TAB 1

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Article

Measuring Temperature in Coral Reef Environments: Experience, Lessons, and Results from Palau

Patrick L. Colin [1,*] and T. M. Shaun Johnston [2]

1 Coral Reef Research Foundation, P.O. Box 1765, Koror 96940, Palau
2 Scripps Institution of Oceanography, University of California, San Diego, La Jolla, CA 92093, USA; tmsjohnston@ucsd.edu
* Correspondence: crrfpalau@gmail.com

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Abstract: Sea surface temperature, determined remotely by satellite (SSST), measures only the thin "skin" of the ocean but is widely used to quantify the thermal regimes on coral reefs across the globe. In situ measurements of temperature complements global satellite sea surface temperature with more accurate measurements at specific locations/depths on reefs and more detailed data. In 1999, an in situ temperature-monitoring network was started in the Republic of Palau after the 1998 coral bleaching event. Over two decades the network has grown to 70+ stations and 150+ instruments covering a 700 km wide geographic swath of the western Pacific dominated by multiple oceanic currents. The specific instruments used, depths, sampling intervals, precision, and accuracy are considered with two goals: to provide comprehensive general coverage to inform global considerations of temperature patterns/changes and to document the thermal dynamics of many specific habitats found within a highly diverse tropical marine location. Short-term in situ temperature monitoring may not capture broad patterns, particularly with regard to El Niño/La Niña cycles that produce extreme differences. Sampling over two decades has documented large T signals often invisible to SSST from (1) internal waves on time scales of minutes to hours, (2) El Niño on time scales of weeks to years, and (3) decadal-scale trends of +0.2 °C per decade. Network data have been used to create a regression model with SSST and sea surface height (SSH) capable of predicting depth-varying thermal stress. The large temporal, horizontal, and vertical variability noted by the network has further implications for thermal stress on the reef. There is a dearth of definitive thermal information for most coral reef habitats, which undermines the ability to interpret biological events from the most basic physical perspective.

Keywords: water temperature; coral reefs; internal waves; upwelling; advection; climate change; coral bleaching

1. Introduction

Water temperature is the most easily quantified physical parameter for shallow-water tropical marine environments. Satellite-derived sea surface temperature (SSST) is used by coral reef scientists for global perspectives on temperature (hereafter abbreviated as "T") patterns/trends and coral bleaching status/predictions [1–5]. There is an "implicit assumption" [6] regarding SSST data that "surface temperature metrics provide useful environmental information with respect to corals that typically live meters to tens of meters below the surface". Satellite data have been thoroughly accepted to document patterns of sea surface T (SST) [3,4,7] to such an extent that some studies concerning coral bleaching do not employ any in situ data, relying solely on SSST [8–12]. The 1998 La Niña warmed the waters around Palau and the western Pacific, which caused coral bleaching, high mortality, and the degradation of reefs [13]. In response to this event, a network of in situ T measurements was initiated in Palau to understand SST variability and its effects on reefs (Figure 1). While SSST describes the broad spatial and temporal patterns, this network reveals large amplitude changes, on periods of minutes to years on the outer reef slopes, some of which are invisible to SSST. The overall Palau network presently comprises over 70 stations and 150 compact T loggers (TL), which are deployed by divers [14]. This paper mainly offers guidance from experience on how to set up and maintain an extensive "value-added" T monitoring network in a coral reef area.

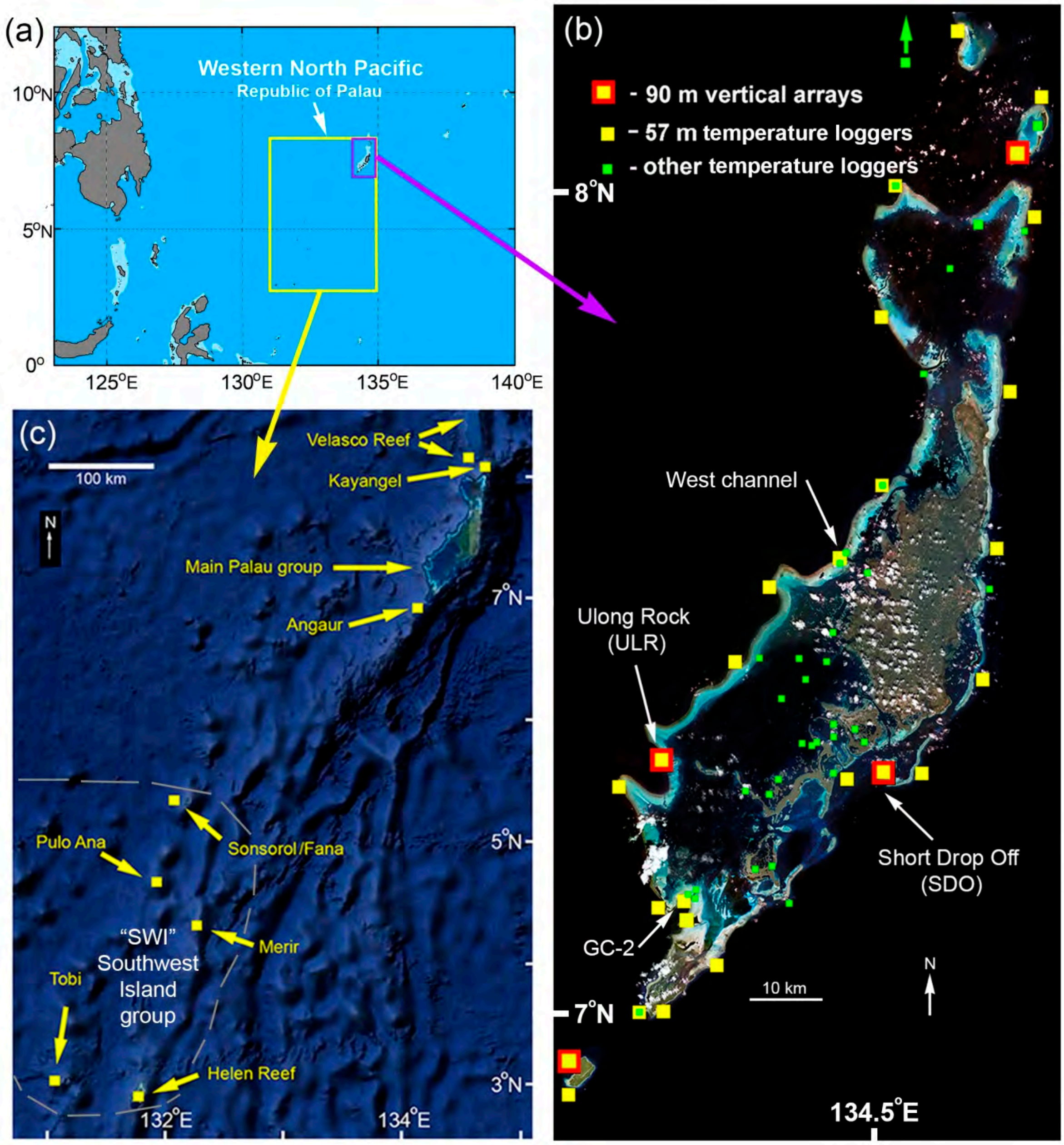

Figure 1. (**a**) General map of the western North Pacific with the location of Palau indicated. The areas shown in (**b**) and (**c**) are indicated by purple and yellow boxes respectively. (**b**) Locations of main temperature monitoring arrays and stations (Ulong Rock, Short Drop Off, GC-2 German Channel, Western Channel) on the outer slope and lagoon regions of Palau. (**c**) Locations of temperature logger stations in outlying areas of Palau, including the Southwest Islands group (SWI) and northern Ngeruangel/Velasco Reef area.

Three concerns about SSST versus in situ data belies uncritical acceptance of the implicit assumption: (1) accuracy compared to shallow (less than 5 to 10 m depth) in situ conditions; (2) diurnal T changes occurring in the upper few meters of the water column; (3) vertical and horizontal variation in thermal conditions. SSST is determined via emitted infrared radiation from the uppermost 20 μm of the water column ("SSTskin") with a 1 to 4 km horizontal resolution and microwave radiation from the upper 1 mm sub-skin ("SSTsubskin") with a circa 25 km resolution [15]. T immediately below these thin layers ("near-surface SST") is not measured by satellite but comes principally from drifting buoys (Global Drifter Program, 20 cm probe depth) and shipboard measurements (various shallow depths of 1 m or more) and are then used to validate SSST data [2]. Oceanic moorings with T probes along their length, such as TAO/TRITON (the nearest to Palau is 260 km away) and ARGO profiling floats (which do not regularly measure T above 5 to 10 m depth) do provide some data at coral reef depths, but almost always in the open ocean far distant from reefs [16]).

The diurnal daytime T changes in the upper few meters of the water column are "visible" to satellites, but not captured as SSST. Solar heating warms water over very shallow reefs [14] with minimum daily SSST measured near dawn [17]. Diurnal patterns expose reefs to higher potential heat stress during the day and important heat content information is lost using only nighttime data. Very shallow stratification can occur, particularly with low wind speeds and calm seas, while wind, waves, and tidal currents can increase shallow mixing and advection of heat at other times. At some depth below the surface, usually a few to several meters, the diurnal heating signal is largely lost, and T remains diurnally stable [14], often to depths of tens of meters. In summary, [15] provide a similar framework for discussing SST defining SSTskin (upper 20 μm), SSTsubskin (upper 1 mm), SSTdepth (about 10 m), and SSTfoundation > 10 m). For our purposes, we refer to SSTskin and SST subskin as SSST. SSTdepth has diurnal variation and SSTfoundation has none. To make sense of these data, environmental conditions at the time of acquisition must be taken into account. On and near reefs, these conditions show extreme variability in periods ranging from minutes to decades, as we show below, some of which cannot be detected in SSST. We focus mainly on SSTdepth and SSTfoundation.

Photophilic reefs occur from the shallows (upward limits determined by sea level) to over 100 m depth in clear tropical waters [18]. Detailed measurement/analysis of thermal patterns over depth ranges and time across a reef tract indicate SSST has a limited capacity to capture the dynamics in the environment [19–21]. On outer slopes once below the diurnally variable depths (usually a few to several meters), "foundation" T in most tropical-subtropical reefs is relatively stable for a few tens of meters. Descending further, however, T (and light levels) decreases in the deepest areas of reefs experiencing consistently lower T, all invisible to satellites. Moving horizontally from ocean slope to inner lagoon or channel areas T patterns vary, but inshore areas are generally warmer. Tidal currents advect water from the ocean to a lagoon (or the reverse) moving shallow water masses of different T/salinity across environments. Adjacent landmasses may influence T in lagoons or over fringing reefs. Even the 5 km pixel size of thermal remote sensing [22] still limits the ability to measure skin T in many areas due to their geography.

