SCIENCE OF CLIMATE CHANGE AND THE CARIBBEAN: FINDINGS FROM THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (IPCC) SIXTH ASSESSMENT CYCLE (AR6)

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TABLE OF CONTENTS

1. EXECUTIVE SUMMARY

This report provides an overview of the scientific consensus on the causes, impacts and risks of climate change for the Caribbean region as well as important scientific research gaps. Drawing from the most recent reports of the Intergovernmental Panel on Climate Change (IPCC), the report highlights historic responsibility for greenhouse gases (GHG) that drive climate change, observed climatic, biophysical and socio-economic impacts of climate change in the Caribbean and projected future risks of climate change, highlighting the importance of limiting global average warming to 1.5°C for the region.

This report draws directly from the seven reports produced in the Sixth Assessment Cycle of the IPCC. We have extracted main findings from the IPCC reports and text is directly quoted from the reports. This provides an objective overview of the scientific assessment of climate change causes, impacts, risks and research gaps that are relevant to the Caribbean.

The report highlights that human activities have unequivocally caused global warming. Emissions of greenhouse gases that have been tracked since 1850 show wide regional disparities, with small island developing states (SIDS) across the globe contributing approximately only 0.5% of historical cumulative emissions. These emissions have caused warming of the atmosphere of approximately 1.1°C, which has resulted in widespread and rapid changes to environments across the globe. However, SIDS, including the countries of the Caribbean, are disproportionately affected by current impacts and future risks of climate change.

In terms of current impacts, much of the Caribbean region shows statistically significant warming of the atmosphere and detectable decreasing trends in precipitation. The most severe drought in the region from 2013 to 2016 was strongly related to anthropogenic warming and increased the severity of the event by 17% and the spatial extent by 7%. Small Islands of the Caribbean have experienced negative changes to terrestrial, freshwater and ocean ecosystems with adverse implications for biodiversity. Negative impacts have been observed on many human systems, including water and food security, health and well-being, and cities, settlements and infrastructure. Tropical cyclones, storms, floods, droughts and coral reef damage are exacerbating existing vulnerabilities among the population and economies of the Caribbean.

For future risks, climate change poses significant challenges for the Caribbean, threatening sustainable development. Even if global warming is limited to 1.5°C, the compounding impacts of climate change are projected to contribute to the loss of critical natural and human systems, including threatening the habitability of some islands and coastal communities. Some impacts may be irreversible, such as the loss of coral reefs with significant consequences for the Caribbean including loss of coastal protection, biodiversity loss and impacts on critical livelihoods such as tourism and fisheries. Sea level rise (SLR) has been projected to impact the terrestrial biodiversity of low-lying islands and coastal regions via large habitat losses. Caribbean islands are among those projected to suffer the most habitat loss with projections of between 8.7% and 49.2% of its islands entirely submerged, respectively, from 1-m to 6-m SLR. Higher levels of global warming limit the options available for Caribbean countries to adapt to escalating risks posed by climate change.

Limiting global warming to a specific level requires transformational change to curb cumulative carbon dioxide emissions, reach net zero and also reduce emissions of other greenhouse gases. Future warming depends on past, current and future emissions. Current emissions as well as future emissions planned by countries and detailed in their submissions to the United Nations Framework Convention on Climate Change (UNFCCC) make it likely that global warming will exceed 1.5°C this century. Surpassing 1.5°C is a critical threshold for SIDS, including in the Caribbean, with escalating impacts of climate change resulting in limits in the ability of people and nature to adapt.

The IPCC reports also highlight that there are regional disparities in data and scientific studies, with significant gaps in the Caribbean. Despite intensive study, many knowledge gaps remain in island-scale data availability, ecosystem services data, vulnerability, resilience and adaptation.

In summary, the science is very clear that Caribbean SIDS have made negligible contributions to the emissions that drive current and future climate change, that they are disproportionately affected by current impacts and future risks of climate change and that there are significant gaps in data and scientific studies that are needed to effectively assess and respond to climate change in the Caribbean.

2. OVERVIEW OF THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (IPCC)

Formed in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP), the IPCC is mandated with providing regular assessments of the scientific evidence of climate change, its current impacts and future risks, and strategies for adaptation and mitigation. Its core mission revolves around furnishing governments at all levels with scientifically robust insights essential for shaping climate policies. IPCC reports play a pivotal role as key points of reference during international climate negotiations at the United Nations Framework Convention on Climate Change (UNFCCC). The IPCC is an organization of governments that are members of the United Nations or WMO and currently has 195 members.

The IPCC produces assessment reports every five-seven years during assessment cycles. The most recent Sixth Assessment Cycle concluded in 2023 and produced seven reports:

- Global Warming of 1.5°C (2018)
- Climate Change and Land (2019)
- The Ocean and Cryosphere in a Changing Climate (2019)
- Climate Change 2021: The Physical Science Basis (2021)
- Climate Change 2022: Impacts, Adaptation and Vulnerability (2022)
- Climate Change 2022: Mitigation of Climate Change (2022)
- Synthesis Report: Climate Change 2023 (2023)

IPCC reports are produced with the highest level of scientific rigor. Hundreds of carefully selected scientists volunteer their time as IPCC authors to evaluate thousands of published scientific papers and provide comprehensive assessments of the literature. Reports are reviewed multiple times by experts and governments around the world in order to ensure an objective assessment that reflects diversity of views and expertise. The IPCC does not conduct its own research, rather it provides an assessment of the strength of scientific agreement in different areas. Confidence language is used to convey this assessment of the strength of different findings and ranges from *very high confidence* to *low confidence*, based on evaluation of underlying evidence and agreement.

Table1: Key abbreviations used in IPCC reports

CO_2	Carbon dioxide
$CO_{2\text{-eq}}$	Carbon dioxide equivalent
ENSO	El Niño-Southern Oscillation
ESL	Extreme sea level
ETC	Extratropical cyclone
FFI	Fossil-fuel combustion and industrial

GHG	Greenhouse gas
GMSL	Global mean sea level
IAS	Invasive alien species
JJA	June, July, August
NDC	Nationally Determined Contribution
SIDS	Small island developing states
SLR	Sea level rise
SST	Sea surface temperature
TC	Tropical cyclone

3. CAUSES OF CLIMATE CHANGE

HISTORICAL

Human activities, principally through emissions of greenhouse gases, have unequivocally caused global warming, with global surface temperature reaching 1.1°C above 1850–1900 in 2011–2020. Global greenhouse gas emissions have continued to increase over 2010–2019, with unequal historical and ongoing contributions arising from unsustainable energy use, land use and land-use change, lifestyles and patterns of consumption and production across regions, between and within countries, and between individuals (*high confidence*). Human-caused climate change is already affecting many weather and climate extremes in every region across the globe. This has led to widespread adverse impacts on food and water security, human health and on economies and society and related losses and damages to nature and people (*high confidence*). Vulnerable communities who have historically contributed the least to current climate change are disproportionately affected (*high confidence*).[1]

Total net anthropogenic GHG emissions have continued to rise during the period 2010–2019, as have cumulative net CO_2 emissions since 1850. Average annual GHG emissions during 2010–2019 were higher than in any previous decade, but the rate of growth between 2010 and 2019 was lower than that between 2000 and 2009. (*high confidence*)[2]

GHG emissions trends over 1990–2019 vary widely across regions and over time, and across different stages of development, as shown in Figure SPM.2. Average global per capita net anthropogenic GHG emissions increased from 7.7 to 7.8 tCO2-eq, ranging from 2.6 tCO2-eq to 19 tCO2-eq across regions. Least developed countries (LDCs) and **Small Island Developing States (SIDS) have much lower per capita emissions (1.7 tCO2-eq and 4.6 tCO2-eq, respectively) than the global average (6.9 tCO2-eq),** excluding CO2-LULUCF. (*high confidence*)[3]

Historical contributions to cumulative net anthropogenic CO2 emissions between 1850 and 2019 vary substantially across regions in terms of total magnitude, but also in terms of contributions to CO2-FFI (1650 ± 73 GtCO2-eq) and net CO2-LULUCF (760 ± 220 GtCO2-eq) emissions. **Globally, the major share of cumulative CO2-FFI emissions is concentrated in a few regions**, while cumulative CO2-LULUCF9 emissions are concentrated in other regions. **LDCs**

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[1] IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 35-115, doi: 10.59327/IPCC/AR6-9789291691647. [**Synthesis Report**] 2.1

[2] IPCC, 2022: Summary for Policymakers [P.R. Shukla, J. Skea, A. Reisinger, R. Slade, R. Fradera, M. Pathak, A. Al Khourdajie, M. Belkacemi, R. van Diemen, A. Hasija, G. Lisboa, S. Luz, J. Malley, D. McCollum, S. Some, P. Vyas, (eds.)]. In: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.001. [**WGIII SPM**] B.1

[3] WGIII SPM B.3.1

contributed less than 0.4% of historical cumulative CO2-FFI emissions between 1850 and 2019, while SIDS contributed 0.5%. (*high confidence*)[4] [*See figures on pages 10-11]*

FUTURE

Limiting human-caused global warming to a specific level requires limiting cumulative CO2 emissions, reaching net zero or net negative CO2 emissions, along with strong reductions in other GHG emissions. Future additional warming will depend on future emissions, with total warming dominated by past and future cumulative CO_2 emissions.[5]

Global GHG emissions in 2030 associated with the implementation of NDCs announced prior to COP26 would make it likely that warming will exceed 1.5°C during the 21st century and would make it harder to limit warming below 2°C – if no additional commitments are made or actions taken.[6]

