limited regions. Respiration by plants and soil organisms, natural disturbances such as fires, and human activities such as deforestation all release CO_2 back into the atmosphere. The combined effect of climate change on these processes is to weaken the future land sink. In particular, extreme temperatures and droughts as well as permafrost thaw (see FAQ 5.2) tend to reduce the land sink regionally. In the ocean,

FAQ 5.1, Figure 1 | Atmospheric carbon dioxide (CO_2) and natural carbon sinks. (Top) Global emissions of CO_2 from human activities and the growth rate of CO_2 in the atmosphere; **(middle)** the net land and ocean CO_2 removal (natural sinks); and **(bottom)** the fraction of CO_2 emitted by human activities remaining in atmosphere from 1960 to 2019. Lines are the five years running mean, error bars denote the uncertainty of the mean estimate. See Table 5.SM.6 for more information on the data underlying this figure.

FAQ 5.1 (continued)

several factors control how much CO_2 is captured: the difference in CO_2 partial pressure between the atmosphere and the surface ocean; wind speeds at the ocean surface; the chemical composition of seawater (that is, its *buffering capacity*), which affects how much CO_2 can be taken up; and the use of CO_2 in photosynthesis by seawater microalgae. The CO_2-enriched surface ocean water is transported to the deep ocean in specific zones around the globe (such as the Northern Atlantic and the Southern Ocean), effectively storing the CO_2 away from the atmosphere for many decades to centuries. The combined effect of warmer surface ocean temperatures on these processes is to weaken the future ocean CO_2 sink.

The ocean carbon sink is better quantified than the land sink, thanks to direct ocean and atmospheric carbon observations. The land carbon sink is more challenging to monitor globally, because it varies widely, even regionally. There is currently no direct evidence that the natural sinks are slowing down, because observable changes in the fraction of human emissions stored on land or in oceans are small compared to year-to-year and decadal variations of these sinks. Nevertheless, it is becoming more obvious that atmospheric and climate changes are affecting the processes controlling the land and ocean sinks.

Since the land and ocean sinks respond to the rise in atmospheric CO_2 and to human-induced global warming, the absolute amount of CO_2 taken up by land and ocean will be affected by future CO_2 emissions. This also implies that, if countries manage to strongly reduce global CO_2 emissions, or even remove CO_2 from the atmosphere, these sinks will take up less CO_2 because of the reduced human perturbation of the carbon cycle. Under future high-warming scenarios, it is expected that the global ocean and land sinks will stop growing in the second half of the century as climate change increasingly affects them. Thus, the total amount of CO_2 emitted to the atmosphere and the responses of the natural CO_2 sinks will both determine what efforts are required to limit global warming to a certain level (see FAQ 5.4), underscoring how important it is to understand the evolution of these natural CO_2 sinks.

Annex 50

"Annex VII – Glossary. Climate Change 2021: The Physical Science Basis", Cambridge University Press, *Intergovernmental Panel on Climate Change,* 2021, pages 2215, 2218, 2230, 2232, 2233, 2236, 2241

AVII

Annex VII: Glossary

Coordinating Editors:

J.B. Robin Matthews (France/United Kingdom), Vincent Möller (Germany), Renée van Diemen (The Netherlands/United Kingdom), Jan S. Fuglestvedt (Norway), Valérie Masson-Delmotte (France), Carlos Méndez (Venezuela), Sergey Semenov (Russian Federation), Andy Reisinger (New Zealand)

Editorial Team:

Rondrotiana Barimalala (South Africa/Madagascar), Roxana Bojariu (Romania), Annalisa Cherchi (Italy), Peter M. Cox (United Kingdom), Sergio Henrique Faria (Spain/Brazil), Piers Forster (United Kingdom), Christopher Jones (United Kingdom), Nana Ama Browne Klutse (Ghana), Charles Koven (United States of America), Svitlana Krakovska (Ukraine), Sawsan K. Mustafa (Sudan), Friederike Otto (United Kingdom/Germany), Matthew D. Palmer (United Kingdom), Tamzin Palmer (United Kingdom), Wilfried Pokam Mba (Cameroon), Roshanka Ranasinghe (The Netherlands/Sri Lanka, Australia), Pedro Scheel Monteiro (South Africa), Joeri Rogelj (United Kingdom/ Belgium), Sharon L. Smith (Canada), Ying Sun (China), Andrew Turner (United Kingdom), Bart van den Hurk (The Netherlands), Émilie Vanvyve (United Kingdom/Belgium), Martin Wild (Switzerland), Cunde Xiao (China), Prodromos Zanis (Greece)

Note:

This glossary defines some specific terms as the Lead Authors intend them to be interpreted in the context of this report. Italicized words in definitions indicate that the italicized term is defined in the Glossary.

Subterms appear in italics beneath main terms.