The vertical distribution of T over different time scales (decades to minutes) can differ considerably from SSST. During La Niña, Palau's reef waters are warmest. In addition, SSST and 2 m depth in situ values are relatively close, but correlations decrease for in situ data at 15 and 35 m [14]. During ENSO neutral conditions, SSST correlations with in situ T decrease at all depths compared to La Niña. During El Niño, the thermocline shoals and cool water is brought closer to the surface. Surface waters remain relatively warm but the correlation of SSTdepth and deeper in situ data are low, while SSST can be several degrees warmer. Near the lower depth limits of photophilic reefs in Palau (roughly 60 to 70 m) differences between SSST and in situ data are even larger (as much as 12 to 15 °C), with high daily variation in T over both short (min to hours) and long periods (weeks to years, ENSO related).

Accepting that SSST is not a panacea for all consideration of T on coral reefs and that the "implicit assumption" may not be universally applicable, increased in situ measurements are needed to understand the scale of differences in thermal conditions on broad reef areas over depth and time. Only accurate in situ reef T data, the "gold standard" [14], can inform researchers and managers regarding how representative are SSST data and to move beyond generalized SSST values to understand that each locality and habitat is different. For most reef areas, a broad reach of monitoring efforts (temporal, vertical, horizontal) is needed to document representative conditions.

2. Materials and Methods

2.1. Palau and It's Monitoring Network

The Republic of Palau is a western Pacific country with extensive and diverse reef systems located at 3° to 8° N (Figure 1). An extensive barrier/fringing reef (300 km in length) surrounds the main island group. Several lagoons total nearly 1000 km^2 in area with many reefs [23] inside the barrier reef. Reefs are found along or close to the shores of islands, producing close interactions between reefs and land masses. Within 50 km of the main Palau reef tract, an oceanic island (Angaur), a small atoll (Kayangel) and a large sunken atoll (Ngeruangel/Velasco Reef-area 400 km^2) occur. Five oceanic islands and one atoll, collectively called the Southwest Islands (SWI) occur 300 to 500 km southwest from the main reef/island complex (Figure 1c). Found at 3° to 5° N, the SWI are usually within the flow of the eastward North Equatorial Counter Current (NECC). The main group, centered on 7° N, lies at the southern edge of the westward North Equatorial Current (NEC) but is impacted by the NECC as it shifts northward seasonally and during ENSO.

Palau is ideal for examining tropical upper ocean T variability over broad to fine spatial and temporal scales. It has a narrow annual shallow-water T range (1.5 to 2.5 °C), but high variation (over 15 °C) in daily/weekly means in the deeper photic zone. It experienced a major coral bleaching event in 1998 [13], a lesser event in 2010 [12], and a series of small localized events in other years [23]. In 1998, excessively warm water caused loss of zooxanthellae (bleaching) in reef corals resulting in high mortality and degradation throughout the depth range of reefs [13]. At that time there was no accurate T data for Palau's reefs, but in the wake of that event efforts to document Palau's ocean T were started. In 1999, an outer reef vertical array of 5 TLs at depths of 2, 15, 35, 57, and 90 m was set up at Short Drop Off (SDO) on the eastern barrier reef (Figure 1b). Concurrently, a few TLs were installed on shallow inshore/lagoon reefs. Initial array results indicated rapid and extreme variations at the 57 and 90 m stations on the profile. In 2000, a second equivalent array was established at "Ulong Rock" (ULR) on the western barrier reef [24], which recorded some of the largest isothermal vertical displacements ever. Since then the network has expanded to over 70 stations with 150 TLs, ranging from all of Palau's SWI to the north reefs (Ngerunagel/Velasco Reef) with broad coverage of habitats and depths within lagoon areas.

To look at deep reef internal waves, a new initiative deployed TLs in 2014 at 57 m depth at 27 stations, which were widely distributed on the outer slopes of the main Palau reef tract, Kayangel Atoll, Angaur Island, and Velasco Reef. Called the "deep network", they record T once a min, each recording 525,600 measurements every regular year. The depth of 57 m was selected due to the high variability during both El Niño and La Niña periods seen in vertical array data and was a depth from which reasonably easy recoveries/deployments were possible by experienced divers. The deeper stations of the four 90 m depth vertical arrays along Palau's main reefs (Figure 1b) also switched to one-min interval data collection in 2013. In 2015, the deep network was extended to the SWI with five 57 m stations (now six), along with shallower loggers at each location. The deep network, as of January 2020, has recorded 110 million high-resolution T measurements while the remainder of the Palau network accounts for about 10 million more.

Do outer reef slope TL data accurately represent T profiles found in adjacent deep ocean? During 2009 to 2019, Spray autonomous glider missions for Office of Naval Research initiatives [25–27] gathered data on T. At the start and end of wide-ranging missions, data were collected within a few km of the reefs (surface to 200 to 500 m depth) for several days. There was close agreement between open ocean glider and outer slope TL data [28,29].

2.2. Selection of Stations

Care in selecting monitoring station sites is important, particularly where geomorphology or oceanographic conditions may influence thermal conditions. The initial outer reef (SDO and ULR) array sites simply added temperature monitoring to ongoing ecological work, but additional outer reefs stations were subsequently positioned to provide geographic/habitat diversity, such as adding stations on the North and South slope to supplement those on East and West. At some level station selection is "logical" but as a network develops, specific sites may be selected solely on the basis of having an interest in knowing of a detailed area, without knowing in advance whether that station will prove interesting (or not). Lagoon and island stations can be located in what are considered "typical" sites where results may be representative of similar habitats. If a truly distinctive habitat is present, stations can be located to delineate the specific conditions found there, which may differ from nearby areas.

Accessibility during most weather conditions and ease in locating them via distinctive surface/shallow features are advantageous. Each site, even with distinctive features, needs its position established by GPS to a resolution of 0.001′ (circa 1.8 m) and recorded, allowing the site to be located if weather is poor and visibility limited. Sites can also be selected based on additional scientific interest, with other long-term studies being undertaken concurrently (e.g., photo transects) without the need for a separate field trip. T records from such study sites are useful when events (coral bleaching, storms) occur and thermal data are relevant. Stations located in broad shallow areas such as barrier reef tops, that may be accessible only at spring high tides, are often disturbed by storm events and may have few distinctive features (i.e., large coral heads) making relocation of TL instruments difficult. Hence, the need for greater care in choosing sites in these areas is implied and using all available methods to ensure that they can be located later for TL exchange.

2.3. TLs and Their Mounting: Considerations Regarding Installation and Deployment of Instruments

Four types of T loggers have been used: (1) Onset Hobo Pro-8; (2) Onset U22 loggers; (3) Seabird Electronics (SBE) 56; (4) RBR Solo loggers, all relatively small and lightweight. Four factors determined the preferred unit for a station: resolution/accuracy, sampling interval, memory capacity, and response time. In the present effort, target accuracy was 0.1 °C, with a higher precision of up to 0.01 °C with the SBE and RBR loggers. The target accuracy was probably a reasonable compromise compared to SSST data, which is also presented as 0.1 °C. Given the many aspects of variation at individual stations for bleaching indices, the existing accuracy is satisfactory especially considering some of the large amplitude signals.

For all TLs it is important to have a weight attached so it has extra negative buoyancy. The Onset U22 is positively buoyant, the RBR Solo near neutral, and the SBE 56 slightly negative. Instruments and attached weights were deployed, either fixed to the bottom or placed unattached (free) onto the bottom. Mounting instruments on a mooring with float and anchor is risky, as the unit may drift away if the mooring anchor fails, and not advised.

2.4. Characteristics of Instruments

1. Onset Hobo-Pro-8 (Onset Computer Corp., Bourne, MA, USA), units (used 1999 to 2006) recorded to 0.01 °C precision but had to be installed in water/pressure proof housings with only their cabled thermistor probe exposed. Other disadvantages were: limited memory (11 months at a 30 min sampling interval); limited battery capacity; the need to disassemble the housing to replace batteries and download data; continuous problems with leaking in the complicated housing/probe system. This caused some unacceptable loss of data in the early years of the program.

2. The Onset Water Temp Pro 2 (U22)(Onset Computer Corp., Bourne, MA, USA), is (2004 to present) pressure-proof to 120 m depth, has easy deployment, recovery, and download with batteries lasting several years over multiple deployments. With a 30-min sampling interval, the memory records for

two and a half years. Disadvantages are positive buoyancy (requires attachment to a weight), slow response time, a special adapter needed for deployment/download, and difficult battery replacement (return to manufacturer). Details are described subsequently. Cost: US $129.

3. The SBE 56 (Seabird Electronics, Bellevue, WA, USA) (2010 to present) has been reliable, but expensive (four to five times the cost of the Onset U22). Advantages are high resolution, quick response time (exposed probe), long battery life, large memory, and simple set-up and download. It has been used for deep-water stations where rapid thermal changes occur, as well as areas with one to three-year recovery/deployment intervals.

4. The RBR Solo (RBR Ltd., Ottawa, ON, Canada) is similar to the SBE 56 in capabilities/cost and is slightly shorter in length. Advantages are comparable to the SBE 56, but some data have been lost due to power (battery) glitches while deployed. This is presently used in "low priority" locations, where loss of data is not as dire, needing short sampling intervals.

5. Other oceanographic instruments (Onset pressure loggers (Onset Computer Corp., Bourne, MA, USA), Acoustic Doppler Current Profilers, wave gauges, conductivity T loggers) have provided additional T data to the program and their data are considered supplementary, not primary. In a few cases, fast logging dedicated T loggers were attached to longer interval sampling ADCPs or others. Direct data comparisons indicate they can be acceptable substitutes for dedicated TLs.

There are other brands and models of TLs available, but none were used in this project.

2.5. Calibration of TLs

New TLs were calibrated in a water bath at 20 to 31 °C before deployment to establish baseline accuracy against a NIST traceable mercury thermometer, as well as cross calibrating each with other new TLs and older units between deployments. Later re-calibration (between deployments) used similar methods. The target accuracy for all measurements was 0.1 °C.

For calibration, all TLs were set to start simultaneously with a 1-min interval. They were bundled together using rubber bands or similar, placed with probes down while immersed in a circulating water bath and equilibrated for 5 min or more prior to measurements. The mercury thermometer, its bulb situated at the level with the thermistors, was read using a magnifier to 0.02–0.03 °C resolution on the minute when TLs logged values. Calibration runs lasted 30 to 120 min at various T in the water bath. After downloading, data were entered into a spreadsheet comparing each TL against all others in the run and the mercury thermometer. A correction factor was calculated for each logger and applied if needed.

2.6. Sampling Intervals

The measurement interval is a compromise between memory size, battery life, and desired temporal resolution. For most stations with depths less than 35 m, a 30 min interval was used. An Onset U22 with a new battery would have adequate battery life for five to six years at that interval, thus although memory-limited, a new unit could be deployed for two successive periods of 2+ years. In a few instances where Onset U-22 TLs needed to be deployed for over two and a half years, a 1-hr interval was selected to extend memory duration [30].