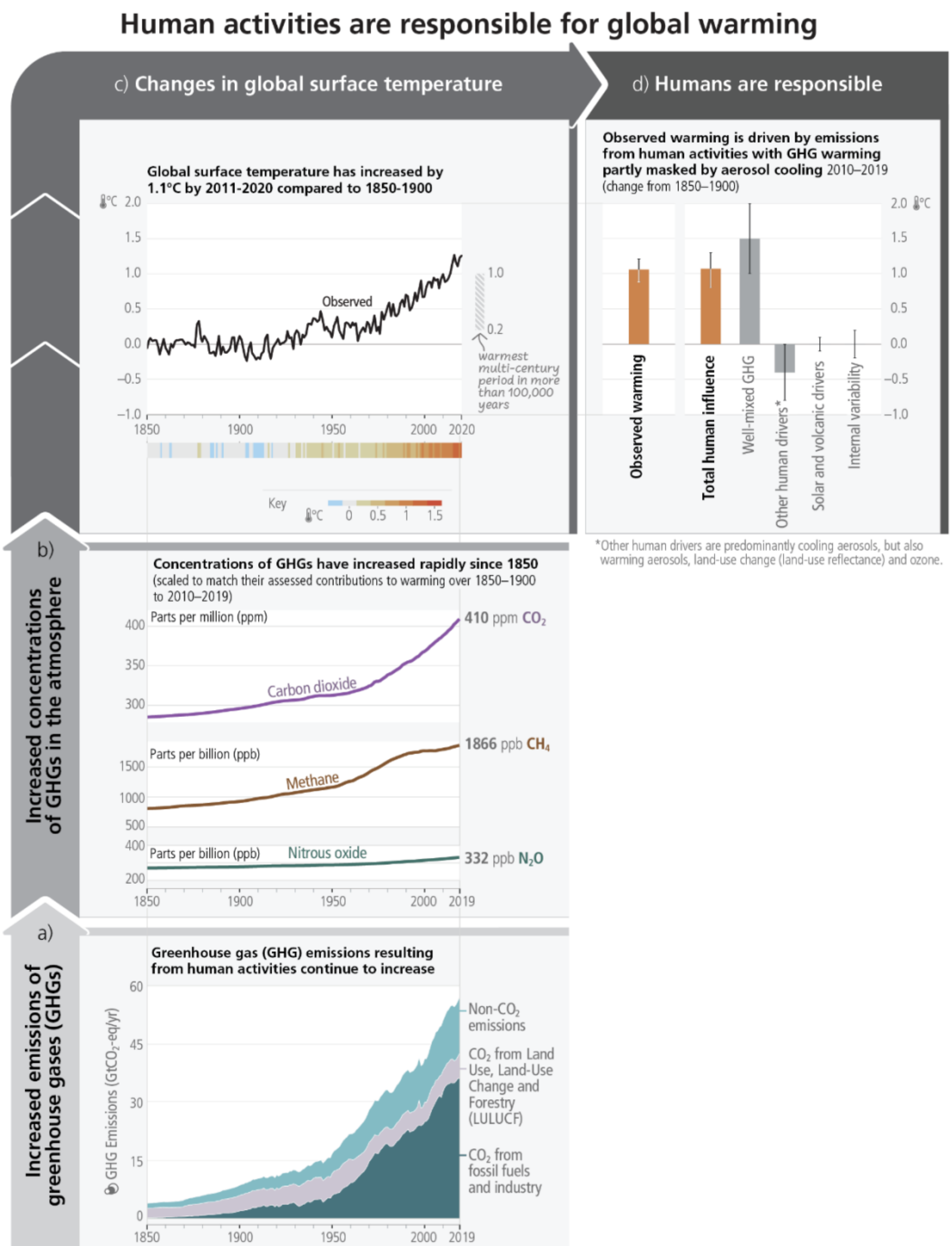
Global warming will continue to increase in the near term (2021–2040) mainly due to increased cumulative CO2 emissions in nearly all considered scenarios and pathways. In the near term, every region in the world is projected to face further increases in climate hazards (*medium to high confidence*, depending on region and hazard), increasing multiple risks to ecosystems and humans (*very high confidence*).[7]

[4] WGIII SPM B.3.2

[5] Synthesis Report Longer Report Cross Section Box.1

[6] Synthesis Report Longer Report Section 2.3.1

[7] Synthesis Report Longer Report Section 4.3



[8]

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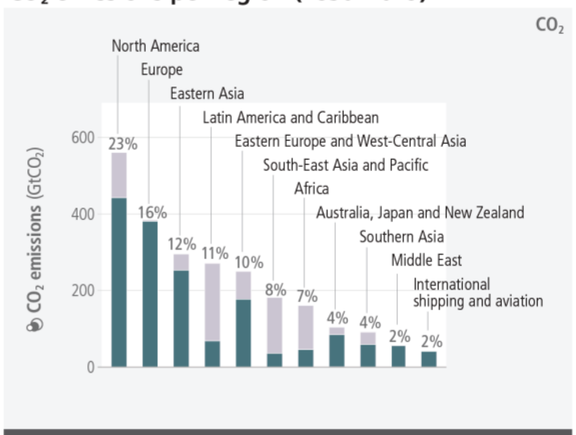
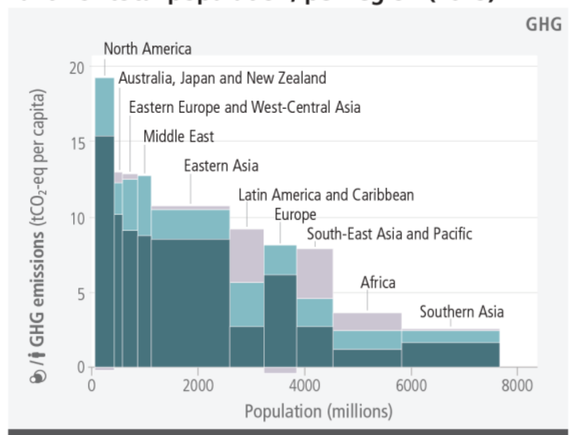
[8] Synthesis Report Figure 2.1: The causal chain from emissions to resulting warming of the climate system.

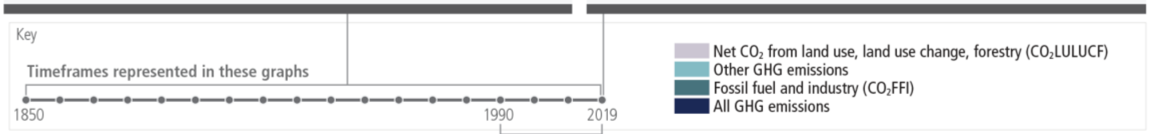
Emissions have grown in most regions but are distributed unevenly, both in the present day and cumulatively since 1850

a) Historical cumulative net anthropogenic CO_2 emissions per region (1850–2019)

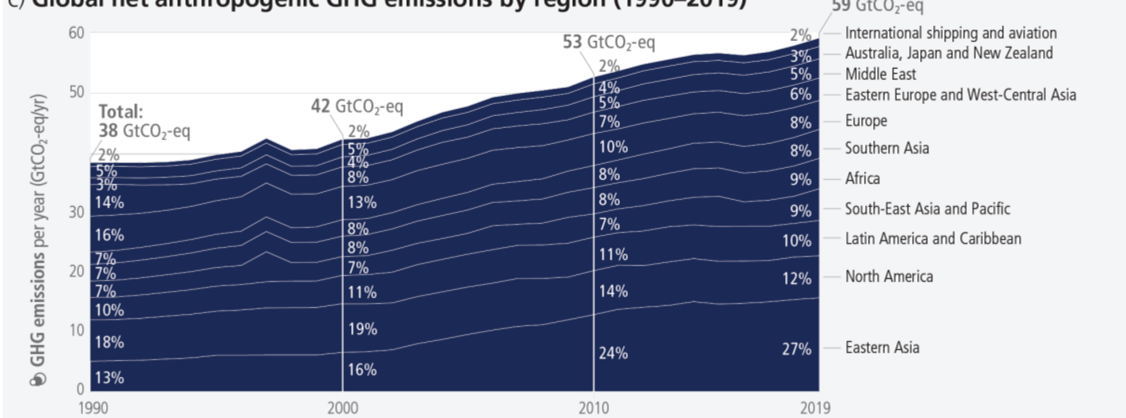


b) Net anthropogenic GHG emissions per capita and for total population, per region (2019)





c) Global net anthropogenic GHG emissions by region (1990–2019)



d) Regional indicators (2019) and regional production vs consumption accounting (2018)

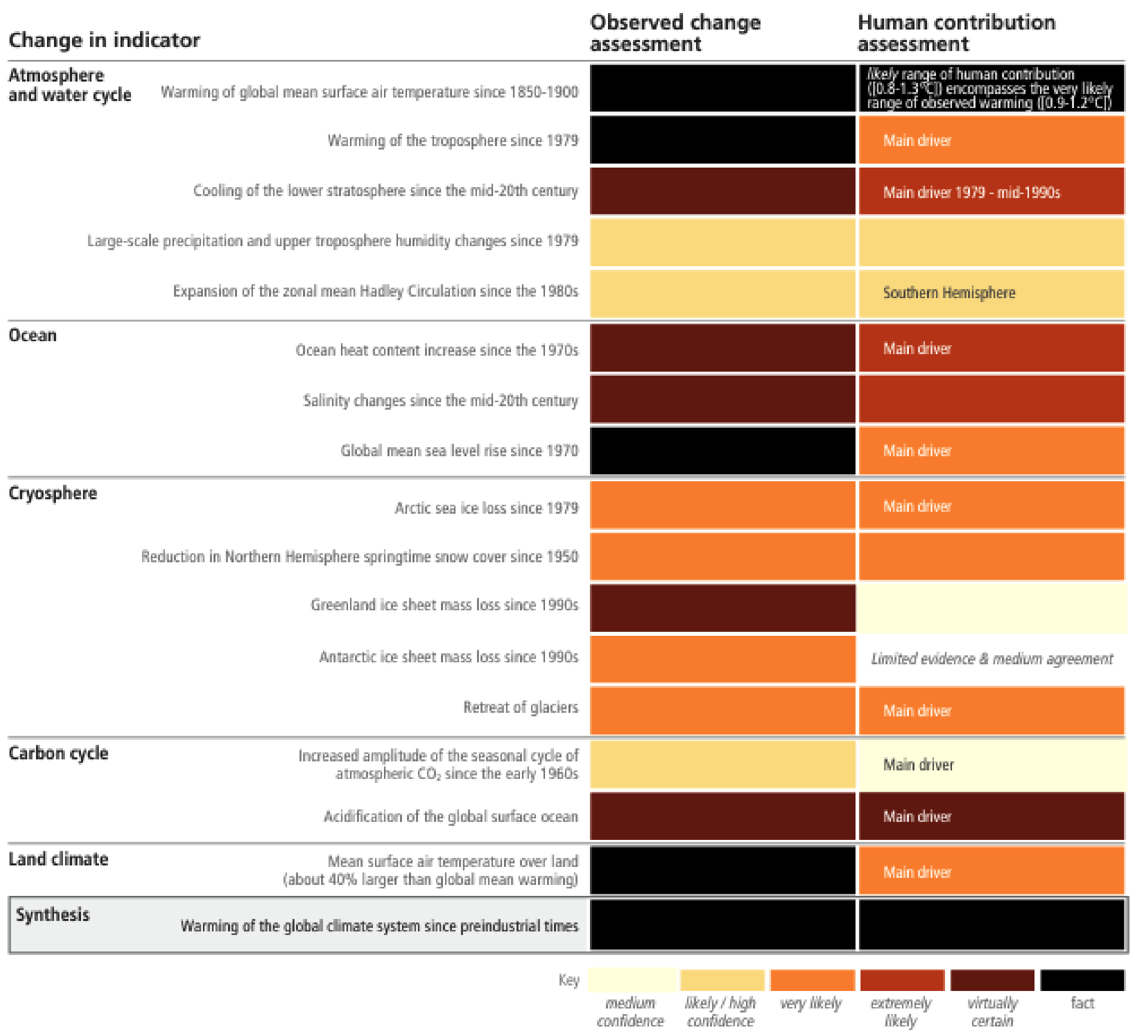
	Africa	Australia, Japan, New Zealand	Eastern Asia	Eastern Europe, West-Central Asia	Europe	Latin America and Caribbean	Middle East	North America	South-East Asia and Pacific	Southern Asia
Population (million persons, 2019)	1292	157	1471	291	620	646	252	366	674	1836
GDP per capita ($USD1000_{PPP}$ 2017 per person) [1]	5.0	43	17	20	43	15	20	61	12	6.2
Net GHG 2019 [2] (production basis)										
GHG emissions intensity (tCO_2-eq / $USD1000_{PPP}$ 2017)	0.78	0.30	0.62	0.64	0.18	0.61	0.64	0.31	0.65	0.42
GHG per capita (tCO_2-eq per person)	3.9	13	11	13	7.8	9.2	13	19	7.9	2.6
CO_2FFI, 2018, per person										
Production-based emissions (tCO_2FFI per person, based on 2018 data)	1.2	10	8.4	9.2	6.5	2.8	8.7	16	2.6	1.6
Consumption-based emissions (tCO_2FFI per person, based on 2018 data)	0.84	11	6.7	6.2	7.8	2.8	7.6	17	2.5	1.5

[1] GDP per capita in 2019 in USD2017 currency purchasing power basis.
[2] Includes CO_2FFI, CO_2LULUCF and Other GHGs, excluding international aviation and shipping.