This annex should be cited as:

IPCC, 2021: Annex VII: Glossary [Matthews, J.B.R., V. Möller, R. van Diemen, J.S. Fuglestvedt, V. Masson-Delmotte, C. Méndez, S. Semenov, A. Reisinger (eds.)]. *In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 2215–2256, doi:10.1017/9781009157896.022.

A positive SAM phase is defined as lower-than-normal pressures over the polar regions and higher-than-normal pressures in the southern mid-latitudes, with a contraction towards Antarctica and strengthening of the westerly wind belt. The negative SAM phase exhibits positive high-latitude pressure anomalies, negative mid-latitude pressure anomalies and a weaker westerly flow expanded towards the equator. See Section AIV.2.2 in Annex IV of the AR6 WGI report. See also *Annular modes*.

Anomaly The deviation of a variable from its value averaged over a *reference period*.

Antarctic amplification See *Polar amplification*.

Antarctic Ice Sheet (AIS) See *Ice sheet*.

Antarctic oscillation (AAO) See *Southern Annular Mode (SAM)* (under *Annular modes*).

Anthropocene A proposed new geological epoch resulting from significant human-driven changes to the structure and functioning of the Earth System, including the *climate system*. Originally proposed in the Earth system science community in 2000, the proposed new epoch is undergoing a formalization process within the geological community based on the stratigraphic *evidence* that human activities have changed the Earth system to the extent of forming geological deposits with a signature that is distinct from those of the *Holocene*, and which will remain in the geological record. Both the stratigraphic and Earth system approaches to defining the Anthropocene consider the mid-20th century to be the most appropriate starting date (Steffen et al., 2016), although others have been proposed and continue to be discussed. The Anthropocene concept has already been informally adopted by diverse disciplines and the public to denote the substantive influence of humans on the Earth system.

Anthropogenic Resulting from or produced by human activities.

Anthropogenic emissions Emissions of *greenhouse gases (GHGs)*, *precursors* of GHGs and *aerosols* caused by human activities. These activities include the burning of *fossil fuels*, *deforestation*, *land use* and *land-use changes* (LULUC), livestock production, fertilization, waste management, and industrial processes. See also *Anthropogenic* and *Anthropogenic removals*.

Anthropogenic removals The withdrawal of *greenhouse gases (GHGs)* from the *atmosphere* as a result of deliberate human activities. These include enhancing biological *sinks* of CO_2 and using chemical engineering to achieve long-term removal and storage. Carbon dioxide capture and storage (CCS), which alone does not remove CO_2 from the atmosphere, can help reduce atmospheric CO_2 from industrial and energy-related sources if it is combined with bioenergy production (BECCS), or if CO_2 is captured from the air directly and stored (DACCS). [Note: In the 2006 IPCC Guidelines for national GHG Inventories (IPCC, 2006), which are used in reporting of emissions to the UNFCCC, 'anthropogenic' land-related GHG fluxes are defined as all those occurring on 'managed land', i.e., 'where human interventions and practices have been applied to perform production, ecological or social functions'. However, some removals (e.g., removals associated with CO_2 fertilization and N deposition) are not considered as 'anthropogenic', or are referred to as 'indirect' anthropogenic effects, in some of the scientific literature assessed in this report. As a consequence, the land-related net GHG emission estimates from global models included in this report are not necessarily directly comparable with land use, land-use change and forestry (LULUCF) estimates in national GHG Inventories.] See also *Carbon dioxide removal (CDR)*, *Afforestation*, *Enhanced weathering*, *Ocean alkalinization/Ocean alkalinity enhancement* and *Reforestation*.

Anthropogenic subsidence Downward motion of the land surface induced by *anthropogenic* drivers (e.g., loading, extraction of hydrocarbons and/or groundwater, drainage, mining activities) causing sediment compaction or subsidence/deformation of the sedimentary sequence, or oxidation of organic material, thereby leading to relative *sea level rise*.

Apparent hydrological sensitivity (η_a) The change in global mean precipitation per degree Celsius of *global mean surface air temperature (GSAT)* change with units of % per °C, although it can also be calculated as W m^{-2} per °C. See also *Hydrological sensitivity (η)*.

Arctic amplification See *Polar amplification*.

Arctic oscillation (AO) See *Northern Annular Mode (NAM)* (under *Annular modes*).

Arid zone Areas where vegetation growth is severely constrained due to limited water availability. For the most part, the native vegetation of arid zones is sparse. There is high rainfall variability, with annual averages below 300 mm. Crop farming in arid zones requires irrigation.

Aridity The state of a long-term climatic feature characterized by low average precipitation or available water in a *region*. Aridity generally arises from widespread persistent atmospheric subsidence or anticyclonic conditions, and from more localized subsidence in the lee side of mountains (adapted from Gbeckor-Kove, 1989; Türkeş, 1999). See also *Drought*.

Artificial ocean upwelling (AOUpw) A potential *carbon dioxide removal (CDR)* method that aims to artificially pump up cooler, nutrient-rich waters from deep in the *ocean* to the surface. The aim is to stimulate phytoplankton activity and thereby increase ocean CO_2 uptake.