For thermally active stations SBE 56 or RBR TLs sampled at 1-min intervals. An Onset U-22 sampling at this interval would fill its memory in only 30 days, thus such short sampling intervals were only practical with the more expensive SBE and RBR loggers. At stations where only minor variation in T is anticipated, deployment of high-resolution SBE and RBR TLs may be appropriate if there is a need to verify low variation.

Software for TLs (Hoboware 3.7.18, Onset Computer Corp., Bourne, MA, USA; Seaterm V2, Seabird Electronics, Bellevue, WA, USA; Ruskin 2.10.4, RBR Ltd., Ottawa, ON, Canada) allowed for delayed starts and if several TLs are prepared for array deployment, they should be set to start logging at the same time. Data logged prior to deployment or after recovery should eventually be deleted after download and carefully noting times of first/last good samples (the time the unit is at the proper depth, not just in the water) will allow data to be deleted. Often shallow TLs were recovered while descending to retrieve deeper units, and logged low Ts on such excursions, which needed to be deleted afterward.

2.7. Preparation of Instruments for Deployment

Onset U22. If deployed/recovered by a diver they are best mounted on individual 1 to 2 kg weights, such as the lead weights used for SCUBA diving (Figure 2a). A vinyl plastic cap is placed over the wide "download" end of the TL, to protect the clear plastic window, and the remainder of the TL wrapped in plastic or electrical tape to reduce biofouling. The thermistor is inside the housing near the mounting lug of the housing and this area should be exposed to the water to retain response time.

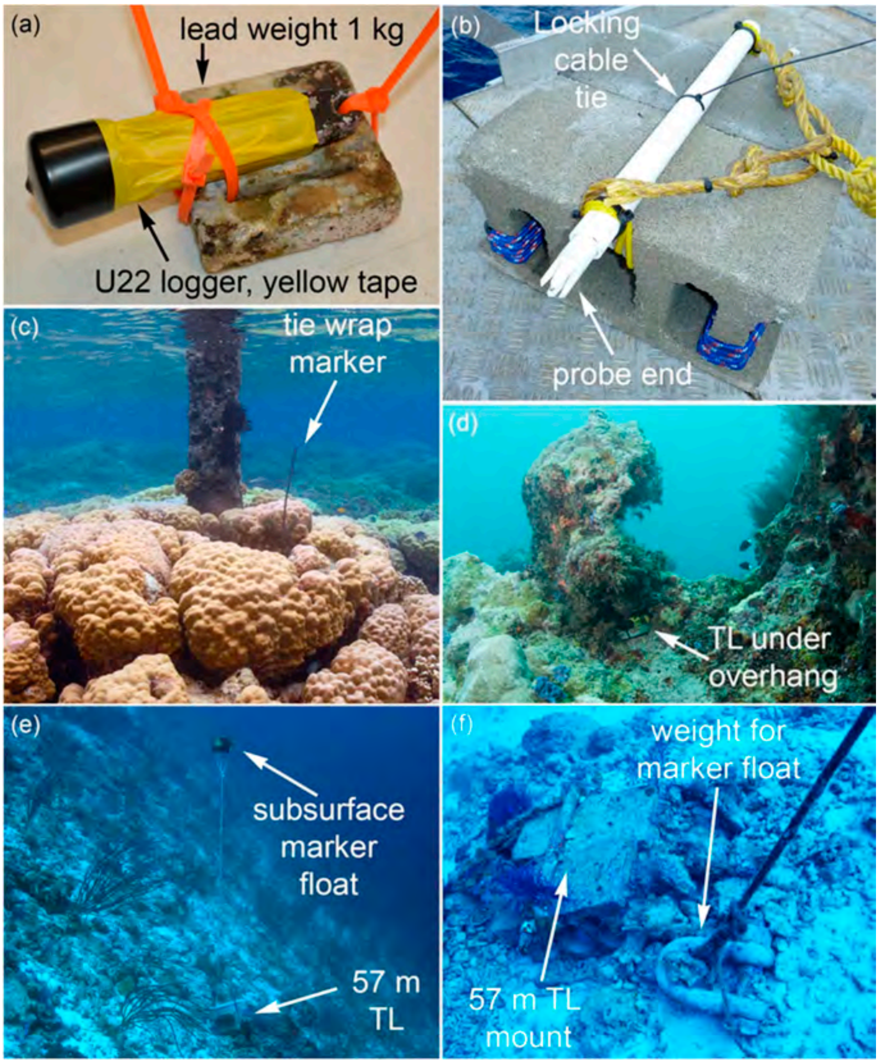

Figure 2. Various TL deployment methods. (**a**) Onset U22 mounted on dive weight with cable ties. (**b**) Deep network (57 m) mount with a tube for SBE or RBR TL, cable tie lock shown. The line shown used was only for lowering the mount to the bottom, then cut and removed. (**c**) Location of U22 temperature logger (TL) on a very shallow reef positioned in a crevice for protection from direct sunlight, and its location indicated by a large cable tie. (**d**) U22 TL on a reef, rarely (if ever) visited by divers, attached by cable tie and openly visible to aid in locating it for recovery. (**e**) Deep network station (T05) on a steep slope at 57 m depth with marker float to assist in locating the instrument. (**f**) T05 station after five years on the bottom, TL mounting tube attached to two concrete blocks. The logger was exchanged each year for a fresh unit. A marker float is on a line with separate weight (a 15 kg shackle) and not attached to the TL mounting.

One way to install the TL on a weight is to drill a 1/4 to 3/8-inch diameter hole in one margin of the weight. The TL, wrapped in tape with plastic cap in place, is then attached using three plastic cable ties (also known as "zip ties"); one going through both the hole drilled in the weight and the mounting lug of the TL, while two others overlapping diagonally are used to secure the TL at the opposite corners of the weight (Figure 2a). If drilling a hole is inconvenient, additional cable ties help to secure the TL to the weight. Cable ties are readily available, inexpensive, and easily cut if needed. It is tempting to simply attach Onset U-22 loggers to the bottom using a cable tie or similar through the mounting lug and then attaching that to something solid on the bottom. The Onset U22, however, is positively buoyant and if the cable tie fails (which occurs surprisingly often with upward force on the latching mechanism), the unit will drift away. If secured to a weight by at least three cable ties, it is improbable for all to fail and the unit to drift away.

SBE 56 and RBR Solo. These cylindrical TLs have a 25 mm outside diameter, fitting inside a 12 inch (30 cm) long piece of 1-inch (25 mm) inside diameter PVC plastic pipe. The bore of the pipe is usually slightly oversized inside (26 mm), a close fit for the TL but still with some clearance. The TLs, a mounting lug with a 5/16" (8 mm) diameter hole on one end and exposed probe on the other, can be inserted inside the pipe to a level so only the probe end of the TL is exposed (Figure 2b). Holes of 3/8 to 1/2" diameter (10 to 13 mm) pre-drilled through the PVC pipe at the correct distance allowed a single cable tie to be inserted through the tube walls and mounting lug, then secured back on itself, to lock the TL into the tube. If holes in the tube for the cable tie "lock" are too small (1/4" or 6 mm diameter), this can make inserting the cable tie at depth difficult. The TL can be exchanged at depth by a diver cutting and removing the single cable tie, pulling the TL out of the tube, inserting a new unit to the correct level, then inserting new cable tie and locking in place. The SBE and RBR TLs are of different lengths and require holes at different distances along the tube (19/26 cm) to have just the probe exposed. When preparing mounting tubes, it is convenient to drill holes at the correct distance for either type of TLs, so tubes are interchangeable.

A completed mounting tube (with or without the TL already installed) can be attached to a 1 to 2 kg weight or another object for securing on the bottom. For the "deep network", standard mountings were made from two concrete blocks tied securely together and with the mounting tube permanently installed on one surface (Figure 2b,f). The blocks and tube are not recovered, instead the diver exchanges the TL by cutting the retaining cable tie, pulling out the TL, inserting a new TL to the proper level in the tube, and then inserting and locking in place with a new cable tie. With practice, this can be accomplished on the bottom in less than 1 min. The recovered TL is placed in a mesh bag carried by the diver and brought up. The time of recovery to the minute should be noted to establish "last good" and "first good" values for the deployment. Mounting instruments on moorings consisting of an anchor weight (or line tied to the reef), line and float is not recommended. They can easily drift away if the mooring fails. In some cases, marker floats are helpful in finding TLs, particularly if diving from a shot line (Figure 2e), but if marker floats are desired, they should be installed separate (unattached) from the TL itself (Figure 2f).

2.8. Divers and Diving Deployments

Nearly all TL deployments were done by free-swimming divers. To depths of 35 m, TLs were readily deployed by recreational-level trained divers. Using nitrox (oxygen-enriched air), instead of compressed air, allows extended bottom times at or quicker repetitive dives to 30 to 35 m depth. Deeper deployments and exchanges were accomplished using deep-air diving (to 60 m) or trimix (helium/air) gases (60 to 95 m depth), requiring specialized training and equipment. Such "technical diving" has become increasingly common, and given the proper equipment, training, and planning, it is feasible to diver deploy/recover TLs to depths of 100 m [31]. In Palau, there were numerous individuals, usually working in the tourism dive industry, who were capable of doing this type of diving; not an unusual situation considering the worldwide development of diving tourism.

2.8.1. Shallow Deployments

"Shallow" TL deployments are considered to range from the surface layer to the depths of 30 to 40 m with no decompression diving. Across this range, different conditions are encountered, and deployments optimized for the conditions expected. A primary consideration when deploying is the ease with which a TL can be located and recovered months to years later. Over time it may become covered in marine growth or the structure to which it was attached crumbled or gone.

TLs secured to a small weight may be put out on the reef, either free on the bottom (not secured, but in a location where their weight makes it unlikely to be moved by currents or waves) or attached to the bottom. The use of SCUBA weights for TLs has the advantage that the belt loops designed into them are convenient openings through which to run cable ties to secure them to the bottom (Figure 2a). Cable ties come in various lengths, making it easy to go around large objects or to thread through small openings for securing TLs (Figure 2d). Often an area of rocky reef will have small rock arches where the TL can be secured by a long cable tie.

In some cases, it is easier not to attach a weight/logger to the bottom. If the unit is located in a slight depression where being moved is unlikely, it can just be dropped off without further attachment. Nevertheless, ideally all TLs should be attached to the bottom, even if only loosely, since if left unattached and it disappears, it is necessary to search around the site (often difficult at depth) and if not found, no reason can truly be ascribed to its loss. The trade-off is that it takes longer to deploy and recover the unit and in deep water seconds are important in this process.

2.8.2. Special Considerations for Very Shallow Sites

Sites less than 5 m deep should be considered "very shallow" and in areas exposed to waves and swell, the TL must be mounted in a manner capable of surviving very rough conditions. TLs securely attached to weights, still need to be attached as a unit to a strong point (rock) on the reef itself. Use of heavy-duty cable ties (strap width 3/8 inches or more, with a breaking strength of 100 kg or more) is the easiest method for securing units in rough areas. Multiple cable ties should be used, and efforts made to ensure the unit once secured cannot be moved, otherwise, over time the unit may work loose and be potentially lost.