The regional groupings used in this figure are for statistical purposes only and are described in WGIII Annex II, Part I.

4. OBSERVED IMPACTS IN THE CARIBBEAN

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[10]



[11]

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[9] Synthesis Report Figure 2.2: Regional GHG emissions, and the regional proportion of total cumulative production-based CO2 emissions from 1850 to 2019

[10] Synthesis Report 2.1.2

[11] Synthesis Report Table 2.1: Assessment of observed changes in large-scale indicators of mean climate across climate system components, and their attribution to human influence

OBSERVED CHANGES TO CARIBBEAN CLIMATE

TEMPERATURE

Significant positive trends in temperature ranging from 0.15°C per decade (over the period 1953–2010) to 0.18°C per decade (over the period 1961–2011) are noted in the tropical western Pacific, where the significant increasing and decreasing trends in warm and cool extremes, respectively, are also spatially homogeneous (Jones et al., 2013; Whan et al., 2014; Wang et al., 2016). Similarly, **much of the Caribbean region showed statistically significant warming (at the 95% level) over the period 1901–2010** (P.D. Jones et al., 2016 b). **Observation records in the Caribbean region indicate a significant warming trend of 0.19°C per decade and 0.28°C per decade in daily maximum and minimum temperatures, respectively, with statistically significant increases (at the 5% level) in the number of warm days and warm nights during 1961–2010** (Taylor et al., 2012; Stephenson et al., 2014; Beharry et al., 2015).[12]

PRECIPITATION

A weather station-based annual precipitation trend analysis over 1901–2010 in the Caribbean region indicated some locations with detectable decreasing trends (Knutson and Zeng, 2018), **which were attributable in part to anthropogenic forcing.** These include southern Cuba, the northern Bahamas, and the Windward Islands, although significant trends were not found over the shorter periods of 1951–2010 and 1981–2010. **In the Caribbean islands, a dataset of the Palmer Drought Severity Index (PDSI) from 1950 to 2016 showed a clear drying trend in the region** (Herrera and Ault, 2017). **The 2013–2016 period showed the most severe drought during the period and was strongly related to anthropogenic warming, which would have increased the severity of the event by 17% and its spatial extent by 7%** (Herrera et al., 2018).

It is very likely that most Small Islands have warmed over the period of instrumental records. The clearest precipitation trend is a likely decrease in JJA[13] rainfall over the Caribbean since 1950. There is limited evidence and low agreement for the cause of the observed drying trend, whether it is mainly caused by decadal-scale internal variability or anthropogenic forcing, but it is likely that it will continue over coming decades.[14]

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[12] Gutiérrez, J.M., R.G. Jones, G.T. Narisma, L.M. Alves, M. Amjad, I.V. Gorodetskaya, M. Grose, N.A.B. Klutse, S. Krakovska, J. Li, D. Martínez-Castro, L.O. Mearns, S.H. Mernild, T. Ngo-Duc, B. van den Hurk, and J.-H. Yoon, 2021: Atlas. 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. 1927–2058, doi:10.1017/9781009157896.021. [**WGI Atlas**].10.2

[13] JJA = June, July, August

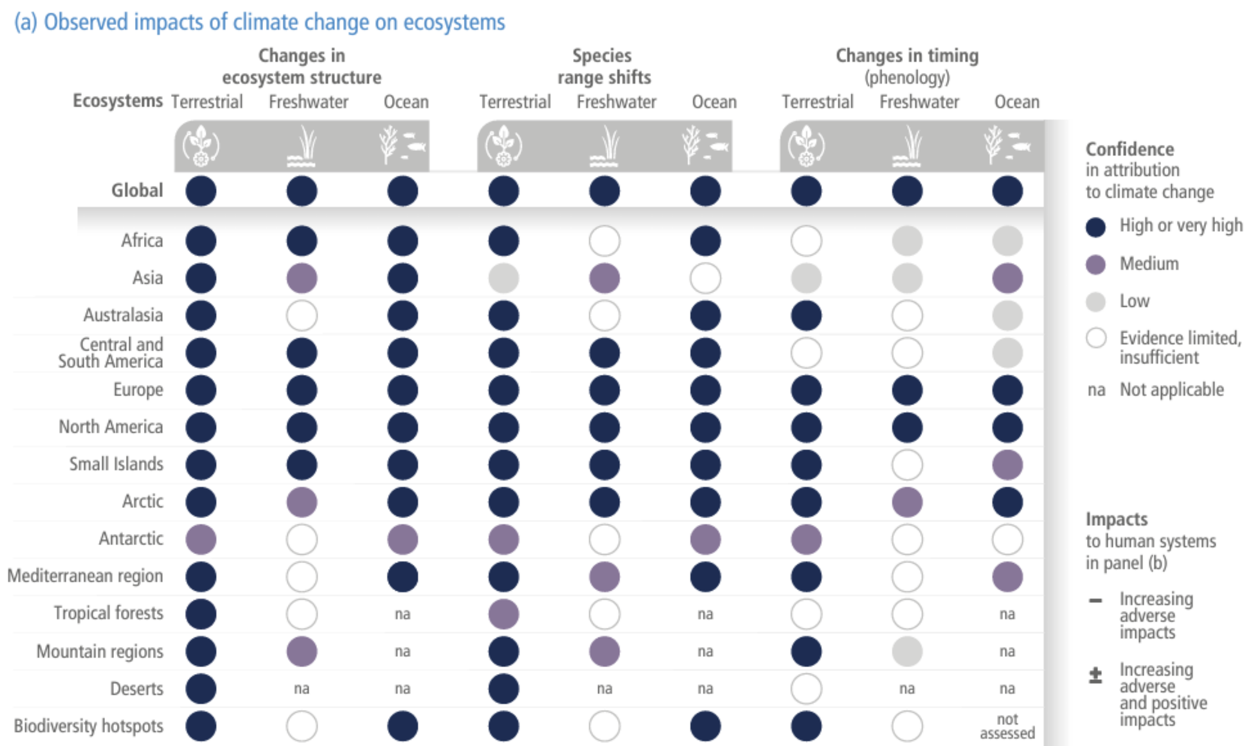
[14] WGI Atlas Cross Chapter Box Atlas.2

Region	Sub-region	Temperature	Rainfall	Other
Caribbean	Whole Caribbean	*High confidence* in increased frequency of hot extremes (Table 11.13)	*Low confidence* of increase in drought intensity during 1950–2016 and in the attribution of the 2013–2016 drought (Herrera and Ault, 2017; Herrera et al., 2018)	
	Jamaica, Cuba, Puerto Rico		*Low confidence* in declining JJA rainfall (CSGM, 2012) and a decreasing trend in Puerto Rico 1955–2009 (Méndez-Lázaro et al., 2014). Mixed trends 1980–2010 (Cavazos et al., 2020)	No attributable JJA rainfall trends 1951–2010 (Knutson and Zeng, 2018)
	Eastern Caribbean		*Low confidence* in an increase in periods of drought since 1999 (Van Meerbeeck, 2020)	*Medium confidence* in SLR of 1–2.5 mm yr^{-1} since 1950 (Van Meerbeeck, 2020)

[15]

OBSERVED BIOPHYSICAL IMPACTS

ECOSYSTEMS



[16]

[15] WGI Atlas Cross Chapter Box Atlas.2, Table 1. Summary of observed trends for Small Island regions.

[16] IPCC, 2022: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA,

BIODIVERSITY

Within the Mediterranean and Caribbean, significant losses to coastal wetlands—critical habitat for migratory birds—has already been observed, with further significant habitat losses, redistribution and changes in quality being projected across island systems such as the Bahamas (Caribbean) and Sardinia (Mediterranean) (Vogiatzakis et al., 2016; Wolcott et al., 2018).[17]

Since 2011, the Caribbean region has witnessed unprecedented influxes of the pelagic seaweed Sargassum. These extraordinary sargassum 'blooms' have resulted in mass deposition of seaweed on beaches throughout the Lesser Antilles, with damage to coastal habitats, mortality of seagrass beds and associated corals, as well as consequences for fisheries and tourism. This recent phenomenon has been linked to climate change as well as the possible influence of nutrients from Amazon River floods and/or Sahara dust.[18]

The spread of IAS is regarded as a significant transboundary threat to the health of biodiversity and ecosystems worldwide. The extent to which IAS (both animals and plants) successfully establish themselves at new locations in a changing climate will be dependent on many variables, but non-climate factors such as transmission pathways, suitability of the destination, ability to compete and adapt to new environments, and susceptibility to invasion of host ecosystems are deemed to be critical. Modelling studies have been used to project the future 'invisibility' of small island ecosystems subject to climate change and therefore to anticipate marine and terrestrial habitat degradation in the future. **Evidence suggests that hurricanes may have hastened the spread of highly invasive Indo-Pacific lionfish (Pterois volitans) throughout the Caribbean in recent years. Two IAS, the Common Green Iguana (Iguana iguana) and Cuban Treefrog (Osteopilus septentrionalis) were reported in the Caribbean island of Dominica, following the passage of TC Maria in 2017.[19]**

Rising sea temperatures are thought to increase the frequency of disease outbreaks affecting reef buildings. Of the range of bacterial, fungal and protozoan diseases known to affect stony corals, many have explicit links to temperature. **Global projections suggest that disease is as likely to cause coral mortality as bleaching in the coming decades at many localities, with effects occurring earlier at sites in the Caribbean compared to the Pacific and Indian oceans.** Model hindcasts suggest that climate-driven changes in SST as well as extreme heatwave events have all played a significant role in the spread of white-band disease throughout the Caribbean. Global food security is threatened by climate-related increases in crop pests and diseases. **Black Sigatoka disease of bananas has recently completed its invasion of Latin American and Caribbean banana-growing areas. Infection risk has increased by a median of 44.2% across the Caribbean since the 1960s, due to increasing canopy wetness and improving temperature conditions for the pathogen.[20]**

3056 pp., doi:10.1017/9781009325844. [**WGII]** Technical Summary Figure TS.3: Observed global and regional impacts on ecosystems and human systems attributed to climate change