Assets Natural or human-made resources that provide current or future utility, benefit, economic or intrinsic value to natural or human systems.

Atlantic Equatorial Mode See *Atlantic Zonal Mode (AZM)* under *Tropical Atlantic Variability (TAV)*.

Atlantic Meridional Mode (AMM) See *Tropical Atlantic Variability (TAV)*.

Atlantic Meridional Overturning Circulation (AMOC) See *Meridional overturning circulation (MOC)*.

Atlantic Multi-decadal Oscillation (AMO) See *Atlantic Multi-decadal Variability (AMV)*.

Atlantic Multi-decadal Variability (AMV) Large-scale fluctuations observed from one decade to the next in a variety of instrumental records and *proxy* reconstructions over the entire North Atlantic ocean and surrounding continents. Fingerprints of

Fitness-for-purpose The suitability of a model (or other resource, such as a dataset or method) for a particular task, such as quantifying the contribution of increased *greenhouse gas* concentrations to recent changes in *global mean surface temperature* or projecting changes in *drought* frequency in a region under a given *scenario*. Assessment of a model's fitness-for-purpose can be informed both by how the model represents relevant physical processes and by how it scores on relevant performance metrics.

Flaring Open air burning of waste gases and volatile liquids, through a chimney, at oil wells or rigs, in refineries or chemical plants, and at landfills.

Flood The overflowing of the normal confines of a stream or other water body, or the accumulation of water over areas that are not normally submerged. Floods can be caused by unusually heavy rain, for example during storms and cyclones. Floods include river (fluvial) floods, flash floods, urban floods, rain (pluvial) floods, sewer floods, *coastal* floods and *glacial lake outburst floods (GLOFs)*.

Flux A movement (a flow) of matter (e.g., water vapour, particles), heat or energy from one place to another, or from one medium (e.g., land surface) to another (e.g., atmosphere).

Foraminifera Single-celled, sand-sized marine organisms (protists) that possess a hard test mainly composed of agglutinated walls (detrital grains glued together with organic cement) or calcium carbonate (predominantly calcite). They are used to reconstruct a range of (paleo)environmental variables such as salinity, temperature, oxygenation, oxygen isotope composition and organic and nutrient flux.

Forcing See *Radiative forcing*.

Forest A vegetation type dominated by trees. Many definitions of the term forest are in use throughout the world, reflecting wide differences in biogeophysical conditions, social structure and economics. [Note: For a discussion of the term forest in the context of National GHG inventories, see the 2006 IPCC Guidelines for National GHG Inventories and their 2019 Refinement, and information provided by the United Nations Framework Convention on Climate Change (IPCC, 2006, 2019; UNFCCC, 2021a, b).] See also *Afforestation*, *Deforestation* and *Reforestation*.

Fossil fuel emissions Emissions of *greenhouse gases (GHGs)* (in particular *carbon dioxide (CO_2)*), other trace gases and *aerosols* resulting from the combustion of fuels from fossil carbon deposits such as oil, gas and coal.

Fossil fuels Carbon-based fuels from fossil hydrocarbon deposits, including coal, oil and natural gas.

Free atmosphere The atmospheric layer that is negligibly affected by friction against the Earth's surface, and which is above the *atmospheric boundary layer*.

Frozen ground Soil or rock in which part or all of the pore water consists of ice. See also *Active layer* and *Permafrost*.

General circulation The large-scale motions of the *atmosphere* and the *ocean* as a consequence of differential heating on a rotating Earth. General circulation contributes to the *energy balance* of the system through transport of heat and momentum.

General circulation model (GCM) A numerical representation of the *atmosphere–ocean–sea ice* system based on the physical, chemical and biological properties of its components, their interactions and feedback processes. General circulation models are used for weather forecasts, seasonal to *decadal prediction*, and *climate projections*. They are the basis of the more complex *Earth system models (ESMs)*. See also *Climate model*.

Geocentric sea level change See *Sea level change (sea level rise/sea level fall)*.

Geoid The equipotential surface having the same geopotential at each latitude and longitude around the world (geodesists denote this potential W0) that best approximates the mean sea level. It is the surface of reference for measurement of altitude. In practice, several variations of definitions of the geoid exist depending on the way the permanent tide (the zero-frequency gravitational tide due to the Sun and Moon) is considered in geodetic studies.

Geostrophic winds or currents A wind or current that is in balance with the horizontal pressure gradient and the Coriolis force, and thus is outside of the influence of friction. Thus, the wind or current is directly parallel to isobars and its speed is proportional to the horizontal pressure gradient.

Glacial isostatic adjustment (GIA) The ongoing changes in *gravity, rotation and viscoelastic solid Earth deformation (GRD)* in response to past changes in the distribution of ice and water on Earth's surface. On a time scale of decades to tens of millennia following mass redistribution, Earth's mantle flows viscously as it evolves toward isostatic equilibrium, causing solid Earth movement and *geoid* changes, which can result in regional-to-local sea level variations. See also *Sea level change (sea level rise/sea level fall)*.