2.8.3. Shelter for Loggers

In very shallow water, direct sunlight may heat a logger resulting in values in excess of in situ water Ts with an observed an increase of 1 to 3 °C for loggers (depending on model) submerged in a flow-through mesocosm, but openly exposed to the sun [32]. It is recommended to either place the logger in a location sheltered from direct sunlight or install a reflective shade over the unit.

2.8.4. Marking Sites

Whether or not to hide TLs on the reef is an important consideration. For shallow water deployments in areas frequented by divers or fishers using SCUBA/snorkeling equipment, it is critical to hide loggers so that they are not seen and picked up inadvertently. Once coated in biofouling, a TL often looks like something that has been lost, perhaps dropped from a boat; not something that has been put in place for scientific research. When TLs are hidden, tucked into crevices or beneath overhangs, it is important to be able to find them again. Marking the general site where a TL is located (but not the TL itself) is helpful, with cable ties attached to a rock or projection nearby as an easy solution (Figure 2c). Photographs of the area (Figure 2d) are also very helpful, covering the area nearby, showing marking cable ties or showing locations of features, which are distinctive to help identify locations of TLs.

In areas where someone finding and picking up a TL is unlikely, efforts can be directed instead at making the TLs more visible underwater and easier to find. Attaching a number of long cable ties (30 to 60 cm), either to the weight or in the areas of the TL, so they stick out in various directions are occasionally helpful in relocating TLs that have been deployed for some time (Figure 2c). The straight tails of the cable ties sticking out are distinctive, even if covered in algae. At times, cable tie tails sticking out of sediment from a buried TL has been the only portion of a TL visible and allowed recovery, otherwise the TL would have been lost.

Covering the TL in colored tape reduces biofouling and helps locate it (yellow is particularly distinctive; Figure 2a). Marking shallow sites with small floats aids visibility at some distance underwater. Careful notes should be taken on the nature of sites, times of deployment, exact depths (using a digital dive computer), and any other features that would help in recovery later.

2.8.5. Photos of Sites

Underwater photos of the sites, particularly showing the exact location where TLs are deployed, are important. Ideally, the TL should be visible in some photos (Figure 2d), to provide clues as to its location after it might be hidden in the reef. Underwater photo trails have proven particularly useful for locating sites on steep reef faces, with a shallow water (5 to 15 m depth) marker (sub-surface float, long cable ties) as a start point. A GoPro or similar camera taking time-lapse photos at 2-sec intervals helps document the routes swum when deploying the unit and can often be retraced if needed all the way to the location of the TL. This technique is especially helpful if the diver recovering the TL did not do the deployment.

2.8.6. Diving for Shallow Reef Deployments

If deployments are needed at depths of 30 to 40 m (the lower limits for "sport diving"), nitrox diving is advantageous as it allows increased bottom time (15 to 20 min) without decompression. If TLs are to be deployed/recovered at various depths moving along transects up a reef slope, the deepest should be done first, then move into shallower water. If doing a number of "swap-outs" of TLs, recovering old ones and setting out new ones, divers should have two mesh "dive bags"; one for recovered TLs and the second for ones to be deployed. The ones being deployed should be labeled indicating depth for each one to avoid confusion while diving. This prevents mistaking a just recovered TL for one that needs to be deployed, which is easy to do in the rush of a working dive.

2.8.7. Deeper Deployments

A number of countries, such as Australia and the United States, have regulations for the workplace and scientific diving which prevent (or make onerous) accessing depths below sport diving limits. Some offer dispensation to undertake advanced diving for research purposes [18]. In Palau, there were no regulations restricting experienced/trained individuals from undertaking the necessary dives to service the TL networks.

Careful selection of areas for deep deployments can simplify the diving involved, particularly for vertical arrays of several instruments. Near-vertical reef profiles are preferred, as this avoids divers having to make time-consuming horizontal or sloping swims between different depth stations. Reef markers, such as very long cable ties or subsurface floats, can be used to mark the route down the slope and individual stations to simplify finding TLs at depth. At the four vertical array sites to 90 m depth (Figure 1b), an experienced diver can exchange all TLs with only a short decompression. Obviously, extra decompression should be done for safety, but the decompression obligation with an efficient dive is not great. It is still incumbent on all persons using these techniques to understand the risks and difficulties involved, prior to attempting what are still very serious dives with risks from decompression sickness (bends), gas toxicity, and drowning. In many cases, scientists may prefer to have diving professionals do deep TL deployments. There is no operational need that would prevent such well-trained competent divers from doing so. As technical diving has become more common, in many locations advanced divers using mixed gas rebreathers can deploy and recover deep TLs.

2.8.8. Shot Line Diving

In some locations, the bottom will be sloping to such an extent that descending and ascending along that slope is not practical as it would require excessive bottom time at depth. In such a situation, the preferred technique is to dive using a "shot-line", an anchor weight (5 to 15 kg) with a line sufficiently long enough to reach the surface from the water depth and a large surface buoy as a position reference. The anchor weight is connected to the line by a clip, which can easily detach the line from the weight, so divers can potentially use the line for ascent leaving the weight on the bottom. When diving on a "shot line" the boat is not anchored ("live boat") but would hold station near the surface float during the dive. Assuming an accurate GPS position is known for the site, the boat slowly approaches the position and once directly over it, the shot line anchor is dropped, and the line is allowed to run free as the weight descends vertically to the bottom. Once on the bottom the remainder of the line and the float(s) are thrown overboard, so the shot line is free of the boat. Ideally, this should be done in conjunction with a depth sounder in the boat, to verify that the sounder depth agrees with the known depth of the TL. Once established on the bottom, the shot line float will indicate if there are currents by leaving a wake behind it, and if excessive, they may drag the anchor over the bottom. The location of the buoy should be monitored for several mins to make sure it is not being dragged over the bottom by currents (which would mean it is no longer at the location of the TL), then the divers prepare and dive.

The divers enter the water at the surface float and swim downward in constant sight of the line. Once near the bottom, they look for the TL location, which should be no more than a few meters away. If a subsurface buoy marking the TL location has been installed earlier (Figure 2e), it may be visible some distance above the bottom and quickly guide the divers to the TL. If not immediately visible, divers search along the correct depth for the TL (assuming a slope).

After locating the TL and exchanging instruments, the divers ascend along the shot line. The weight is detached and either abandoned or sent to the surface with a lift bag. The divers then use the shot line for the ascent. The boat remains close by and once the shot line weight with lift bag comes to the surface, it is picked up and then the boat follows the divers via the surface float. Bubbles should be visible on the surface as well. Divers complete any decompression hanging on the line in mid-water and after surfacing, are picked up by the boat. This technique is efficient when properly used, but like all deep-diving methods, divers need to be carefully trained and completely comfortable with the techniques involved.

In situations where diving cannot be used for deep TL deployment and recovery, remotely operated vehicles [33] or submersibles [34] could be used. These represent a major escalation in costs with uncertain recovery prospects, making extremely difficult what is often a relatively easy process if done by properly trained divers using advanced diving techniques [31].

2.8.9. Deep Moorings

It is tempting to deploy a heavy anchor weight, with a TL near the bottom on a long float line (20 to 30 m for a 57 m deployment). Often such floats are lost and if attached to the anchor weight create extra drag via the mooring line that may pull the entire mooring some distance. Such losses occurred with a few of the original deep network deployments.

One exception to this generality was an extremely deep difficult deployment at Ngaraard Pinnacle [30]. Due to the depth (95 m) over a 100 m deep bottom, currents, and the need to ascend in open water, the TL had been installed on a short mooring line with a weight and depth resistant plastic float and dropped from a boat. To recover the instrument two years later the mooring line was cut by a diver below the TL, allowing the float to carry the TL to the surface (where it was recovered by a boat) abandoning the weight on the bottom. A replacement TL mooring was dropped at the same spot, again by boat, with eventual plans to recover it in the same manner.

2.8.10. Data Management and Availability

Loggers were downloaded using the relevant software and raw data files archived on multiple computers. The raw data, which covered variable periods of time, were saved as Ascii text (i.e., as comma-separated values) or Excel files for further use. The variable deployment length data were put into discrete annual spreadsheets for each station/depth at the appropriate time resolution. The spreadsheet calculated daily/weekly means, range, and standard deviation.

Data are not presently in an open-access database, as they are actively being worked upon prior to publication. Selected data are made available to researchers on request via the CRRF website, which has a catalog of data files (https://wtc.coralreefpalau.org/).

3. Results

Data from TL networks can be used to address general questions (T regime of a reef area) or focus on specific patterns or dynamics within a larger reef tract (e.g., coral bleaching and ENSO changes). Here we provide (1) analysis of thermal patterns and variance on the Palau reef tract; (2) examples of why such a network is useful; (3) how it can be focused on obtaining information on poorly known aspects of reef science. Some examples shown use data from the 2015 to 2016 El Niño, as it was an exceptionally dynamic period, but other years (such as 2010 with coral bleaching) would have been equally informative.

3.1. Outer Reef Temperatures Over Time and Depth of "Coral Reef Conditions"

A vertical array of TLs (i.e., at several depths along the outer reef slope; Figure 3a) shows that the vertical profile of T is an important determinant of maximum reef depth. All TLs recorded at the same interval with an appropriate temporal resolution to document change over time periods ranging from minutes to years (Figure 3b) [14]. The initial array deployments (Figure 1b) on the East and West reef slopes (Short Drop Off in 1999 and Ulong Rock in 2000, Figure 3c) quickly identified two variable temporal patterns on the lower slope. Long-term (month/years) patterns of T varied by about 13 °C, while short term variability (min/hours) was almost as large at about 8 °C (Figure 3d). Initially, a 30-min sampling interval was used due to memory and battery limitations. After 2014 with new TLs, intervals were shortened to 1-min providing evidence of significant variation beyond that measured with a 30-min interval. The deepest depth of the array at 90 m (due to reef slope morphology and diving limitations) proved definitive because T values at 90 m were often well below the accepted limits for coral reefs. Based on data from all depths, 60 to 70 m was established as the approximate lower depth limit of coral reefs is Palau [29].

If full 30-min or 1-min data (respectively 17,560 and 525,600 data points per regular year) for multiple depth TLs at a single station are plotted together, patterns of short and long-term changes over that year are often evident (Figure 3c). The 1-min interval, in particular, reveals new dynamic patterns, such as during the El Niño of 2015 to 2016 [35]. Early in 2016, Ts at 57 m depth were much cooler than at 15 m depth, with a difference of roughly 10 to 12 °C, indicating a highly stratified water column. In March 2016, Ts at 57 and 90 m depth started increasing, along with a lesser increase at 11 m depth, rapidly hitting peaks from June to July 2016 (Figure 3b). The shift over 10 weeks away from strong El Niño conditions produced a "quasi" coral bleaching event [14], which reversed in July with shifts in oceanic conditions [35].