[17] WGII Chapter 15 Section 15.3.3.3

[18] WGII Chapter 15 Table 15.5

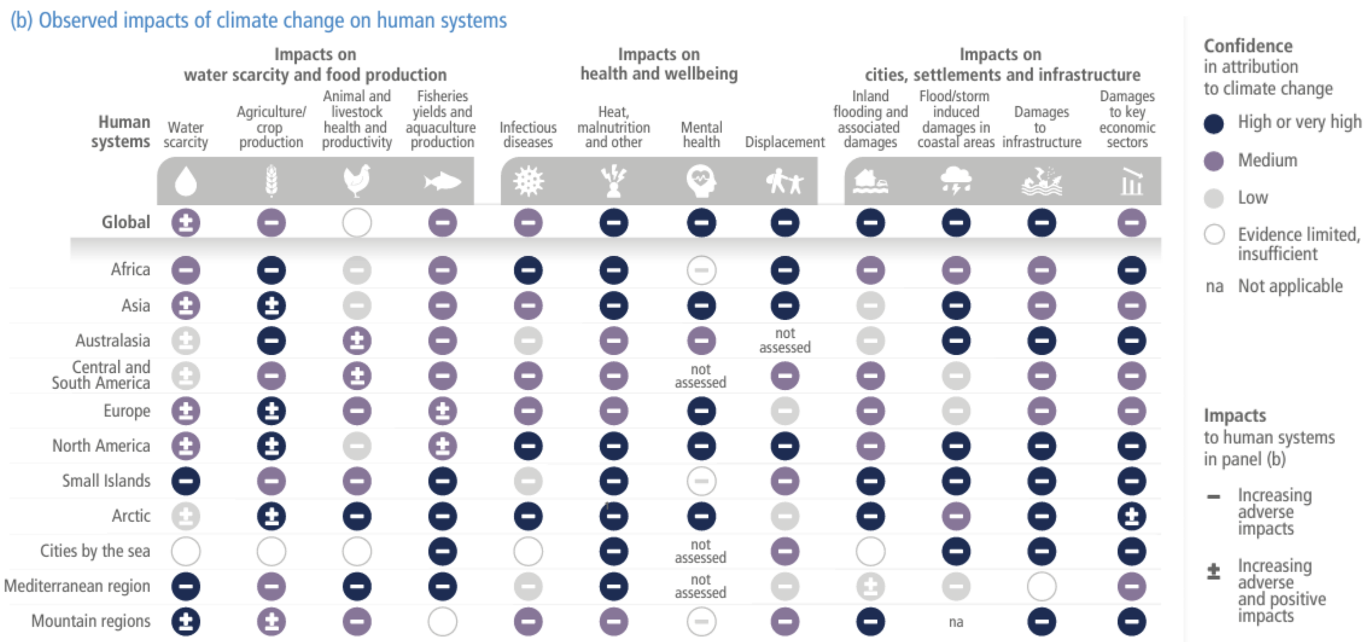
[19] WGII Chapter 15 Table 15.5

[20] WGII Chapter 15 Table 15.5

COASTAL EROSION

Despite important knowledge gaps on coastal erosion in high tropical islands, **recent studies confirmed increasing shoreline retreat and beach loss over the past decades, mainly due to TC and ETC waves and human disturbances (*high confidence*) (e.g., in the Caribbean region: Anguilla, Saint-Kitts, Nevis, Montserrat, Dominica and Grenada** (Cambers, 2009; Reguero et al., 2018)), and Pacific (Hawaii (Romine and Fletcher, 2013); Tubuai, French Polynesia (Salmon et al., 2019)) and Indian Oceans (Anjouan, Comoros (Ratter et al., 2016).[21]

OBSERVED SOCIO-ECONOMIC IMPACTS



[22]

FRESHWATER STRESS AND WATER SECURITY

Climate change impacts on freshwater systems frequently exacerbate existing pressure, especially in locations already experiencing water scarcity (Section 15.3.3.2 and Cross-Chapter Box INTERREG in Chapter 16; Schewe et al., 2014; Holding et al., 2016; Karnauskas et al., 2016), making water security a key risk (KR4 in Figure 15.5) in small islands. Small islands are usually environments where demand for resources related to socioeconomic factors

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[21] WGII Chapter 15 Section 15.3.3.1.2

[22] WGII Technical Summary Figure TS.3 Observed global and regional impacts on ecosystems and human systems attributed to climate change

such as population growth, urbanisation and tourism already place increasing pressure on limited freshwater resources. In many small islands, water demand already exceeds supply. **For example, in the Caribbean, Barbados is utilising close to 100% of its available water resources and St. Lucia has a water supply deficit of approximately 35% (Cashman, 2014).**[23]

The Caribbean and Pacific regions have historically been affected by severe droughts (Peters, 2015; FAO, 2016; Barkey and Bailey, 2017; Paeniu et al., 2017; Trotman et al., 2017; Anshuka et al., 2018) **with significant physical impacts and negative socioeconomic outcomes.** Water quality is affected by drought as well as water availability. The El Niño related 2015–1016 drought in Vanuatu led to reliance on small amounts of contaminated water left at the bottom of household tanks (Iese et al., 2021a). The highest land disturbance percentages have coincided with major droughts in Cuba (de Beurs et al., 2019). **Drought has been shown to have an impact on rainwater harvesting in the Pacific (Quigley et al., 2016) and Caribbean (Aladenola et al., 2016), especially in rural areas where connections to centralised public water supply have been difficult. Increasing trends in drought are apparent in the Caribbean** (Herrera and Ault, 2017) although trends in the western Pacific are not statistically significant (McGree et al., 2016).[24]

Climate change has intensified the global hydrological cycle, causing several societal impacts, which are felt disproportionately by vulnerable people (*high confidence*). Human-induced climate change has affected physical aspects of water security through increasing water scarcity and exposing more people to water-related extreme events like floods and droughts, thereby exacerbating existing water-related vulnerabilities caused by other socioeconomic factors (*high confidence*). Many of these changes in water availability and water-related hazards can be directly attributed to anthropogenic climate change (*high confidence*). Water insecurity disproportionately impacts the poor, women, children, Indigenous Peoples and the elderly in low-income countries (*high confidence*) and specific marginal geographies (e.g., small island states and mountain regions). Water insecurity can contribute to social unrest in regions where inequality is high and water governance and institutions are weak (*medium confidence*).[25]

SUBMERGENCE AND FLOODING OF ISLANDS AND COASTAL AREAS

Recent studies confirmed that observed ESL events causing extensive flooding generally resulted from compound effects, including the combination of SLR (Section 3.2.2.2 and Cross-Chapter Box SLR in Chapter 3) with ETCs, TCs and tropical depressions (WGI AR6 Sections 11.7.1 and 11.7.2, Seneviratne, 2021), ENSO-related highwater levels associated with high or spring tide and/or local human disturbances amplifying impacts (*high confidence*).[26]

Despite important knowledge gaps on coastal erosion in high tropical islands, **recent studies confirmed increasing shoreline retreat and beach loss over the past decades, mainly due to TC and ETC waves and human**

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[23] WGII Chapter 15 Section 15.3.4.3

[24] WGII Chapter 15 Section 15.3.4.3

[25] WGII Technical Summary TS.B.4.1

[26] WGII Chapter 15 Section 15.3.3.1.1

disturbances (*high confidence*) (e.g., in the Caribbean region: Anguilla, Saint-Kitts, Nevis, Montserrat, Dominica and Grenada (Cambers, 2009; Reguero et al., 2018))[27]

FOOD SECURITY

Climate change influences food and nutritional security through its effects on food availability, quality, access and distribution (Paterson and Lima, 2010; Thornton et al., 2014; FAO, 2016). **More than 815 million people were undernourished in 2016**, and 11% of the world's population has experienced recent decreases in food security, **with higher percentages in** Africa (20%), southern Asia (14.4%) and **the Caribbean (17.7%)** (FAO et al., 2017).[28]

Climate-related extremes have affected the productivity of all agricultural and fishery sectors, with negative consequences for food security and livelihoods (*high confidence*). The frequency of sudden food production losses has increased since at least the mid20th century on land and sea (medium evidence, high agreement). The impacts of climate-related extremes on food security, nutrition and livelihoods are particularly acute and severe for people living in sub-Saharan Africa, Asia, small islands, Central and South America and the Arctic and small-scale food producers globally (*high confidence*).[29]

TOURISM

Many small island economies are sustained by tourism and have invested heavily in associated infrastructure and capacity building (Cannonier and Burke, 2018). Some rural island communities have become dependent on tourism to the point that it would be difficult to revert to subsistence living (Lasso and Dahles, 2018). Coast-focused (beach-sea) tourism in island contexts is already being impacted by beach erosion, elevated high SST causing coral bleaching, and associated marine-biodiversity loss, as well as more intense TCs (Tapsuwan and Rongrongmuang, 2015; Parsons et al., 2018; Wabnitz et al., 2018)[30]

ECONOMIC IMPACTS

The extreme events occurring today, such as storms, tropical cyclones (TC), droughts, floods and marine heat waves (Herring et al., 2017), provide striking illustrations of the vulnerability of small island systems (*high confidence*) (Section 6.8.5, Box 4.2, Box 6.1). Societal dimensions can combine with climate changes, e.g., sea level

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[27] WGII Chapter 15 Section 15.3.3.1.2

[28] IPCC, 2018 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. 3-24. https://doi.org/10.1017/9781009157940.001. [**SR 1.5C**], Cross-Chapter Box 6

[29] WGII Technical Summary TS.B.3.3

[30] WGII Chapter 15 Section 15.3.4.5

rise, to amplify the impact of TCs, storm surge and ocean acidification in small islands contributing to loss and damage (Moser and Hart, 2015; Noy and Edmonds, 2016). For example, Category 5 TC Pam devastated Vanuatu in 2015 with 449.4 million USD in losses for an economy with a GDP of 758 million USD (Government of Vanuatu, 2015; Handmer and Iveson, 2017). Kiribati, Papua New Guinea, Solomon Islands and Tuvalu were all impacted by the TC Pam system (IFRC, 2018). In 2016, TC Winston caused 43 deaths in Fiji and losses of more than one third of the GDP (Government of Fiji, 2016; Cox et al., 2018). **In 2017, Hurricanes Maria and Irma swept through 15 Caribbean countries, causing major damages and casualties across numerous islands. Rebuilding in three countries alone – Dominica, Barbuda and the British Virgin Islands – will cost an estimated 5 billion USD (UNDP, 2017). The Post-Disaster Needs Assessment for Dominica concluded that hurricane Maria resulted in total damages amounting to 226% of 2016 GDP (The Government of the Commonwealth of Dominica, 2017).**[31]

HEALTH

The transport of airborne Saharan dust across the Atlantic into the Caribbean has been intensively studied. In the West African Sahel, where drought has been persistent since the mid-1960s, analysis has shown that there have been remarkable changes in dust emissions since the late 1940s. Variability in Sahel dust emissions may be related not only to droughts, but also to changes in the North Atlantic Oscillation (NAO), North Atlantic SST and the Atlantic Multidecadal Oscillation (AMO). The frequency of dust storms has been on the rise during the last decade. Forecasts suggest that their incidence will increase further. **Transboundary movement of Saharan dust into the island regions of the Caribbean and the Mediterranean has been associated with human health problems including asthma cases in the Caribbean,** cardiovascular morbidity in Cyprus and pulmonary disease in the Cape Verde islands.[32]