Glacial lake outburst flood (GLOF)/Glacier lake outburst A sudden release of water from a glacier lake, including any of the following types – a glacier-dammed lake, a pro-glacial moraine-dammed lake or water that was stored within, under or on the *glacier*.

Glacial or glaciation A period characterized by the establishment of expanded *ice sheets* and *glaciers*, and associated with global mean sea level (GMSL) substantially lower than present; generally coincides with even-numbered *marine isotope stages*. Glacial intervals were interrupted by *interglacial* intervals. The Last Glacial Maximum (LGM) is a specific interval within the most recent glaciation, when ice sheets were near their global maximum volume (Clark et al., 2009; Gowan et al., 2021) and GMSL was nearly at its lowest level (Lambeck et al., 2014; Yokoyama et al., 2018). Local or regional glacial maxima may be diachronous, for example ranging from about 29,000 years ago and 16,000 years ago. For purposes of global synthesis, IPCC AR6 adopts a practical chronostratigraphic definition of LGM of 23,000–19,000 years BP (before 1950; chronozone level 1 of Mix et al., 2001). For modelling purposes, LGM is defined by the model time step nearest to the centre of this interval, 21,000 years ago (Kageyama et al., 2017). See also *Deglacial or deglaciation or glacial termination*, *Glacial–interglacial cycles*, *Ice age* and *Interglacial or interglaciation*.

Glacial termination See *Deglacial or deglaciation or glacial termination*.

Pakistan, Thailand, Laos, Cambodia, Vietnam and the Philippines. The SAsiaM starts in late May/early June and progresses towards the northeast, ending in late September/early October. During the core monsoon season, maxima of SAsiaM precipitation are located over the west coast, north-east and central north India, Myanmar and Bangladesh, whereas minima are located over north-west and south-eastern India, western Pakistan, and south-eastern and northern Sri Lanka. Further details on how SAsiaM is defined and used throughout the Report are provided in Annex V.

West African monsoon (WAfriM)
The West African monsoon (WAfriM) is a seasonal reversal in wind and precipitation whose domain includes Benin, Burkina-Faso, northern Cameroon, Cape Verde, northern Central African Republic, Chad, Gambia, Ghana, Guinea, Guinea Bissau, Ivory Coast, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone and Togo. The WAfriM is characterized by the northward progression from May to September of moist low-level south-westerlies from the Gulf of Guinea. In May and June, rainfall essentially remains along the Guinean coast with a maximum occurring near 5°N, followed by a sudden decrease of rainfall, marking the 'short dry season' in the Guinean coast and the monsoon onset in the Sahel. Then rainfall continues to progress northward up to about 18–20°N, with a maximum near 12°N in late August/September, until it retreats starting from October towards the Guinean coast for a second maximum. Further details on how WAfriM is defined and used throughout the Report are provided in Annex V.

Global surface temperature See *Global mean surface temperature (GMST)* and *Global mean surface air temperature (GSAT)*. See also *Global warming*.

Global warming Global warming refers to the increase in *global surface temperature* relative to a baseline *reference period*, averaging over a period sufficient to remove interannual variations (e.g., 20 or 30 years). A common choice for the baseline is 1850–1900 (the earliest period of reliable observations with sufficient geographic coverage), with more modern baselines used depending upon the application. See also *Climate change* and *Climate variability*.

Global warming potential (GWP) An index measuring the *radiative forcing* following an emission of a unit mass of a given substance, accumulated over a chosen time horizon, relative to that of the reference substance, *carbon dioxide (CO_2)*. The GWP thus represents the combined effect of the differing times these substances remain in the *atmosphere* and their effectiveness in causing radiative forcing. See also *Lifetime* and *Greenhouse gas emission metric*.

Gravitational, rotational and deformational (GRD) effects See *Sea level change (sea level rise/sea level fall)*.

Gravity Recovery and Climate Experiment (GRACE) A pair of satellites that measured the Earth's gravity field anomalies from 2002 to 2017. These fields have been used, among other things, to study mass changes of the polar *ice sheets* and *glaciers*.

Greenhouse effect The infrared radiative effect of all infrared-absorbing constituents in the *atmosphere*. *Greenhouse gases (GHGs)*, clouds, and some *aerosols* absorb *terrestrial radiation* emitted by the Earth's surface and elsewhere in the atmosphere. These substances emit *infrared radiation* in all directions, but, everything else being equal, the net amount emitted to space is normally less than would have been emitted in the absence of these absorbers because of the decline of temperature with altitude in the *troposphere* and the consequent weakening of emission. An increase in the concentration of GHGs increases the magnitude of this effect; the difference is sometimes called the enhanced greenhouse effect. The change in a GHG concentration because of *anthropogenic emissions* contributes to an instantaneous radiative forcing. Earth's surface temperature and *troposphere* warm in response to this *forcing*, gradually restoring the radiative balance at the top of the atmosphere.