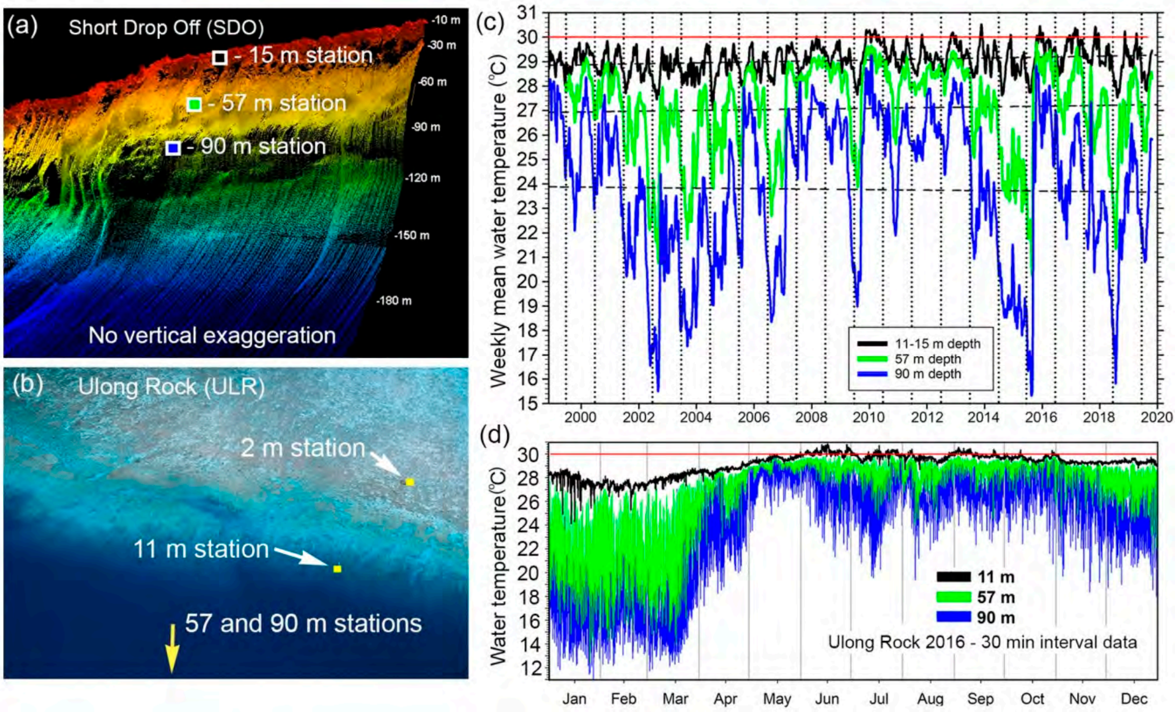

Figure 3. (**a**) Outer slope profile showing locations of TLs along the slope at Short Drop Off (SDO). The location of SDO is shown in Figure 1b. (**b**) Aerial view of Ulong Rock (ULR) station with general locations of TLs indicated, showing the horizontal displacement sometimes necessary to position TLs at certain depths. The location of ULR is shown in Figure 1b. (**c**) Weekly mean temperatures on outer reef slopes 1999 to 2020 in Palau. Only three nominal depths (15, 57, and 90 m) are shown; data also collected at additional depths. Nominal coral bleaching threshold of 30 °C is shown by the red line. Dashed lines are straight line regressions of all data at the three depths. (**d**) Year pattern for 2016 showing all 30-min interval data at the same depths as (**c**). Nominal 30 °C bleaching threshold is shown by the red line.

During La Niña, the deep reefs of Palau become extremely warm, with bleaching level T throughout the water column where reefs occur [14]. Mesophotic reef bleaching is largely unknown due to a lack of deep reef T data and surveys of bleaching at depth during times when bleaching conditions are present [18]. SSST provides no information to estimate deep bleaching. The linking of sea surface height (SSH) and SSST has the potential to estimate thermal conditions on deeper reefs [36,37], although this has not yet been incorporated into global bleaching estimations.

3.2. Impact of Internal Waves on Temperature Dynamics

Preliminary work documented the variable nature of deep T in Palau caused by internal waves/tides, suggesting 60 m depths were near the lower limits of photophilic reefs [24]. In 2014, the enhanced "deep network" was set up with 27 TLs recording at 1 min intervals at 57 m depth (Figure 1b), a depth with high thermal variation (Figures 1b and 3c,d). While this number of stations may seem excessive, preliminary data revealed that each station has a distinct short-term pattern of T variation but when all stations are considered together general patterns are apparent (e.g., a coherent diurnal internal wave in Figure 4). While a complete analysis has not been done, preliminary results indicate island-trapped internal waves can circulate part of the way around the outer slope [38].

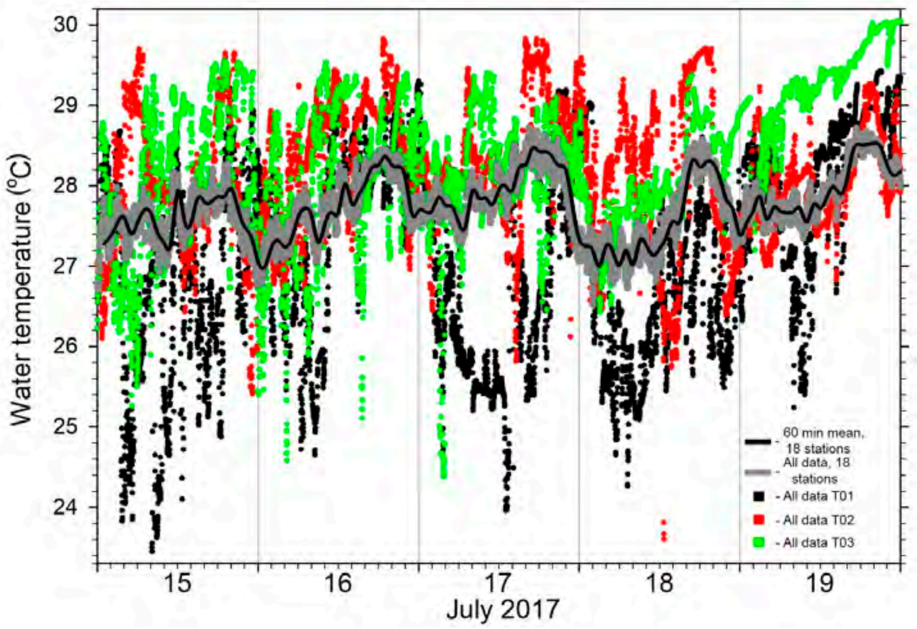

Figure 4. The "deep network" TLs at 57 m depth all around Palau measure once per min providing a wealth of data. This example shows over five days in July 2017, with the hourly mean values of 18 stations (those on the outer slope of the main group) (black line), the mean value each min for those stations (gray area), and examples of raw minute-by-minute data from three stations (T01-black, T02-red, T03-green) in the northern part of Palau indicating the high short-term variation at individual stations.

While most deep network stations are along steep (45° or more) slopes, a few are in areas with lower and more consistent slopes from deep water, where shoaling internal tides (internal waves forced by the semidiurnal or diurnal surface tides) are transformed into internal bores. A station at the South end of Angaur Island (Figure 5) had a remarkable T drop of 12.25 °C in one min (14.4 °C in 3 min). The generation and propagation of these waves are sensitive to stratification [39], which shifted dramatically during the end of the 2015 to 2016 El Niño [35].

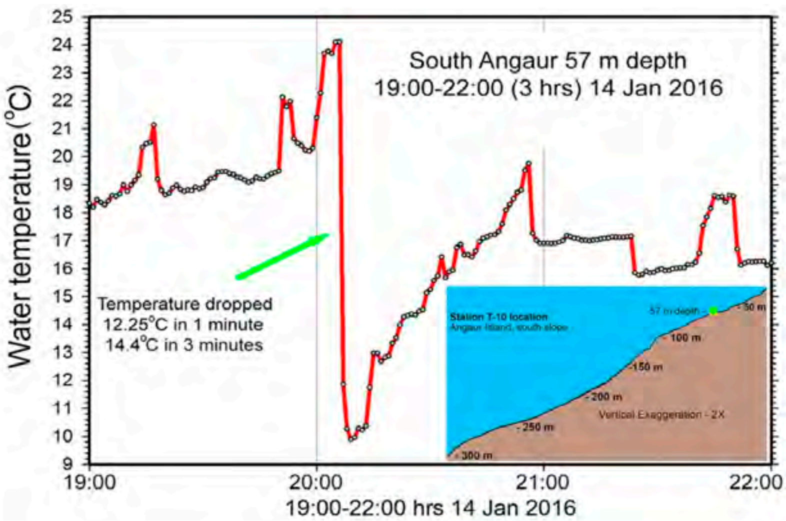

Figure 5. Extreme temperature changes at the southern end of Angaur Island, Station T10 at 57 m depth over three hours. The temperature dropped over 14 °C in three mins, although before and after this event, relatively normal variation in temperature at the station occurred. The gentle slope offshore of the South Angaur station is unusual for Palau's outer reefs (insert-lower right).

3.3. Mixing of Ocean and Lagoon Water while Advecting through Barrier Reef Channels

The deep channels bisecting the barrier reef between ocean and lagoon are likely sufficiently deep (35 to 75 m) to ingress water from ocean to lagoon that is vertically stratified, particularly during El Niño periods (Figure 6). Does this occur and how quickly would thermal stratification dissipate as water is mixed and moves into the lagoon? In 2010 a series of six stations with vertical TL arrays at 15, 30, 45, and 57 m (stations five to six without 57 m) depth were set up along the sides of the west/inner channel corridor west of Babeldaob Island (Figure 6a). At times thermally stratified water brought into the channel mouth penetrated several km into the lagoon on a diurnal cycle, but stratification vanished farther into the lagoon (Figure 6c) and water exiting the lagoon on falling tides was well mixed. In August 2010, a La Niña period, coral bleaching was occurring [12] and to a limited extent channels intermittently brought some cooler water into lagoons possibly due to a shoaling diurnal internal tide, which turns into a bore with steep/shallow isothermal slopes on the leading/trailing edge (Figure 6c). The potential effects of these processes on reefs are uncertain.