CULTURAL LOSSES

The unquantifiable and highly localised cultural losses resulting from climate drivers are less researched and less acknowledged in policy than physical and economic losses (Karlsson and Hovelsrud, 2015; Thomas and Benjamin, 2018a**). In the Bahamas, prolonged displacement of the entire population of Ragged Island following Hurricane Irma (2017) highlighted the cultural losses that can result from climate-induced displacement from ancestral homelands.** Threats to identity, sense of place and community cohesion resulted from displacement, although all were important foundational features of the Islanders' self-initiated rehabilitation efforts and eventual return. Nonetheless, non-economic losses were not accounted for by policy addressing displacement (Thomas and Benjamin, 2018a). **In the case of Monkey River Village in Belize, coastal erosion is threatening the community's cemetery. Residents place significant spiritual and emotional value on the cemetery, which serves important community functions, and, thus, threats to it are perceived to be serious and necessary to be taken into account in any planned response** (Karlsson and Hovelsrud, 2015). **A similar situation exists on Carriacou in the West Indies where culturally and historically significant archaeological sites are being lost due to coastal**

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[31] IPCC, 2019 IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 3–35. https://doi.org/10.1017/9781009157964.001. **[SROCC]**, CCB9

[32] WGII Chapter 15. Table 15.5

erosion caused by a combination of sand mining and extreme climate-ocean events exacerbated by SLR (Fitzpatrick et al., 2006).[33]

SETTLEMENTS AND INFRASTRUCTURE

Categories 4 and 5 TCs are severely impacting settlements and infrastructure in small islands. TC Maria in 2017 destroyed nearly all of Dominica's infrastructure and losses per unit of GDP amounted to more than 225% of the annual GDP (Eckstein et al., 2018). Destruction from TC Winston in 2016 amounted to more than 20% of Fiji's current GDP (Cox et al., 2018). Additionally, living conditions in human settlements are changing due to storm surge which is already penetrating further inland compared with a few decades ago (IPCC, 2018, Section 3.4.4.3; Brown et al., 2018).[34]

As a result of slow-onset ocean and climate changes and changes in extreme events, settlements and infrastructure of small islands are at growing risk due to climate change in the absence of adaptation measures (*high confidence*). Ocean acidification and deoxygenation, increased ocean temperatures and relative SLR are impacting marine, coastal and terrestrial biodiversity and ecosystem services, making settlements more exposed and vulnerable to climate-related hazards. **Changes in rainfall patterns such as heavy precipitation result in annual flood events that damage major assets and result in a loss of human life. Examples of settlements where this has occurred are Port of Spain (Mycoo, 2014b; 2018a), Haiti** (Weissenberger, 2018), Viti Levu (Brown et al., 2017; Singh-Peterson and Iranacolaivalu, 2018), urban areas of Fiji and Kiribati (McAneney et al., 2017; Cauchi et al., 2021), Male', Maldives (Wadey et al., 2017), and Mahé, in the Seychelles (Etongo, 2019).[35]

Coastal settlements with high inequality, for example a high proportion of informal settlements, as well as deltaic cities prone to land subsidence (e.g., Bangkok, Jakarta, Lagos, New Orleans, Mississippi, Nile, Ganges-Brahmaputra deltas) and **small island states are highly vulnerable and have experienced impacts from severe storms and floods in addition to, or in combination with, those from accelerating sea level rise (*high confidence*).**[36]

HUMAN MOBILITY

The most common climatic drivers for migration and displacement are drought, tropical storms and hurricanes, heavy rains and floods (*high confidence*). Extreme climate events act as both direct drivers (e.g., destruction of homes by tropical cyclones) and indirect drivers (e.g., rural income losses during prolonged droughts) of involuntary migration and displacement (*very high confidence*). The largest absolute number of people displaced by extreme weather each year occurs in Asia (South, Southeast and East), followed by sub-Saharan Africa, but

[33] WGII Chapter 15 Section 15.3.4.7

[34] WGII Chapter 15 Section 15.3.4.1

[35] WGII Chapter 15 Section 15.3.4.1

[36] WGII Technical Summary TS.B.8.2

small island states in the Caribbean and South Pacific are disproportionately affected relative to their small population size (*high confidence*).[37]

[37] WGII Technical Summary TS.B.6.1

5. PROJECTED RISKS IN THE CARIBBEAN

It is widely recognized that small islands are very sensitive to climate change impacts such as sea level rise, oceanic warming, heavy precipitation, cyclones and coral bleaching (*high confidence*) (Nurse et al., 2014; Ourbak and Magnan, 2017). **Even at 1.5°C of global warming, the compounding impacts of changes in rainfall, temperature, tropical cyclones and sea level are likely to be significant across multiple natural and human systems. There are potential benefits to small island developing states (SIDS) from avoided risks at 1.5°C versus 2°C, especially when coupled with adaptation efforts**. In terms of sea level rise, by 2150, roughly 60,000 fewer people living in SIDS will be exposed in a 1.5°C world than in a 2°C world (Rasmussen et al., 2018). Constraining global warming to 1.5°C may significantly reduce water stress (by about 25%) compared to the projected water stress at 2°C, for example in the Caribbean region (Karnauskas et al., 2018), and may enhance the ability of SIDS to adapt (Benjamin and Thomas, 2016). Up to 50% of the year is projected to be very warm in the Caribbean at 1.5°C, with a further increase by up to 70 days at 2°C versus 1.5°C (Taylor et al., 2018). By limiting warming to 1.5°C instead of 2°C in 2050, risks of coastal flooding (measured as the flood amplification factors for 100-year flood events) are reduced by 20–80% for SIDS (Rasmussen et al., 2018). **A case study of Jamaica with lessons for other Caribbean SIDS demonstrated that the difference between 1.5°C and 2°C is likely to challenge livestock thermoregulation, resulting in persistent heat stress for livestock (Lallo et al., 2018).**[38]

Global warming of 1.5°C is expected to prove challenging for small island developing states (SIDS) that are already experiencing impacts associated with climate change (*high confidence*). At 1.5°C, compounding impacts from interactions between climate drivers may contribute to the loss of, or change in, critical natural and human systems (*medium to high confidence*). There are a number of reduced risks at 1.5°C versus 2°C, particularly when coupled with adaptation efforts (*medium to high confidence*).[39]

SIDS are home to 65 million people (UN-OHRLLS, 2015). More than 80% of small island residents live near the coast where flooding and coastal erosion already pose serious problems (Nurse et al., 2014) and **since the IPCC 5th Assessment Report (AR5) and the Special Report on Global Warming of 1.5°C (SR1.5), there is consensus on the increasing threats to island sustainability in terms of land, soils and freshwater availability. As a result, there is growing concern that some island nations as a whole may become uninhabitable due to rising sea levels and climate change, with implications for relocation, sovereignty and statehood** (Burkett, 2011; Gerrard and Wannier, 2013; Yamamoto and Esteban, 2014; Donner, 2015).[40]

Key risks for Small Islands include: Loss of terrestrial, marine and coastal biodiversity and ecosystem services- Loss of lives and assets, risk to food security and economic disruption due to destruction of settlements and infrastructure- Economic decline and livelihood failure of fisheries, agriculture, tourism and from biodiversity loss from traditional agroecosystems - Reduced habitability of reef and non-reef islands leading to increased displacement- Risk to water security in almost every small island.[41] *[See Figure pg. 23]*

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[38] SR 1.5C, Section 3.5.4.9

[39] SR 1.5C, Box 3.5

[40] SROCC, CCB9

[41] WGII Technical Summary Figure TS.4

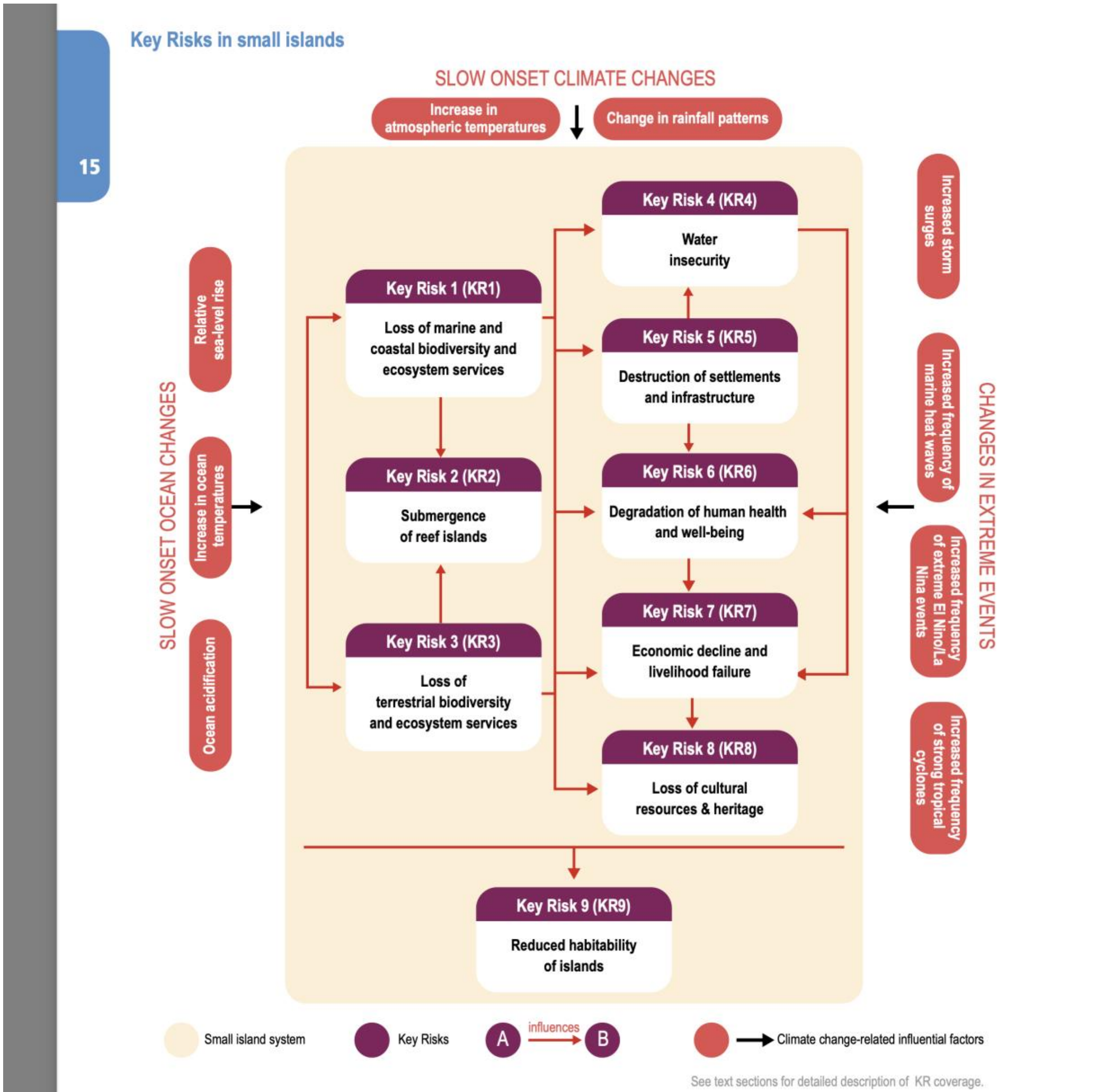

Figure 15.5 | Key risks in small islands. KR1 to KR8 are interconnected as shown by *arrows*, which causes risk accumulation leading to reduced island habitability. The main interconnections are shown in this figure: for example, loss of marine and coastal and terrestrial biodiversity and ecosystem services (KR1 and KR3, respectively) are projected to cause the submergence of reef islands (KR2), water insecurity (KR4), destruction of settlements and infrastructure (KR5), degradation of human health and well-being (KR6), economic decline and livelihood failure (KR7), and loss of cultural resources and heritage (KR8). Importantly, KRs result from both direct effects (e.g., decrease in rainfall will increase water insecurity) and indirect effects (e.g., loss of terrestrial biodiversity and ecosystem services will increase water insecurity, which in turn cause the degradation of human health and well-being).