Greenhouse gas emission metric A simplified relationship used to quantify the effect of emitting a unit mass of a given *greenhouse gas* on a specified key measure of *climate change*. A relative GHG emission metric expresses the effect from one gas relative to the effect of emitting a unit mass of a reference GHG on the same measure of climate change. There are multiple emission metrics, and the most appropriate metric depends on the application. GHG emission metrics may differ with respect to (i) the key measure of climate change they consider, (ii) whether they consider climate outcomes for a specified point in time or integrated over a specified time horizon, (iii) the time horizon over which the metric is applied, (iv) whether they apply to a single emission pulse, emissions sustained over a period of time, or a combination of both, and (v) whether they consider the climate effect from an emission compared to the absence of that emission or compared to a reference emissions level or climate state.

Notes: Most relative GHG emission metrics (such as the *global warming potential (GWP)*, global temperature change potential (GTP), global damage potential, and GWP*) use *carbon dioxide (CO_2)* as the reference gas. Emissions of non-CO_2 gases, when expressed using such metrics, are often referred to as 'carbon dioxide equivalent' emissions. A metric that establishes equivalence regarding one key measure of the *climate system* response to emissions does not imply equivalence regarding other key measures. The choice of a metric, including its time horizon, should reflect the policy objectives for which the metric is applied.

Greenhouse gas neutrality Condition in which metric-weighted anthropogenic *greenhouse gas (GHG)* emissions associated with a subject are balanced by metric-weighted anthropogenic GHG removals. The subject can be an entity such as a country, an organization, a district or a commodity, or an activity such as a service or an event. GHG neutrality is often assessed over the life cycle, including indirect ('scope 3') emissions, but can also be limited to the emissions and removals, over a specified period, for which the subject has direct control, as determined by the relevant scheme. The quantification of GHG emissions and removals depends on the GHG emission metric chosen to compare emissions and removals of different gases, as well as the time horizon chosen for that metric.

Note 1: GHG neutrality and net zero GHG emissions are overlapping concepts. The concepts can be applied at global or sub-global scales (e.g., regional, national and sub-national). At a global scale, the terms greenhouse gas neutrality and net zero greenhouse gas emissions are equivalent. At sub-global scales, net zero greenhouse gas emissions is generally applied to emissions and removals under direct control or territorial responsibility of the reporting entity, while greenhouse gas neutrality generally includes emissions and removals within and

beyond the direct control or territorial responsibility of the reporting entity. Accounting rules specified by GHG programmes or schemes can have a significant influence on the quantification of relevant emissions and removals.

Note 2. Under the Paris Rulebook (Decision 18/CMA.1, annex, paragraph 37), parties have agreed to use GWP100 values from the IPCC AR5 or GWP100 values from a subsequent IPCC Assessment Report to report aggregate emissions and removals of GHGs. In addition, parties may use other metrics to report supplemental information on aggregate emissions and removals of GHGs.

Note 3: In some cases, achieving greenhouse gas neutrality may rely on the supplementary use of offsets to balance emissions that remain after actions by the reporting entity are taken into account.

See also *Carbon neutrality*, *Greenhouse gas emission metric* and *Net zero greenhouse gas emissions*.

Greenhouse gases (GHGs) Gaseous constituents of the *atmosphere*, both natural and *anthropogenic*, that absorb and emit radiation at specific wavelengths within the spectrum of radiation emitted by the Earth's surface, by the atmosphere itself, and by clouds. This property causes the *greenhouse effect*. Water vapour (H_2O), *carbon dioxide (CO_2)*, *nitrous oxide (N_2O)*, *methane (CH_4)* and *ozone (O_3)* are the primary GHGs in the Earth's atmosphere. Human-made GHGs include *sulphur hexafluoride (SF_6), hydrofluorocarbons (HFCs)*, *chlorofluorocarbons (CFCs)* and perfluorocarbons (PFCs); several of these are also O_3-depleting (and are regulated under the *Montreal Protocol*). See also *Well-mixed greenhouse gas*.

Greenland Ice Sheet (GrIS) See *Ice sheet*.

Gross Primary Production (GPP) See *Primary production*.

Ground-level ozone Atmospheric *ozone (O_3)* is formed naturally or from human-emitted *precursors* near Earth's surface, thus affecting human health, agriculture and *ecosystems*. Ozone is a *greenhouse gas (GHG)*, but ground-level ozone, unlike stratospheric ozone, also directly affects organisms at the surface. Ground-level ozone is sometimes referred to as tropospheric ozone, although much of the *troposphere* is well above the surface and thus does not directly expose organisms at the surface.

Grounding line The junction between a *glacier* or *ice sheet* and an *ice shelf*; the place where ice starts to float. This junction normally occurs over a zone, rather than at a line.