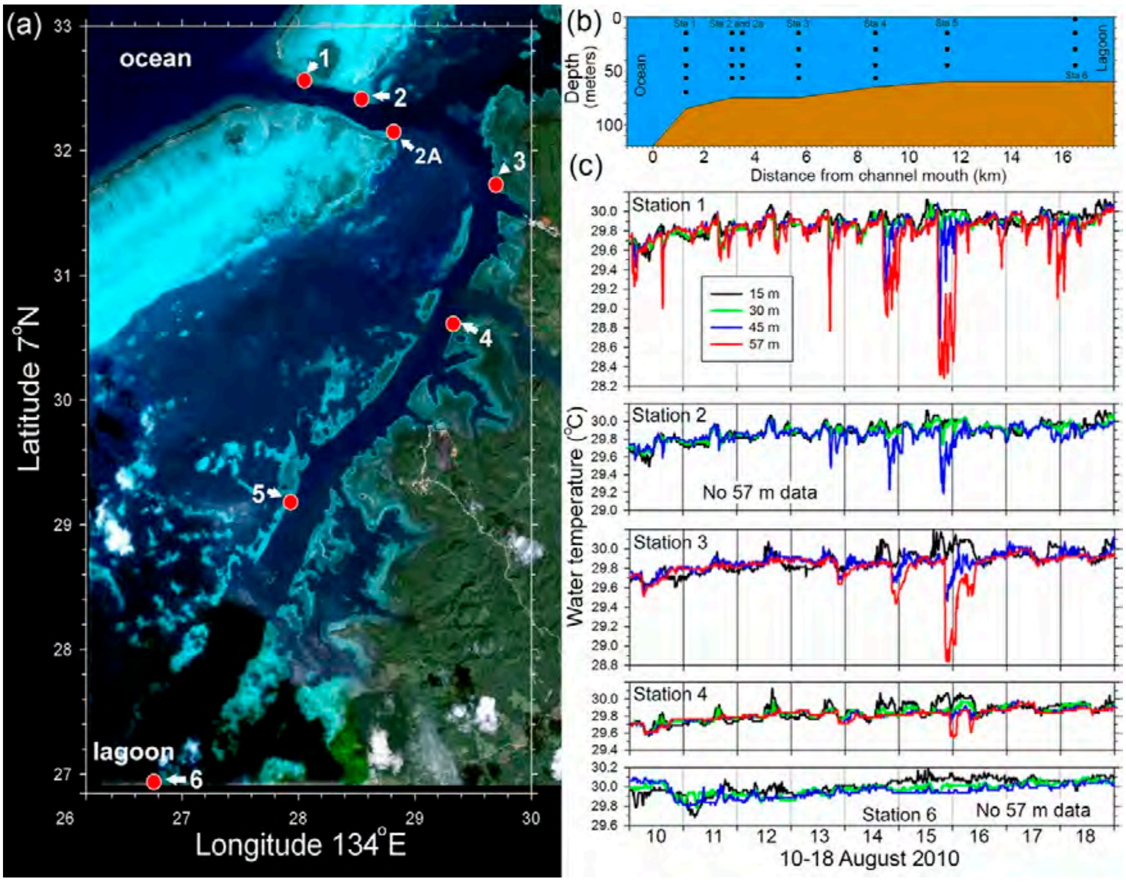

Figure 6. West Channel TL array. (**a**) Locations of stations with vertical arrays of TLs (indicated by numbers) along the sides of the West and Inner Channel into the lagoon. Minutes of latitude (7° N) and longitude (134° E) are indicated on the y- and x- axes. (**b**) Schematic of relative locations of numbered sampling stations along channel axis with the bottom depth of the channel shown. Black dots indicate depths of TLs. (**c**) Vertical structure of water temperature over nine days at stations along the West and Inner channels. Downward spikes in temperature are seen from 15 to 16 August 2010, with stations nearest the channel showing the largest decreases.

Different ENSO conditions change the nature of the offshore water column [28] and are reflected in the water brought into channels on rising tides. During the 2015 to 2016 El Niño water at 35 m depth on the slope of "German Channel" (GC-2 in Figure 1b) had quite variable Ts (Figure 7a). One year later, when the El Niño had dissipated, there was almost no variation in the Ts of incoming and outgoing water (Figure 7b) and again the impacts of this variable T on channel reefs are unknown. Substantial variability is noted around Palau in observations from this network and elsewhere [40]. Furthermore, since these bores are turbulent [41] they can suspend and transport sediment, nutrients, or other properties into shallower water [42,43], which we have noted at this site or nearby.

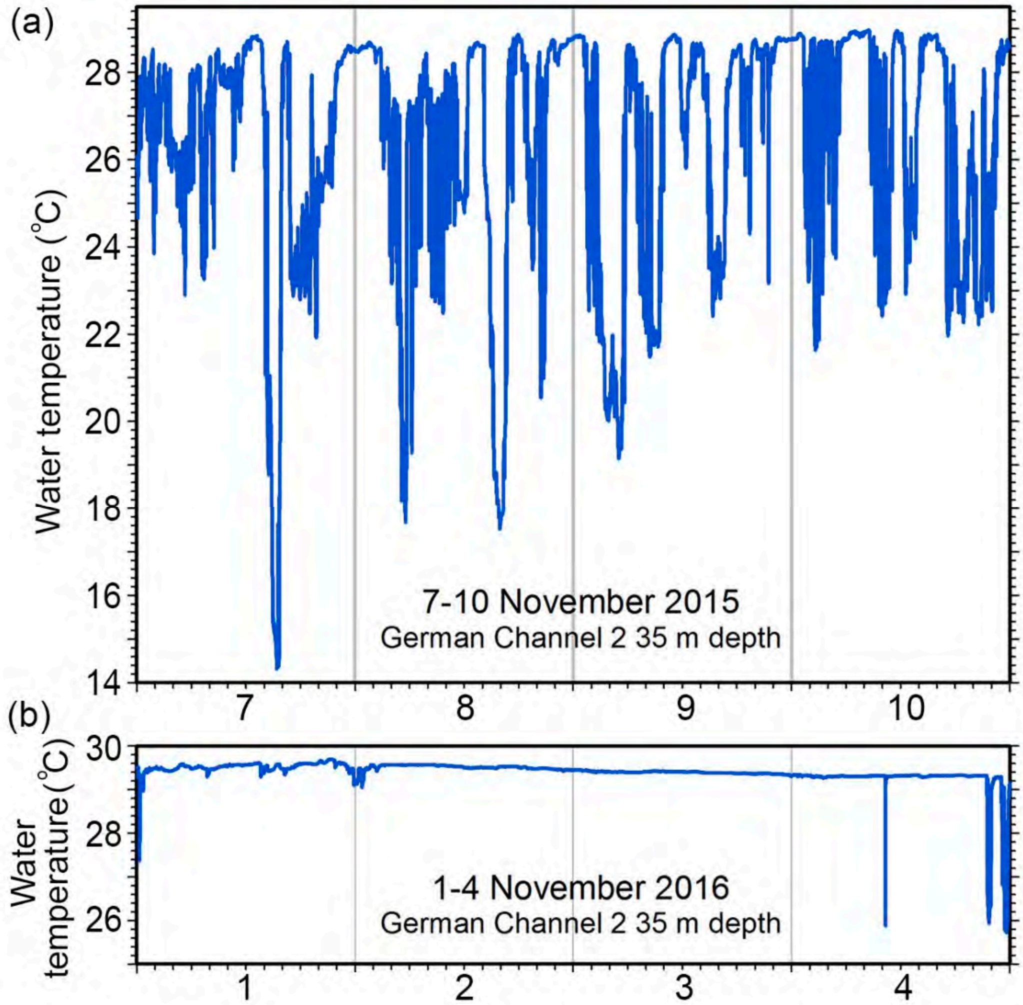

Figure 7. Temperatures at 35 m depth over four days on the slope of the German Channel station 2 (GC-2 location shown in Figure 1b) during (**a**) an El Niño period (7 to 10 November 2015) and (**b**) a period after the end of the El Niño (1 to 4 November 2016), one year later.

3.4. Temperature Patterns across Broad Regions and Current Patterns

With TL stations distributed over a wide geographic range (100 s of km), the network may capture differences attributable to broad oceanographic conditions. The SWI (Figure 1c) are within the eastward NECC, while the main island/reef group is normally dominated by the westward NEC, with occasional intrusions of the NECC. The main Palau group underwent a dramatic shift in currents, sea level, and T in 2016, while the SWI had a lesser shift in thermocline structure at the same time [35]. During the peak of the 2015 to 2016 El Niño in early 2016, shallow (11 to 15 m) daily mean T was very similar between Tobi and the main Palau group (Ulong Rock), separated by 600 km (Figure 8). However, at 57 m depth conditions were very different with Tobi near 25 °C while Ulong Rock was much cooler at 19 to 23 °C. As the El Niño ended in spring 2016, Ulong Rock had a major increase in T over 10 weeks. However, at Tobi T did not spike similarly, but started rising two months later (May) and more gradually; these large differences explained in terms of the dynamics of equatorial currents and equatorial waves [35]. The result is that as the El Niño terminated, water moved back into the western Pacific, and forced the NECC northward towards the main Palau group.

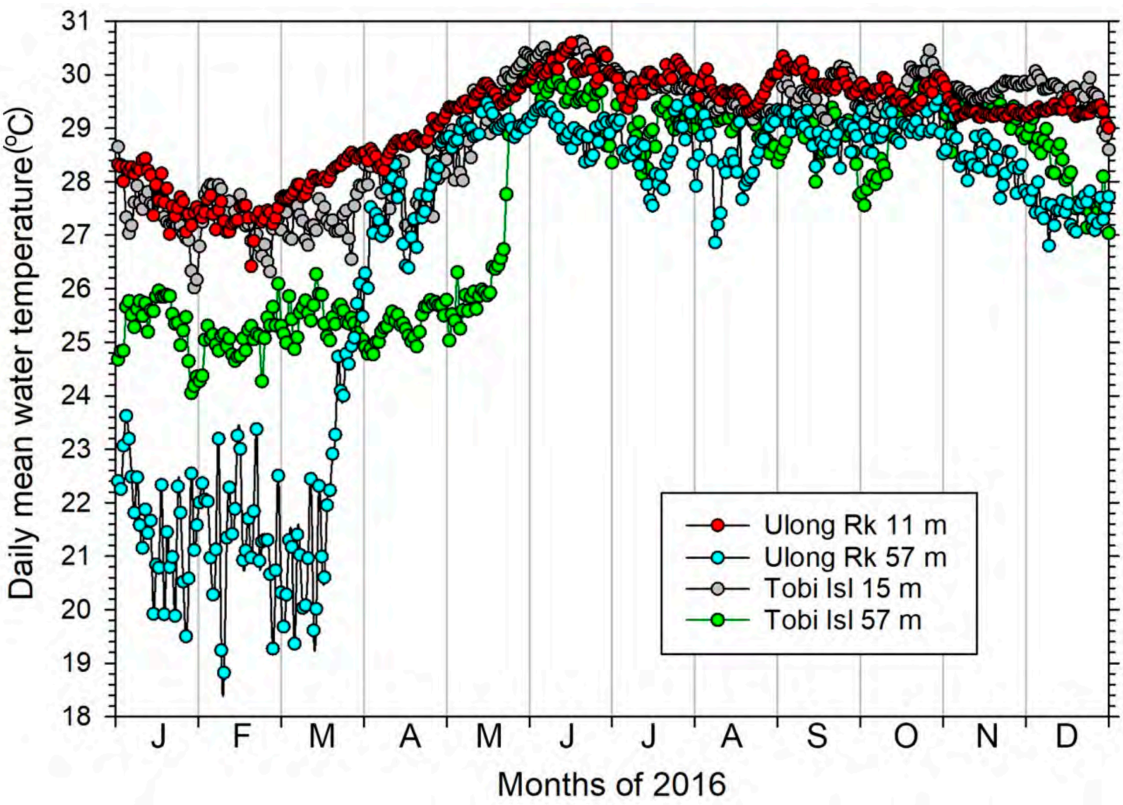

Figure 8. Daily mean temperatures at Tobi, Southwest Islands, and Ulong Rock, main Palau group at 15 and 57 m depths during 2016.