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[42] WGII Chapter 15. Figure 15.5 Key risks in small islands

PROJECTED RISKS FOR CARIBBEAN CLIMATE

TEMPERATURE

Small Islands will very likely continue to warm this century, though at a rate less than the global average (Figure Atlas.28), with consequent increased frequency of warm extremes for the Caribbean and western Pacific islands, and heatwave events for the Caribbean (*high confidence*).[43]

Mean surface temperature is projected to increase in SIDS at 1.5°C of global warming (*high confidence*). The Caribbean region will experience 0.5°C–1.5°C of warming compared to a 1971–2000 baseline, with the strongest warming occurring over larger land masses (Taylor et al., 2018). Under the Representative Concentration Pathway (RCP)2.6 scenario, the western tropical Pacific is projected to experience warming of 0.5°C–1.7°C relative to 1961–1990. Extreme temperatures will also increase, with potential for elevated impacts as a result of comparably small natural variability (Reyer et al., 2017a). **Compared to the 1971–2000 baseline, up to 50% of the year is projected to be under warm spell conditions in the Caribbean at 1.5°C, with a further increase of up to 70 days at 2°C** (Taylor et al., 2018).[44]

PRECIPITATION

Rainfall is very likely to decline over the Caribbean, in the annual mean and especially in JJA, with a stronger and more coherent signal in CMIP6 compared to CMIP5 (Figure Atlas.28 and Interactive Atlas) and reductions of 20–30% by the end of the century under high future emissions (SSP5-8.5). This JJA drying has been linked to a future strengthening of the Caribbean low level jet (CLLJ) (Taylor et al., 2013a), a westward expansion and intensification of the NASH, stronger low-level easterlies over the region, a southwardly-placed eastern Pacific ITCZ (Rauscher et al., 2008), and changing dynamics due to increased greenhouse gas concentrations (*very high confidence*) (W. Li et al., 2012). Projections from 15 GCM and two RCM experiments for 2080–2089 relative to 1970–1989 were for a generally drier Caribbean and a robust summer drying (Karmalkar et al., 2013). More recent downscaling studies (e.g., Taylor et al., 2018; Vichot-Llano et al., 2021a) also project a drier Caribbean and longer dry spells (Van Meerbeeck, 2020).[45]

Changes in precipitation patterns, freshwater availability and drought sensitivity differ among small island regions (*medium to high confidence*). **In accordance with an overall drying trend, an increasing drought risk is projected for Caribbean SIDS (Lehner et al., 2017), and moderate to extreme drought conditions are projected to be about 9% longer on average at 2°C versus 1.5°C for islands in this region** (Taylor et al., 2018).[46]

Projected increases in aridity and decreases in freshwater availability at 1.5°C of warming, along with additional risks from SLR and increased wave-induced run-up, might leave several atoll islands uninhabitable (Storlazzi et al.,

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[43] WGI Atlas Cross Chapter Box Atlas.2

[44] SR 1.5C, Box 3.5

[45] WGI Atlas Cross Chapter Box Atlas.2

[46] SR 1.5C, Box 3.5

2015; Gosling and Arnell, 2016). Changes in the availability and quality of freshwater, linked to a combination of changes to climate drivers, may adversely impact SIDS' economies (White and Falkland, 2010; Terry and Chui, 2012; Holding and Allen, 2015; Donk et al., 2018). Growth-rate projections based on temperature impacts alone indicate robust negative impacts on gross domestic product (GDP) per capita growth for SIDS (Sections 3.4.7.1, 3.4.9.1 and 3.5.4.9; Pretis et al., 2018). These impacts would be reduced considerably under 1.5°C but may be increased by escalating risks from climate-related extreme weather events and SLR (Sections 3.4.5.3, 3.4.9.4 and 3.5.3).[47]

TROPICAL CYLCONES (HURRICANES)

It is likely that the proportion of major (Category 3–5) tropical cyclones (TCs) and the frequency of rapid TC intensification events have increased over the past four decades. The average location of peak TC wind-intensity has very likely migrated poleward in the western North Pacific Ocean since the 1940s, and TC forward translation speed has likely slowed over the contiguous USA since 1900. It is likely that the poleward migration of TCs in the western North Pacific and the global increase in TC intensity rates cannot be explained entirely by natural variability. **There is high confidence that average peak TC wind speeds and the proportion of Category 4–5 TCs will increase with warming and that peak winds of the most intense TCs will increase.** There is medium confidence that the average location where TCs reach their maximum wind-intensity will migrate poleward in the western North Pacific Ocean, while the total global frequency of TC formation will decrease or remain unchanged with increasing global warming. {11.7.1}[48]

Additional regional changes in Small Islands, besides those features described in Section TS.4.3.1, include a likely decrease in rainfall during boreal summer in the Caribbean and in some parts of the Pacific islands poleward of 20° latitude in both the Northern and Southern Hemispheres. These drying trends will likely continue in coming decades. **Fewer but more intense tropical cyclones are projected starting from a 2°C Global Warming Level** (medium confidence). {9.6, 11.3, 11.4, 11.7, 11.9, 12.4.7, Atlas.10.2, Atlas.10.4, Cross-Chapter Box Atlas.2}[49]

OCEAN AND CRYOSPHERE

Ocean and cryosphere changes already impact Low-Lying Islands and Coasts (LLIC), including Small Island Developing States (SIDS), with cascading and compounding risks. Disproportionately higher risks are expected in the course of the 21st century. Reinforcing the findings of the IPCC Special Report on Global Warming of 1.5°C, vulnerable human communities, especially those in coral reef environments and polar regions, may exceed adaptation limits well before the end of this century and even in a low greenhouse gas emission pathway (*high confidence*).[50]

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[47] SR 1.5C, Box 3.5

[48] WGI Technical Summary Section TS2.3

[49] WG1 Technical Summary Section TS4.3.2.7

[50] SROCC. Technical Summary

Due to projected GMSL rise, ESLs that are historically rare (for example, today's hundred-year event) will become common by 2100 under all RCPs (*high confidence*). Many low-lying cities and small islands at most latitudes will experience such events annually by 2050. Greenhouse gas (GHG) mitigation envisioned in low-emission scenarios (e.g., RCP2.6) is expected to sharply reduce but not eliminate risk to low-lying coasts and islands from SLR and ESL events. Low-emission scenarios lead to slower rates of SLR and allow for a wider range of adaptation options. For the first half of the 21st century differences in ESL events among the scenarios are small, facilitating adaptation planning.[51]

Extreme precipitation in small island regions is often linked to tropical storms and contributes to the climate hazard (Khouakhi et al., 2017). Similarly, **extreme sea levels for small islands, particularly in the Caribbean, are linked to tropical cyclone occurrence (Khouakhi and Villarini, 2017). Under a 1.5°C stabilization scenario, there is a projected decrease in the frequency of weaker tropical storms and an increase in the number of intense cyclones** (Section 3.3.6; Wehner et al., 2018a).[52]

PROJECTED BIOPHYSICAL RISKS

BIODIVERSITY

Even achieving emission reduction targets consistent with the ambitious goal of 1.5°C of global warming under the Paris Agreement will result in the further **loss of 70–90% of reef-building corals compared to today, with 99% of corals being lost under warming of 2°C or more above the pre-industrial period (*high confidence*)** (Hoegh-Guldberg et al., 2018).[53]

Marine systems and associated livelihoods in SIDS face higher risks at 2°C compared to 1.5°C (*medium to high confidence*). **Mass coral bleaching and mortality are projected to increase because of interactions between rising ocean temperatures, ocean acidification, and destructive waves from intensifying storms** (Section 3.4.4 and 5.2.3, Box 3.4). At 1.5°C, approximately 70–90% of global coral reefs are projected to be at risk of long-term degradation due to coral bleaching, with these values increasing to 99% at 2°C (Frieler et al., 2013; Schleussner et al., 2016b). Higher temperatures are also related to an increase in coral disease development, leading to coral degradation (Maynard et al., 2015). For marine fisheries, limiting warming to 1.5°C decreases the risk of species extinction and declines in maximum catch potential, particularly for small islands in tropical oceans (Cheung et al., 2016a).[54]

The majority of studies modelling geographical range changes of small island species, to even the most optimistic 21st century climate change scenarios, imply a reduction in climate refugia (Table 15.3, Box CCP1.1). This is due to projected strong shifts, reductions or even complete losses of climatic niches resulting from

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[51] SROCC. Technical Summary

[52] SR 1.5C, Box 3.5

[53] WGII Chapter 15. Section 15.3.3.1.3

[54] SR 1.5C, Box 3.5

inadequate geographic space for species to track suitable climate envelopes (*high confidence*) (e.g., Maharaj and New, 2013; Fortini et al., 2015; Struebig et al., 2015b). **Because of the high proportion of global endemics hosted within small and especially isolated islands, the resulting increased extinction risk of such species (up to 100%) could lead to disproportionate losses in global biodiversity (*medium to high confidence*)** (Harter et al., 2015; Manes et al., 2021).[55]

SLR has been projected to impact the terrestrial biodiversity of lowlying islands and coastal regions via large habitat losses both directly (e.g., submergence) and indirectly (e.g., salinity intrusion, salinization of coastal wetlands and soil erosion) at even the 1-m scenario (*medium to high confidence*). However, these impacts vary depending on the islands' topographical differences. **In a study of SLR impacts on insular biodiversity hotspots, Bellard et al. (2013a) reported that the Caribbean islands**, Sundaland and the Philippines **were projected to suffer the most habitat loss** while the East Melanesian islands were projected to be less (but not minimally) affected. **The most threatened of these, the Caribbean, was projected to have between 8.7% and 49.2% of its islands entirely submerged, respectively, from 1-m to 6-m SLR** (Bellard et al., 2013a). However, many current projection studies consider marine flooding directly and seldom incorporate other indirect impacts such as increased habitat losses from horizontal erosion loss, increased salinity levels, tidal ranges and extreme events. **These projections are considered to be conservative**, underestimating the extent of habitat loss to terrestrial biodiversity (Bellard et al., 2013b).[56]