Gyre Basin-scale *ocean* horizontal circulation pattern with slow flow circulating around the ocean basin, closed by a strong and narrow (100 to 200 km wide) boundary current on the western side. The subtropical gyres in each ocean are associated with high pressure in the centre of the gyres; the subpolar gyres are associated with low pressure.

Hadley cell See *Hadley circulation*.

Hadley circulation A direct, thermally driven overturning cell in the *atmosphere* consisting of poleward flow in the upper *troposphere*, subsiding air into the subtropical anticyclones, return flow as part of the trade winds near the surface, and with rising air near the equator in the so-called *Inter-tropical Convergence Zone*.

Halocarbons A collective term for the group of partially halogenated organic species, which includes the *chlorofluorocarbons (CFCs)*, hydrochlorofluorocarbons (HCFCs), *hydrofluorocarbons (HFCs)*, halons, methyl chloride and methyl bromide. Many of the halocarbons have large *global warming potentials*. The chlorine and bromine-containing halocarbons are also involved in the depletion of the *ozone layer*.

Halocline A layer in the oceanic water column in which salinity changes rapidly with depth. Generally, saltier water is denser and lies below less salty water. In some high-latitude *oceans* the surface waters may be colder than the deep waters, and the halocline is responsible for maintaining water column stability and isolating the surface waters from the deep waters.

Halosteric See *Sea level change (sea level rise/sea level fall)*.

Halosteric sea level change See *Sea level change (sea level rise/sea level fall)*.

Hazard The potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury, or other health *impacts*, as well as damage and loss to property, infrastructure, *livelihoods*, service provision, *ecosystems* and environmental resources. See also *Impacts (consequences, outcomes)* and *Risk*.

Heat index A measure of how hot the air feels to the human body. The index is mainly based on surface air temperature and *relative humidity*; thus it reflects the combined effect of high temperature and humidity on human physiology and provides a relative indication of potential health risks.

Heat stress A range of conditions in, for example, terrestrial or aquatic organisms when the body absorbs excess heat during overexposure to high air or water temperatures or thermal radiation. In aquatic water-breathing animals, hypoxia and acidification can exacerbate *vulnerability* to heat. Heat stress in mammals (including humans) and birds, both in air, is exacerbated by a detrimental combination of ambient heat, high humidity and low wind speeds, causing regulation of body temperature to fail.

Heatwave A period of abnormally hot weather, often defined with reference to a relative temperature threshold, lasting from two days to months. Heatwaves and warm spells have various and, in some cases, overlapping definitions. See also *Marine heatwave*, *Blocking*, *Heat index* and *Heat stress*.

Heavy precipitation event See *Extreme/heavy precipitation event*.

Heinrich event Distinct layers of coarse-grained sediments comprised of ice-rafted debris identified across marine sediment cores in the North Atlantic. These sedimentary layers are closely associated with millennial-scale cooling events in the North Atlantic and a distinct pattern of global temperature and hydrological changes that are largely consistent with evidence for a slowdown, or even near-collapse, of the *Atlantic Meridional Overturning Circulation (AMOC)* during these times.

Heterotrophic respiration The conversion of organic matter to *carbon dioxide (CO_2)* by organisms other than autotrophs.

Deglacial or deglaciation or glacial termination, *Glacial-interglacial cycles*, *Glacial or glaciation* and *Ice age*.

Internal climate variability See *Internal variability* (under *Climate variability*).

Interstadial or interstade A brief period of regional climatic warming during a *glacial* or *interglacial* interval, often characterized by transient glacial retreats. Interstadials are generally of short duration (hundreds to a few thousand years) compared to glacial or interglacial intervals (lasting many thousands to tens of thousands of years). One example of a regional interstadial event is based on millennial scale warming recorded by oxygen *isotope* ratios in Greenland *ice cores*, the so called "Greenland Interstadials" (Johnsen et al., 1992). See also *Stadial or stade*.

Irreversibility A perturbed state of a *dynamical system* is defined as irreversible on a given time scale if the recovery from this state due to natural processes takes substantially longer than the time scale of interest. See also *Tipping point*.

Isostatic or Isostasy Isostasy refers to the response of the Earth to changes in surface load. It includes the deformational and gravitational response. This response is elastic on short time scales, as in the Earth–*ocean* response to recent changes in mountain glaciation, or viscoelastic on longer time scales, as in the response to the last *deglaciation* following the *Last Glacial Maximum*.

Isotopes Atoms of the same chemical element that have the same the number of protons but differ in the number of neutrons. Some proton–neutron configurations are stable (stable isotopes), others are unstable undergoing spontaneous radioactive decay (radioisotopes). Most elements have more than one stable isotope. Isotopes can be used to trace transport processes or to study processes that change the isotopic ratio. Radioisotopes provide, in addition, time information that can be used for radiometric dating. See also ^{13}C and ^{14}C.

Key climate indicators See *Climate indicator*.