3.5. Climate Change Values from Long-Term Data

To identify climate change (decadal or longer-scale trends) long records are needed, which also resolve considerable variability from internal waves (minutes to hours). ENSO T shifts add another complication, with deeper areas having extreme variation. Periods of months to a few years clearly do not provide a sufficient length to observe whether a climate change signal is present.

With two decades of data from consistent locations, it is now possible to begin examining whether the data show trends potentially related to global climate change. The 11 m weekly mean data (30 min interval) from Ulong Rock ranges from below 27 to over 30 °C (Figure 9) while the 2 m data has a slightly greater range, reflective of diurnal variability in shallower depths. A nominal 30 °C "bleaching threshold" line (Figure 9, red line) [14] indicates this high T level has occurred during several years since 2007, but not between 1999 and 2007. Severe bleaching occurred in 1998, prior to the start of the T network, and temperatures were certainly above the "bleaching threshold". A straight-line regression from the data shows an upward trend of 0.4 °C over twenty years, or 0.2 °C per decade (Figure 9, green line). The rate of increase changes slightly as new data are added each successive year. The trend is about 0.1 °C per decade around Palau from 1971 to 2010 averaged from 0 to 700 m [44], while SST shows a trend of about 0.2 °C per decade from 1900 to 2008 [45]. If our measured trend of 0.2 °C per decade extends to 90 m, it still explains only a fraction (up to 30 mm per decade based on the thermal expansion of seawater) of the 1990s decade long change in sea level in Palau, which appears mainly due to trade wind intensification during that time [46].

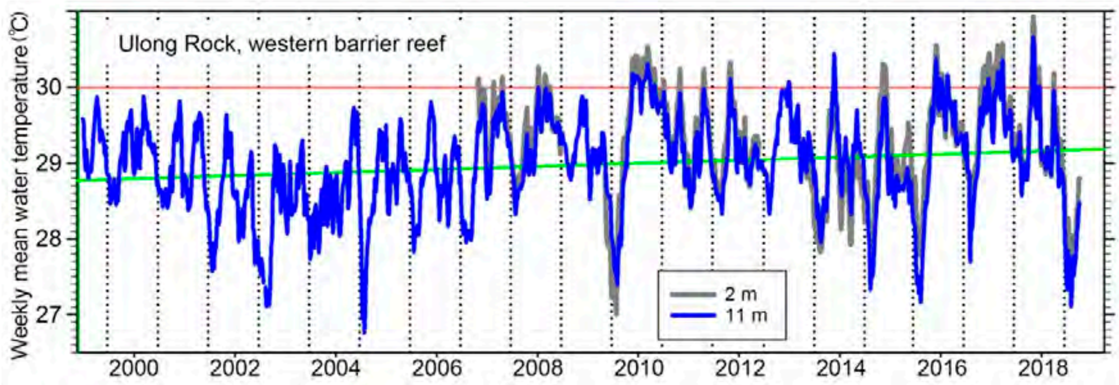

Figure 9. Weekly mean temperatures, 2 and 11 m, at Ulong Rock 2000 to 2019. The red line indicates a nominal 30 °C bleaching threshold above which a few weeks of exposure is associated with coral bleaching. The green is a straight-line regression of the 15 m data indicating a rise of about 0.2 °C per decade since 2000.

4. Discussion

4.1. SSST Versus in Situ Data

Both SSST and in situ data sets have their strengths. SSST provides the global perspective, but in situ data supplies most detail and serves as a ground truth for SSST. In terms of the calculation of heat stress and other T related parameters on reefs, accurate in situ are superior (and essential) when looking at a specific reef or site because of considerable horizontal, vertical, and temporal variability, some of which is invisible to SSST. Monthly mean climatology (MMC) based on SSST is used to define threshold Ts for coral bleaching and calculation of Degree Heating Weeks (DHW), an index of heat stress in a reef area to predict bleaching. If MMC and DHW are calculated from in situ data, the values are different, and one of the strengths of in situ data is that these indices can be determined for locations and depths, not just for single generalized location at the skin surface.

Detailed examination of T and coral bleaching has not been included here, although work has revealed without question the presence of thermal conditions inducing bleaching to 90 m depth in Palau. Deep (mesophotic) reef T conditions and subsequent coral bleaching has been largely ignored in the Indo-West Pacific [18]. Some areas, such as Australia, have experienced severe shallow bleaching events, particularly related to the 2015 to 16 El Niño, and are beginning to examine deep reef Ts/bleaching below 20 to 25 m [33]. While SSST alone cannot indicate Ts at the lower depths where reefs occur, the merging of sea surface height (SSH) data, either from satellites or tide gauges, with SSST provides a new way to assess heat stress in reef environments [36,38] and opens a remote sensing window into events at the lower limits of reefs. While this method required in situ data for validation, it can be expanded to other locations in the tropical Pacific where we expect the relation between Ts and SSH holds.

4.2. Why Is a Network with Many Instruments Needed in Coral Reef Areas?

The Palau network in the main island group provides about 54,000 discrete location–depth–time measurements per day while the NOAA Reef Watch virtual station data for Palau, https://coralreefwatch.noaa.gov/product/vs/data/palau, provides one daily set of SSST measurements (mean, maximum, and minimum), thus cannot capture the thermal dynamics within a reef area, particularly where ENSO related changes are large, internal wave variability is considerable, and diverse types of habitats are present. Without a network appropriately sized for the area to be covered, unknown aspects of the physical environment, along with the biological implications, will be invisible. Each of the vertical TL arrays (four at 2 to 90 m depth, several others at 2 to 57 m), plus the dozens of the widely distributed single 57 m TLs, have shown different patterns. It is not yet clear what is driving these differences, but the ocean current dynamics, documented recently [27,47] and others in the same volume, as well as smaller-scale effects [29], produce a complex physical environment which continues to reveal new layers of complexity. The passages between island groups, such as between Peleliu/Angaur (Lukes Passage) and Kayangel/Ngeruangel (Velasco Reef) and the northern reef tract of the main group (Euchelel Ngeruangel, Kekerel Euchel) are exceptionally dynamic and influence the reefs in those areas greatly. Wake eddies and internal lee waves at 1-km scales are noted at points and over submarine ridges [48–50]. The seasonal shifts of the NEC and NECC, as well as with ENSO, are exceptionally important, changing the nature of the oceanic environment throughout Palau [35]. The same applies to ENSO cycles in the open ocean directly impacting reefs through impressive shifts in the conditions in the photic zone, poorly documented for western tropical Pacific waters [14,25].

The examples presented are largely concerned with outer reef vertical and temporal changes, but examples from back reefs, lagoon patches, and reefs near island shores could alternately have been used. All have different thermal environments and should be within the full scope of T monitoring. Stations inside lagoon areas should provide broad geographic distributions, moving from offshore to inshore habitats and, where water depths are sufficient, established at different depths to capture vertical stratification. The arrays forming the transect of the West Channel (Figure 6) are one extreme of such lagoon arrays. The Rock Island areas of Palau [23], a series of basins separated by sills, have instruments from very shallow to the maximum depths in basins that have minimal water exchange. These inner reef arrays have been important in documenting small scale bleaching events in 2007, 2016, and 2018 [23] for which T information would otherwise have not been available.

4.3. Will a More Modest Network Suffice?

A network of 100 or more TLs may not be feasible (or necessary) for many reef locations. The Palau network developed gradually, and early results indicated the benefits of expanding the network. A more limited suite of TLs can focus on areas where data are most needed. If knowing outer slope conditions relative to reefs is desirable, depth coverage is more important than geographic coverage. Ideally, the deepest levels of reefs in a given area are instrumented. Once the outer slopes of fringing or barrier reefs are covered, inshore areas are then important to determine whether such areas are thermally distinct and if there is any depth stratification of T.

Atolls provide a simpler system (than Palau) to document, usually having a broad scale lagoon circulation. T regimes might differ on opposite outer slopes of an atoll, and vertical arrays in two areas might be informative. Patch reefs within lagoons are convenient locations to establish vertical arrays from near-surface to maximal lagoon depths. Reef flats would also be important to instrument, as they may have significantly higher T. Channels through the reef rim are also important locations for monitoring, as they are the only connections between ocean and lagoon of sufficient depth to ingress stratified water from offshore.

Lagoon areas with islands, such as those that occur in Palau, are more complex and often tidal currents course through shallow channels advecting water to new areas that may have warmed over shallow bottoms. Fresh or brackish water may enter lagoons from streams, springs or groundwater flows, and are another area where documentation would be important. In special cases, such as caves, caverns, siphons, and other areas where groundwater intrudes, different T conditions are expected to occur and should be documented.

4.4. Need for Long-Term Measurements

Short-term in situ T monitoring may not accurately capture broad patterns, particularly with regard to El Niño/La Niña cycles that produce extreme differences [51]. Furthermore, measurement intervals must be short enough to resolve energetic internal waves, although, with sufficient averaging, their effects on a record with long sampling intervals can be reduced. Monitoring networks can take advantage of geography while small oceanic islands can serve as "mooring" equivalents for some global climate considerations. Present-day technical diving capability has expanded the depth range accessible for diver deployment of instruments.

5. Conclusions

We have focused on the techniques for developing and maintaining a network of diver-deployed compact, research-quality T loggers for measuring T from a few meters depth on the reef crest to 90 m on the reef slope. This T network targets a wide variety of environments (reef crest, reef slope, reef channel, atolls, lagoons, pinnacles, and headlands), covers an area from 3° N to 8°30′ N impacted by the NEC and NECC, and for periods over 20 years for some stations.

In terms of ocean physics, the network offers a sometimes astounding view of an energetic environment. With sampling over two decades, we have documented large T signals often invisible to SSST from (1) internal waves on time scales of minutes to hours, (2) El Niño on time scales of weeks to years, and (3) decadal-scale trends of +0.2 °C per decade. The latter is a component of variable sea-level rise in the western Pacific, while the other two signals show 14 °C changes over minutes due to internal bores and over weeks during the termination of El Niño and a dramatic blockage of the NECC's usual path. The T network data have been used to create a regression model with SST and SSH capable of predicting depth-varying thermal stress from satellite measurements, which can be tested now at other locations in the tropics. The large temporal, horizontal, and vertical variability noted by the network has further implications for thermal stress on the reef.