PROJECTED SOCIO-ECONOMIC RISKS

MOBILITY

Risks of impacts across sectors are projected to be higher at 1.5°C compared to the present, and will further increase at 2°C (*medium to high confidence*). **Projections indicate that at 1.5°C there will be increased incidents of internal migration and displacement (Sections 3.5.5, 4.3.6 and 5.2.2; Albert et al., 2017), limited capacity to assess loss and damage (Thomas and Benjamin, 2017) and substantial increases in the risk to critical transportation infrastructure from marine inundation** (Monioudi et al., 2018).[57]

FRESHWATER STRESS

Projected changes in aridity are expected to impose freshwater stress on many small islands, especially SIDS (*high confidence*). **These changes are congruent with drought risk projections for Caribbean SIDS (Lehner et al., 2017; Taylor et al., 2018) and aligned with observations from the Shared Socioeconomic Pathway (SSP) 2 scenario, where a 1°C increase in temperature (from 1.7°C to 2.7°C) could result in a 60% increase in the number of people**

[55] WGII Chapter 15. Section 15.3.3.3

[56] WGII Chapter 15. Section 15.3.3.3

[57] SR1.5 Chapter 3 Box3.5

projected to experience severe water resources stress from 2043 to 2071 (Schewe et al., 2014; Karnauskas et al., 2018).[58]

Projected changes in aridity are expected to impose freshwater stress on many small islands, especially SIDS (*high confidence*). It is estimated that with a warming of 1.5°C or less, freshwater stress on small islands would be 25% less as compared to 2.0°C. While some island regions are projected to experience substantial freshwater decline, an opposite trend is observed for some western Pacific and northern Indian Ocean islands. **Drought risk projections for Caribbean SIDS aligned with observations from the Shared Socioeconomic Pathway (SSP) 2 scenario indicate that a 1°C increase in temperature (from 1.7°C to 2.7°C) could result in a 60% increase in the number of people projected to experience severe water resources stress from 2043 to 2071**. In some Pacific atolls, freshwater resources could be significantly affected by a 0.40-m SLR. **Similar impacts are anticipated for some Caribbean countries with the worst-case scenario (RCP8.5) indicating a 0.5-m SLR by the mid-century (2046–2065) and a 1-m SLR by the end-of-century (2081–2100). SIDS with high projected population growth rates are expected to experience the most severe freshwater stress by 2030 under a 2°C warming threshold scenario** {15.3.3.2}[59]

AGRICULTURE AND FOOD SECURITY

In the Caribbean, additional warming by 0.2°–1.0°C could lead to a predominantly drier region (5–15% less rain than present-day), a greater occurrence of droughts (Taylor et al., 2018) along with associated impacts on agricultural production and yield in the region (Gamble et al., 2017; Hoegh-Guldberg et al., 2019; Nicolas et al., 2020). **Crop suitability modelling on several commercially important crops grown in Jamaica found that even an increase of less than 1.5°C could result in a reduction in the range of crops that farmers may grow** (Rhiney et al., 2018).[60]

Climate change will increasingly add significant pressure and regionally different impacts on all components of food systems, undermining all dimensions of food security (*high confidence*). Extreme weather events will increase risks of food insecurity via spikes in food prices, reduced food diversity and reduced income for agricultural and fishery livelihoods (*high confidence*), preventing achievement of the UN SDG 2 ('Zero Hunger') by 2030 in regions with limited adaptive capacities, including Africa, small island states and South Asia (*high confidence*).[61]

TOURISM

The tourism sector is also affected by climate-induced changes in environmental assets critical for tourism, including biodiversity, beaches, glaciers and other features important for environmental and cultural heritage. Limited analyses of projected risks associated with 1.5°C versus 2°C are available (Section 3.4.4.12). A global analysis of sea level rise (SLR) risk to 720 UNESCO Cultural World Heritage sites projected that about 47 sites might

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[58] WGII Chapter 15. Section 15.3.3.1.4

[59] WGII Chapter 15. ES.

[60] WGII Chapter 15. Section 15.3.4.4

[61] WGII Technical Summary TS.C.3.3

be affected under 1°C of warming, with this number increasing to 110 and 136 sites under 2°C and 3°C, respectively (Marzeion and Levermann, 2014). Similar risks to vast worldwide coastal tourism infrastructure and beach assets remain unquantified for most major tourism destinations and small island developing states (SIDS) that economically depend on coastal tourism. One exception is the projection that **an eventual 1 m SLR could partially or fully inundate 29% of 900 coastal resorts in 19 Caribbean countries, with a substantially higher proportion (49–60%) vulnerable to associated coastal erosion** (Scott and Verkoeyen, 2017).[62]

SUBMERGENCE AND FLOODING OF ISLANDS AND COASTAL AREAS

In the absence of adaptation, more intense and frequent ESL events, together with trends in coastal development will increase expected annual flood damages by 2-3 orders of magnitude by 2100 (*high confidence*). However, well designed coastal protection is very effective in reducing expected damages and cost efficient for urban and densely populated regions, but generally unaffordable for rural and poorer areas (high confidence). Effective protection requires investments on the order of tens to several hundreds of billions of USD yr-1 globally (*high confidence*). While investments are generally cost efficient for densely populated and urban areas (*high confidence*), rural and poorer areas will be challenged to afford such investments with relative annual costs for some small island states amounting to several percent of GDP (*high confidence*). Even with well-designed hard protection, the risk of possibly disastrous consequences in the event of failure of defences remains.[63]

In Hawaii and the Caribbean, SLR is projected to exponentially increase flooding, with nearly every centimetre of SLR causing a doubling of the probability of flooding (Taherkhani et al., 2020).[64]

Long-term risks of coastal flooding and impacts on populations, infrastructure and assets are projected to increase with higher levels of warming (*high confidence*). **Tropical regions including small islands are expected to experience the largest increases in coastal flooding frequency, with the frequency of extreme water-level events in small islands projected to double by 2050** (Vitousek et al., 2017). Wave-driven coastal flooding risks for reef-lined islands may increase as a result of coral reef degradation and SLR (Quataert et al., 2015). Exposure to coastal hazards is particularly high for SIDS, with a significant share of population, infrastructure and assets at risk (Sections 3.4.5.3 and 3.4.9; Scott et al., 2012; Kumar and Taylor, 2015; Rhiney, 2015; Byers et al., 2018). **Limiting warming to 1.5°C instead of 2°C would spare the inundation of lands currently home to 60,000 individuals in SIDS by 2150** (Rasmussen et al., 2018). However, such estimates do not consider shoreline response (Section 3.4.5) or adaptation.[65]

Reef island and coastal area habitability in small islands is expected to decrease because of increased temperature, extreme sea levels and degradation of buffering ecosystems, which will increase human exposure to sea-related hazards (*high confidence*). Climate and non-climate drivers of reduced habitability are context specific. On small islands, coastal land loss attributable to higher sea level, increased extreme precipitation and wave impacts and increased aridity have contributed to food and water insecurities that are likely to become more acute in many

[62] SR 1.5C, Section 3.4.9.1

[63] SROCC. Technical Summary

[64] WGII Chapter 15 Section 15.3.3.1.1

[65] SR 1.5C, Box 3.5

places (*high confidence*). **In the Caribbean, additional warming by 0.2°–1.0°C, could lead to a predominantly drier region (5–15% less rain than present day), a greater occurrence of droughts along with associated impacts on agricultural production and yield in the region**. Crop suitability modelling on several commercially important crops grown in Jamaica found that even an increase of less than + 1.5°C could result in a reduction in the range of crops that farmers may grow.[66]

TC intensification in the future is likely to cause severe damage to human settlements and infrastructure in small islands. Additionally, SLR is expected to cause significant losses and damages (Martyr-Koller et al., 2021). Based on SLR projections, almost all port and harbour facilities in the Caribbean will suffer inundation in the future (Cashman and Nagdee, 2017). In Jamaica and St. Lucia, SLR and ESLs are projected to be key risks to transport infrastructure at 1.5°C unless further adaptation is undertaken (Monioudi et al., 2018).[67]

HEALTH

Small islands face disproportionate health risks associated with changes in temperature and precipitation, climate variability, and extremes (Cross-Chapter Box INTERREG in Chapter 16; KR4 in Section 15.3.9, Figure 15.5). Climate change is projected to increase the current burden of climate-related health risks (Weatherdon et al., 2016; Ebi et al., 2018; Schnitter et al., 2019). Health risks can arise from exposures to extreme weather and climate events, including heatwaves; changes in ecological systems associated with changing weather patterns that can result, for example, in more disease vectors, or in compromised safety and security of water and food; and exposures related to disruption of health systems, migration, and other factors (see Cross-Chapter Box ILLNESS in Chapter 2; McIver et al., 2016; Mycoo, 2018a; WHO, 2018).[68]

Heat-related mortality and risks of occupational heat stress in small island states are projected to increase with higher temperatures (HoeghGuldberg et al., 2018; Mendez-Lazaro et al., 2018). Higher temperatures can also affect the productivity of outdoor workers (Taylor et al., 2021). Climate change, urbanisation, and air pollution are risk factors for the rise of allergic diseases in Asia Pacific (Pawankar et al., 2020).[69]

Tropical and subtropical islands face risks from vector-borne diseases, such as malaria, dengue fever, and the Zika virus. El Niño events can increase the risk of diseases such as Zika virus by increasing biting rates, decreasing mosquito mortality rates and shortening the time required for the virus to replicate within the mosquito (Caminade et al., 2017). **By combining disease prediction models with climate indicators that are routinely monitored, alongside evaluation tools, it is possible to generate probabilistic dengue outlooks in the Caribbean and early warning systems (Oritz et al., 2015; Lowe et al., 2018). Projections suggest that more individuals will become at risk of dengue fever by the 2030s and beyond because of an increasing abundance of mosquitos and larger geographic range** (Ebi et al., 2018). Projected increases in mean temperature could double the dengue burden in New Caledonia by 2100 (Teurlai et al., 2015). **In the Caribbean, Saharan dust transported across the Atlantic can**

[66] WGII Chapter 15 ES

[67] WGII Chapter 15. Section 15.3.4.1

[68] WGII Chapter 15. Section 15.3.4.2

[69] WGII Chapter 15. Section 15.3.4.2

interact with Caribbean seasonal climatic conditions to become respirable and contribute to asthma presentations at the emergency department (See Table 15.5; Akpinar-Elci et al., 2015).[70]

LIMITS TO ADAPTATION AND ADAPTIVE CAPACITY

At 1.5°C, limits to adaptation will be reached for several key impacts in SIDS, resulting in residual impacts, as well as loss and damage (Section 1.1.1, Cross-Chapter Box 12 in Chapter 5). Limiting temperature increase to 1.5°C versus 2°C is expected to reduce a number of risks, particularly when coupled with adaptation efforts that take into account sustainable development (Section 3.4.2 and 5.6.3.1, Box 4.3 and 5.3, Mycoo, 2017; Thomas and Benjamin, 2017). Region-specific pathways for SIDS exist to address climate change (Section 5.6.3.1, Boxes 4.6 and 5.3, Cross-Chapter Box 11 in Chapter 4).[71]