Kriging Kriging is a method of interpolation (normally spatial interpolation when used with atmospheric or oceanographic data) in which the interpolated values are estimated using a Gaussian process governed by prior covariances.

La Niña See *El Niño–Southern Oscillation (ENSO)*.

Land The terrestrial portion of the biosphere that comprises the natural resources (soil, near-surface air, vegetation and other biota, and water), the ecological processes, topography, and human settlements and infrastructure that operate within that system (UNCCD, 1994; FAO, 2007).

Land cover The biophysical coverage of *land* (e.g., bare soil, rocks, *forests*, buildings and roads or lakes). Land cover is often categorized in broad land-cover classes (e.g., deciduous forest, coniferous forest, mixed forest, grassland, bare ground). [Note: In some literature, land cover and *land use* are used interchangeably, but the two represent distinct classification systems. For example, the land cover class woodland can be under various land uses such as livestock grazing, recreation, conservation, or wood harvest.]

Land–cover change Change from one *land cover* class to another, due to change in *land use* or change in natural conditions (Pongratz et al., 2018). See also *Land-use change (LUC)*.

Land surface air temperature (LSAT) The near-surface air temperature over land, typically measured at 1.25–2 m above the ground using standard meteorological equipment.

Land use The total of arrangements, activities and inputs applied to a parcel of *land*. The term land use is also used in the sense of the social and economic purposes for which land is managed (e.g., grazing, timber extraction, conservation and city dwelling). In national *greenhouse gas (GHG)* inventories, land use is classified according to the IPCC land-use categories of forest land, cropland, grassland, wetlands, settlements, other lands (see the 2006 IPCC Guidelines for National GHG Inventories and their 2019 Refinement for details (IPCC, 2006, 2019)).

Land-use change (LUC) The change from one *land use* category to another. Note that in some scientific literature, land-use change encompasses changes in land-use categories as well as changes in land management. See also *Afforestation, Deforestation* and *Reforestation*.

Indirect land-use change (iLUC) Land-use change outside the area of focus that occurs as a consequence of change in use or management of land within the area of focus, such as through market or policy drivers. For example, if agricultural land is diverted to biofuel production, *forest* clearance may occur elsewhere to replace the former agricultural production. See *Land-use change (LUC)*.

Land water storage (LWS) Land water storage (LWS) includes all surface water, *soil moisture*, groundwater storage and snow, but excludes water stored in *glaciers* and *ice sheets*. Changes in LWS can be caused either by direct human intervention in the water cycle (e.g., storage of water in reservoirs by building dams in rivers, groundwater extraction from groundwater reservoirs for consumption and irrigation, or *deforestation*) or by *climate* variations (e.g., changes in the amount of water in endorheic lakes and *wetlands*, the canopy, the soil, the *permafrost* and the snowpack). Land water storage changes caused by climate variations may also be indirectly affected by *anthropogenic* influences. See also *Sea level change (sea level rise/sea level fall)*.

Lapse rate The rate of change of an atmospheric variable, usually temperature, with height. The lapse rate is considered positive when the variable decreases with height.

Large-scale The *climate system* involves process interactions from the micro- to the global-scale. Any threshold for defining 'large-scale' is arbitrary. Understanding of large-scale *climate variability* and change requires knowledge of both the response to external *forcings* and the role of *internal variability*. Many external forcings have substantial hemispheric or continental scale variations. *Modes of climate variability* are driven by *ocean*-basin-scale processes. Thus we define large-scale to include ocean-basin and continental scales as well as hemispheric and global scales.

Last deglacial transition See *Deglacial or deglaciation or glacial termination* and *Younger Dryas*.

a vast North Atlantic–Europe domain, and thus with fluctuations in the embedded *extratropical cyclones* and associated frontal systems leading to strong *teleconnection* over the entire North Atlantic adjacent continents. The positive and negative phases of the NAO show similar characteristics described for the *Northern Annular Mode (NAM)*. See Section AIV.2.1 in Annex IV of the AR6 WGI report.

Northern polar vortex See *Stratospheric polar vortex*.

Ocean The interconnected body of saline water that covers 71% of the Earth's surface, contains 97% of the Earth's water and provides 99% of the Earth's biologically habitable space. It includes the Arctic, Atlantic, Indian, Pacific and Southern Oceans, as well as their marginal seas and coastal waters.

Ocean acidification (OA) A reduction in the *pH* of the *ocean*, accompanied by other chemical changes (primarily in the levels of carbonate and bicarbonate ions), over an extended period, typically decades or longer, which is caused primarily by *uptake* of *carbon dioxide (CO_2)* from the *atmosphere*, but can also be caused by other chemical additions or subtractions from the ocean. *Anthropogenic* OA refers to the component of pH reduction that is caused by human activity (IPCC, 2011, p. 37).

Ocean alkalinization/Ocean alkalinity enhancement A proposed *carbon dioxide removal (CDR)* method that involves deposition of alkaline minerals or their dissociation products at the *ocean* surface. This increases surface *total alkalinity*, and may thus increase ocean *carbon dioxide (CO_2)* uptake and ameliorate surface *ocean acidification*. See also *Anthropogenic removals*.

Ocean carbon cycle The ocean *carbon cycle* is the set of processes that exchange carbon between various *pools* within the *ocean*, as well as between the *atmosphere*, Earth's interior, *cryosphere*, and the sea-floor. See also *Carbon cycle*.

Ocean deoxygenation The loss of oxygen in the *ocean*. It results from ocean warming, which reduces oxygen solubility and increases oxygen consumption and *stratification*, thereby reducing the mixing of oxygen into the ocean interior. Deoxygenation can also be exacerbated by the addition of excess nutrients in the *coastal* zone.

Ocean dynamic sea level change See *Sea level change (sea level rise/sea level fall)*.

Ocean fertilization A proposed *carbon dioxide removal (CDR)* method that relies on the deliberate increase of nutrient supply to the near-surface *ocean* with the aim of *sequestering* additional CO_2 from the *atmosphere* through biological production. Methods include direct addition of micro-nutrients or macro-nutrients. To be successful, the additional carbon needs to reach the deep ocean where it has the potential to be sequestered on climatically relevant time scales. See also *Anthropogenic removals* and *Carbon dioxide removal (CDR)*.

Ocean heat uptake efficiency This is a measure ($W\,m^{-2}\,°C^{-1}$) of the rate at which heat storage by the global *ocean* increases as global surface temperature rises. It is a useful parameter for *climate change* simulations in which the *radiative forcing* is changing monotonically, when it can be compared with the *climate feedback parameter* to gauge the relative importance of radiative response and ocean heat *uptake* in determining the rate of *climate change*. It can be estimated from such an experiment as the ratio of the rate of increase of ocean heat content to the surface temperature change.

Ocean stratification See *Stratification*.

Orbital forcing Orbital *forcing* is the influence of slow, systematic and predictable changes in orbital parameters (eccentricity, obliquity and precession of the equinox) on incoming *solar radiation* (*insolation*), especially its latitudinal and seasonal distribution. It is an *external forcing* and a key driver of *glacial–interglacial cycles*.

Organic aerosol Component of the *aerosol* that consists of organic compounds, mainly carbon, hydrogen, oxygen and lesser amounts of other elements.

Outgoing longwave radiation Net outgoing radiation in the infrared part of the spectrum at the top of the *atmosphere.*

Outlet glacier See *Glacier*.

Overshoot pathways See *Pathways*.

Oxygen minimum zone (OMZ) The midwater layer (200–1000 m) in the open *ocean* in which oxygen saturation is the lowest in the ocean. The degree of oxygen depletion depends on the largely bacterial consumption of organic matter, and the distribution of the OMZs is influenced by large-scale ocean circulation. In coastal oceans, OMZs extend to the shelves and may also affect benthic *ecosystems*.

Ozone (O_3) The triatomic form of oxygen, and a gaseous *atmospheric* constituent. In the *troposphere*, O_3 is created both naturally and by photochemical reactions involving gases resulting from human activities (e.g., smog). Tropospheric O_3 acts as a *greenhouse gas (GHG)*. In the *stratosphere*, O_3 is created by the interaction between solar ultraviolet radiation and molecular oxygen (O_2). Stratospheric O_3 plays a dominant role in the stratospheric radiative balance. Its concentration is highest in the *ozone layer*. See also *Ground-level ozone*, *Ozone hole*, *Ozone-depleting substances (ODSs)*, *Ozonesonde* and *Short-lived climate forcers (SLCFs)*.

Ozone layer A layer of Earth's *stratosphere* that absorbs most of the Sun's ultraviolet radiation. It contains high concentrations of *ozone (O_3)* in relation to other parts of the *atmosphere*, although still small in relation to other gases in the *stratosphere*. The ozone layer contains less than 10 parts per million of ozone, while the average ozone concentration in Earth's atmosphere as a whole is about 0.3 parts per million. The ozone layer is mainly found in the lower portion of the stratosphere, from approximately 15 to 35 kilometres (9.3 to 21.7 miles) above Earth, although its thickness varies seasonally and geographically. See also *Ozone hole* and *Ozone-depleting substances (ODSs)*.

Ozone-depleting substances (ODSs) Man-made gases that destroy *ozone (O_3)* once they reach the *ozone layer* in the *stratosphere*. Ozone-depleting substances include: *chlorofluorocarbons (CFCs)*, hydrochlorofluorocarbons (HCFCs), hydrobromofluorocarbons (HBFCs), halons, methyl bromide, carbon tetrachloride and methyl chloroform. They are used as refrigerants in commercial, home and vehicle air conditioners and refrigerators, foam blowing agents, components in electrical equipment, industrial solvents, solvents for cleaning (including dry cleaning), aerosol spray propellants and fumigants. See also *Ozone layer*, *Ozone (O_3)* and *Stratospheric ozone*.