Risks to natural and human systems are expected to be lower at 1.5°C than at 2°C of global warming (*high confidence*). This difference is due to the smaller rates and magnitudes of climate change associated with a 1.5°C temperature increase, including lower frequencies and intensities of temperature-related extremes. Lower rates of change enhance the ability of natural and human systems to adapt, with substantial benefits for a wide range of terrestrial, freshwater, wetland, coastal and ocean ecosystems (including coral reefs) (*high confidence*), as well as food production systems, human health, and tourism (medium confidence), together with energy systems and transportation (*low confidence*).[72]

Current ecosystem services from the ocean are expected to be reduced at 1.5°C of global warming, with losses being even greater at 2°C of global warming (*high confidence*). The risks of declining ocean productivity, shifts of species to higher latitudes, damage to ecosystems (e.g., coral reefs, and mangroves, seagrass and other wetland ecosystems), loss of fisheries productivity (at low latitudes), and changes to ocean chemistry (e.g., acidification, hypoxia and dead zones) are projected to be substantially lower when global warming is limited to 1.5°C (*high confidence*).[73]

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[70] WGII Chapter 15 Section 15.3.4.2

[71] SR 1.5C, Box 3.5

[72] SR1.5C ES

[73] SR1.5C ES

6. RESEARCH GAPS

Despite intensive study, many knowledge gaps remain due to the complexity of biophysical and social interactions as well as the local and regional diversity of small islands. Research and data gaps exist in four areas: island-scale data availability; ecosystem services data; vulnerability and resilience, and adaptation. [74]

Research gap	Elaboration
Unavailability of adequately downscaled climate data	There is a lack of oceanographic (e.g., tidal), meteorological, high-resolution topographic and bathymetric data, as well as future sea level and wave climate projections for most islands, which severely constrain modelling studies and therefore improved understanding of future coastal flooding, erosion, and rates of saline intrusion into aquifers (Giardino et al., 2018; Lal and Datta, 2019)
	There is a need for further developing context-specific numerical models, especially through the inclusion of sediment transport, production and delivery (Shope and Storlazzi, 2019), coastal and marine ecosystems' responses (Beetham et al., 2017), and various societal responses (e.g., engineering and ecosystem-based solutions (Giardino et al., 2018)) under different climate change and SLR scenarios
	The complexity and specificities of small island environments and unavailability of robust baseline data considerably challenge modelling studies in small islands contexts, as reflected by the serious limitations of global modelling impact studies for these (Mentaschi et al., 2018; Vousdoukas et al., 2020)
	Data and model developments are therefore urgently needed to assess the future habitability or exploitability of the islands that are the most critical to small island countries and territories, and to help identify and promote appropriate (especially in technical terms) solutions
	Adequately downscaled Regional Climate Model (RCM) data (sub-5 km^2) is also required to conduct modelling assessments for small island terrestrial ecosystems. This is particularly needed for islands with complex topography which could be important in providing much-needed climate refugia for the survival of narrow range species such as endemics (Balzan et al., 2018). Such spatial data could be used to maximise the potential of islands to deliver critical ecosystem services (Katovai et al., 2015; Balzan et al., 2018)
	Widely used WorldClim data may not be suitable when applied to the small island context (Box CCP1.1). Without such data, robust ecosystem-based adaptation strategies such as climate-smart PA planning and management under changing climate conditions cannot be developed
	Thomas and Benjamin (2017) highlighted the lack of data as an area of concern related to assessing loss and damage at 1.5°C. Understanding losses and damages also requires more detail on island-specific losses and damages accruing from anthropogenic climate change impacts. At the moment, such assessments are limited, and most of the small islands have not yet documented these factors in their national adaptation plans or policies (Handmer and Nalau, 2019). There is a need for specific studies also on biophysical variables and species (e.g., impact of temperature rise on mangroves); long-term impacts of ocean acidification on species, including relationship to disease outbreaks, and changing breeding grounds of marine species and impacts on fisheries and marine-based livelihoods; incorporating biophysical feedback and interconnectivity of environments into models; and more detailed datasets (e.g., bathymetry, coastal assets) (World Bank, 2016; McField, 2017; Wilson, 2017)

[74] WGII Chapter 15 Section 15.8

Vulnerability and resilience	There is need for new research that investigates the variability of vulnerability within and between islands and states, typologies of best practice (Oculi and Stephenson, 2018), frequency of knowledge sharing among islands and regions (Foley, 2018), identification of regional framework mechanisms, and mapping the complex impact and hazard interactions at a regional scale (Duvat et al., 2017b; Neef et al., 2018; Scandurra et al., 2018; Thiault et al., 2018). Research needs to also examine resilience-building efforts within the four domains of islandness (boundedness, smallness, isolation, and littorality) to effectively capture subjective nuances associated with climate development efforts on islands (Kelman, 2018)
	Research gaps in place-based assessments of social service bundles coupled with policy actions (Balzan et al., 2018) highlight the need for new knowledge to strengthen communication, collaboration and networks between academia, donors, the private sector, community and government (Allahar and Brathwaite, 2016; Schipper et al., 2016) so as to improve understanding of vulnerability and resilience in small islands
	A paucity of research exists currently on the vulnerability of island ecosystem services to climate change (Balzan et al., 2018). While there is rich scientific evidence on the pressures of habitat loss and degradation, impacts of natural hazards and invasive species, far less is known about the interactions of these factors with adaptive capacity and livelihood conditions on islands. In small island contexts, there is a specific need for assessing the effectiveness and cost of ecosystem- and community-based solutions where the latter have been implemented (Filho et al., 2020). The design of generic assessment methods and tools is required to allow for comparative analyses that will, in turn, provide useful guidance for the promotion of context-specific adaptation strategies (Blair and Momtaz, 2018). For many of the small islands, especially SIDS, the economic valuation of marine and coastal ecosystem services—coastal protection, fisheries, tourism—is of great importance, as well as the subsequent losses in these sectors and related livelihoods due to climate change impacts (Waite et al., 2014; Schuhmann and Mahon, 2015; World Bank, 2016; Layne, 2017; Duijndam et al., 2020). There are few integrated modelling studies to inform future habitability of differentiated small island types and how these models can inform decision support processes for ridge to reef stewardship (Povak et al., 2020). Existing studies (Rasmussen et al., 2018) have progressed knowledge since AR5, but island-specific analyses are required to robustly estimate the future ability of land to support life and livelihoods, taking into account multiple climate-drivers, future population exposure, and adaptation responses
	More research is also needed in understanding how ecosystem benefits are modified under changing climate conditions and how these benefits can be quantified (Doswald et al., 2014). For example, many small islands lack comprehensive (and disaggregated) data related to food security, which makes it challenging to attribute climate impacts on local food systems (Taylor et al., 2019). Balzan et al. (2018) highlight the importance of quantifying the role of biodiversity in delivering key ecosystem services and demonstrate how such data could provide insights into the interrelatedness of island ecosystems and transboundary service benefits
Adaptation	In the last decade or so, there has been a significant increase in climate-related financing for small island states. However, monitoring and tracking of funding and metrics to evaluate overall impact are lacking (Boyd et al., 2017; Mallin, 2018). Research into adaptation costs could benefit from the inclusion of indirect effects of climate change such as psychological costs (Vincent and Cull, 2014; Gibson et al., 2019) but to date this research is missing. Greater effort could also be placed on quantifying the relationship between adaptation costs and adverse events (Adelman, 2016). There is also a need for overall land use planning guidelines in small coastal communities, including small islands (Major and Juhola, 2016). The usefulness and utility of insurance mechanisms for building resilience to climate hazards require up-to-date information on assets at risk (Tietze and van Anrooy, 2018) and further exploration of adaptation measures in small island contexts (Baarsch and Kelman, 2016). Additionally, the differences between theoretical adaptation practices and observed results from actual implementation, along with the integration of IKLK and external knowledge, are currently not well understood (Mercer et al., 2014b; Kelman, 2015b; Saint Ville et al., 2015; Robinson and Gilfillan, 2016; Robinson, 2017b). Documenting experience-based knowledge of adaptation projects and programme implementation could fill important data gaps. At the project design stage, the paucity of climate finance data is a barrier to accessing climate finance (Bhandary et al., 2021)
	Although studies examining the association between climate and weather extremes, events and conditions and mobility in small islands have increased since AR5 (Birk and Rasmussen, 2014; Kelman, 2015a; Connell, 2016; Stojanov et al., 2017; Barnett and McMichael, 2018), few studies robustly examine the attribution of migration of small island populations, communities and individuals to anthropogenic climate change and other non-climate migration drivers. Biophysical, socioeconomic and in situ adaptation thresholds that force small island populations to migrate remain under-explored (Barnett, 2017; Handmer and Nalau, 2019). The implications of forced and voluntary immobility (Allgood and McNamara, 2017; Farbotko, 2018; Suliman et al., 2019), the socioeconomic, health, psychological and cultural outcomes of climate migrants, and gender dimensions of climate migration all remain under-researched
	Limits to adaptation is still a largely under-researched topic globally (Nalau and Filho, 2018) and specifically in small island contexts, as are the linkages between adaptation limits, loss and damage and transformative adaptation (Thomas et al., 2020). In terms of projected risks and adaptation responses, further work is needed to improve knowledge of commonalities, differences, successes, and failures of natural and human adaptation responses (Kuruppu and Willie, 2015). One of the failings of the current literature on limits to adaptation revolves largely around the use of barriers for sector-specific or small-scale scenarios, which provides an understanding only for that particular scenario and does not identify common constraints (Kuruppu and Willie, 2015). Research gaps on loss and damage include: how to assess the economic costs of loss and damage; mechanisms to develop robust policies in small island contexts; specific data on experienced loss and damage across socioeconomic groups and demographics; monitoring and tracking of slow-onset events (Thomas and Benjamin, 2017; Thomas et al., 2020) and the non-economic aspects including sense of place, health and community cohesion (Thomas and Benjamin, 2019)
	More studies are needed on the role that organisations (international, national and regional) play in adaptation efforts—their effectiveness at achieving desired outcomes, roles and accountability (Robinson and Gilfillan, 2016; Scobie, 2016; Mallin, 2018). It is also important that the impacts of sociopolitical relations inter-state are researched (Belmar et al., 2015) and more focus on climate justice (Baptiste and Devonish, 2019; Moulton and Machado, 2019; Gahman and Thongs, 2020) and gender is similarly needed (McLeod et al., 2018). Given the high number of place-specific case studies in the adaptation literature, more reviews are needed that synthesise key lessons and principles of adaptations in small island contexts from this knowledge. Further research is also needed to capture the lessons from COVID-19 response in small islands and how these could enable more robust adaptation and climate resilient development transitions as has been suggested at a broader scale by Schipper et al. (2020). There is also little to no information on impacts upon terrestrial and freshwater biodiversity from the relocation of coastal human populations inland due to SLR

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[75] WGII Chapter 15 Table 15.8: Research gaps in small islands