In terms of biology, the data points to numerous areas of investigation, although the program was focused initially on obtaining definitive data on the physical environment that could be correlated with events such as coral bleaching. In general, the program has pointed out a dearth of definitive thermal information for most coral reef habitats within Palau and elsewhere, which undermines the ability to interpret biological events from the most basic physical perspective.

Author Contributions: P.L.C. conceived and developed the network, fieldwork, data analysis and archiving, and writing and editing. T.M.S.J. Field worked on oceanography, analysis and interpretation of data, and writing and editing. All authors have read and agreed to the published version of the manuscript.

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TAB 2

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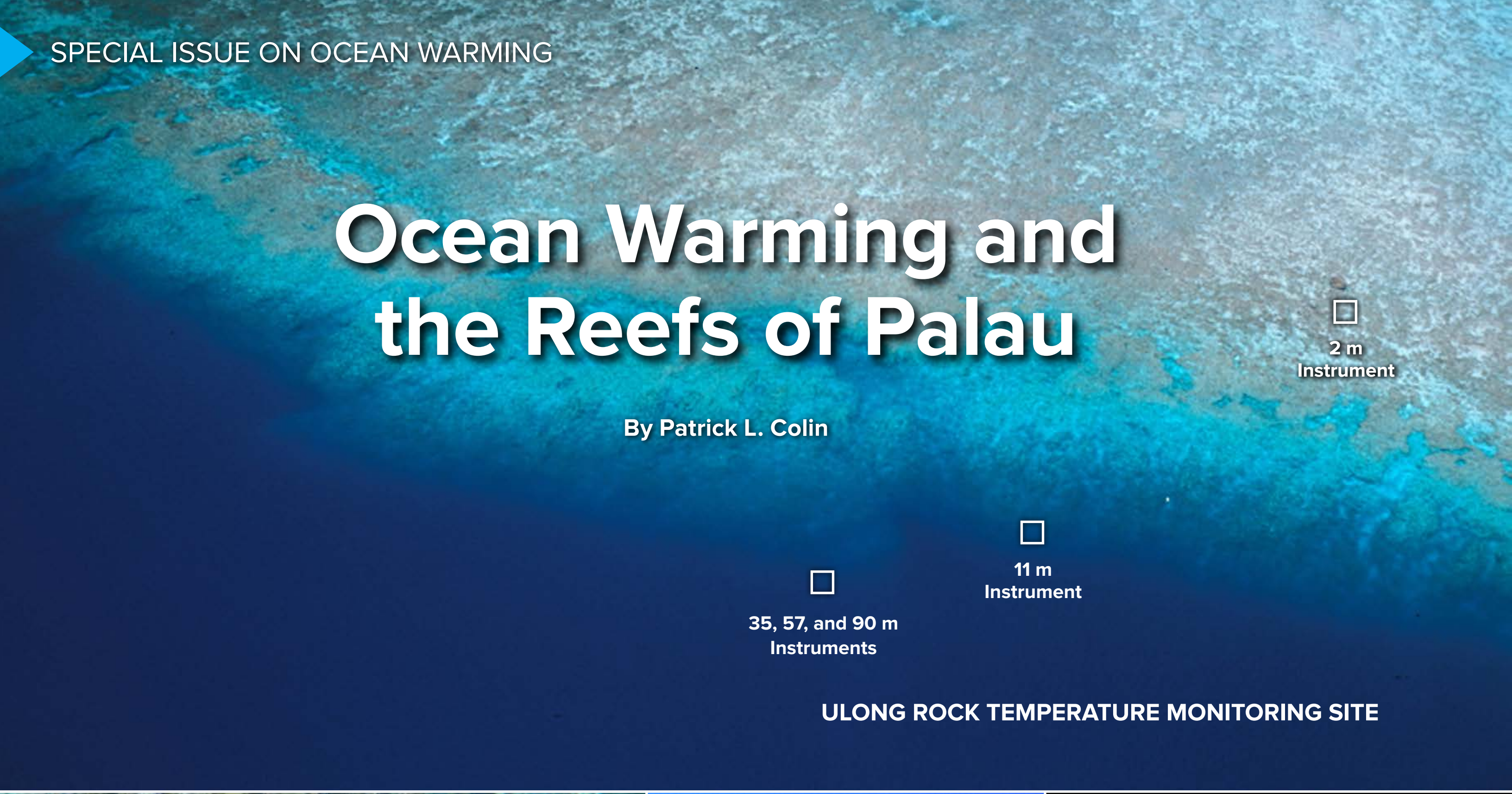
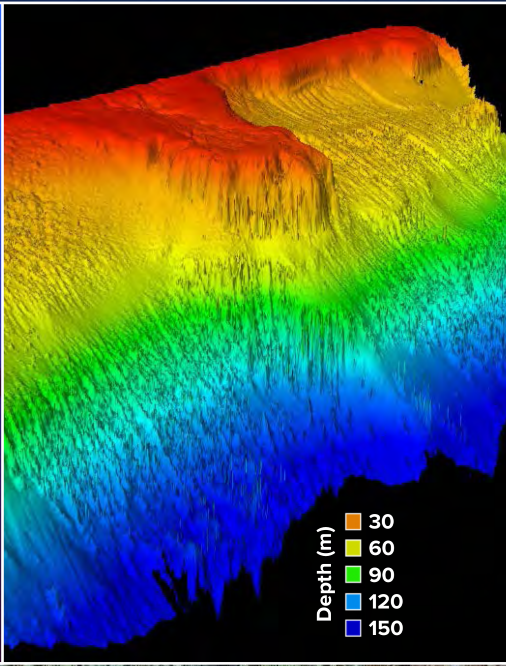
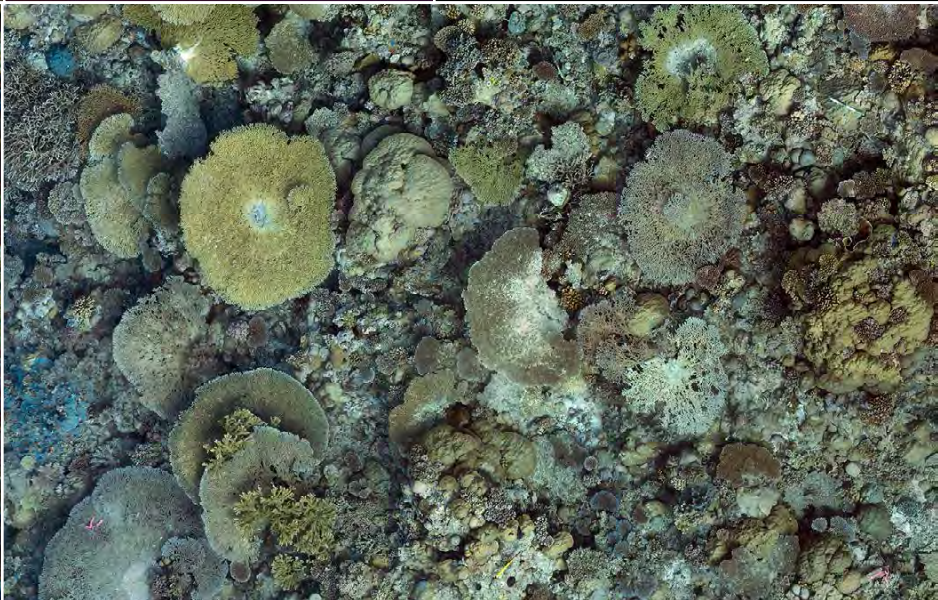
Ocean Warming and the Reefs of Palau

By Patrick L. Colin







> Combined with other types of information… the detailed breakdown of temperature is important when evaluating the actual thermal environments where reefs exist, and provides a needed counterbalance to and accuracy check on [satellite sea surface temperature] observations.

ABSTRACT. After a coral bleaching event in 1998, a comprehensive temperature monitoring program was started in the Pacific Island nation of Palau using vertical arrays of instruments that collected data from near the surface to 90 m depth along outer reef slopes. Data from 1999 to the present show highly variable temperatures at deeper stations, attributed to internal waves/tides, and a correlation between monthly mean temperatures and mean sea levels. A La Niña bleaching event in 2010 recorded temperatures of 29°–30°C throughout the depth range of corals and a breakdown in upwelling mechanisms during the event. No evidence of a deep reef thermal "refuge" from bleaching conditions was observed. An abortive bleaching event in 2016 provided insight into how reef conditions can change from El Niño to La Niña in only two to three months. Trends from 1999 to 2017 indicate possible temperature increases at all depths. Temperature monitoring networks are important to help inform the relationship between remotely sensed satellite and in situ temperature data and should be included in more coral bleaching studies. New approaches to determining thermal stress on reefs, such as incorporating data on mean sea level, are needed.

INTRODUCTION

The health and survival of coral reefs is a major concern in a future with a warmer ocean. These reefs occur in the tropics and subtropics on continental (Great Barrier Reef, Florida Keys) and large island shelves (New Guinea, Madagascar), as well as at small oceanic islands and atolls that are removed from continents and most of humanity. For the latter group, the outer reefs usually face the deep ocean and drop steeply, so adjacent ocean water is continually in contact with them and imports the dynamics of upper ocean thermal structure evidenced by internal waves and upwelling measurable on the outer slope.

Current ocean warming concerns for coral reefs largely focus on bleaching, the condition where the symbiotic zooxanthellae algae found inside the cells of coral polyps are expelled, leaving the tissue largely colorless and the white coral skeleton visible. Thermal stress is usually the cause of bleaching, and without their symbionts, the colonies die within a few days to weeks. If thermal stress is relieved by water temperatures decreasing below a threshold level, the corals can reacquire their zooxanthellae and recover. Other factors are of concern to long-term reef health, such as ocean acidification, land-based pollution, and overfishing, but they pale in comparison to the immediate specter of bleaching. Bleaching events spanning the global tropics began in 1997–1998, and were observed more recently in 2010 and again in 2014–2016; as they apparently are becoming more frequent, reefs have less time to recover between them (Hughes et al., 2018).

The data used to examine global level ocean temperature dynamics come from remote measurements made via satellite radiometers (infrared and microwave) and in situ instruments on drifting buoys, Argo floats, transiting ships, and other platforms (Hausfather et al., 2017). The presence of isolated reefs and islands in areas presently without monitoring instruments or undersampled by Lagrangian systems such as Argo suggest the potential for using these locations as

FACING PAGE. (upper) Aerial view of the Ulong Rock temperature monitoring station, western barrier reef, Palau. The locations of the various thermographs are indicated, with the deeper stations being down the near vertical slope that disappears into the blue. (middle left) Shallow-water corals located just behind the barrier reef were starting to bleach in June 2017. (middle center) A rebreather-equipped diver prepares to descend along the slope to recover recording thermographs to 90 m depth. (middle right) Multibeam sonar image (no vertical exaggeration) of the "Croc Head" thermograph site on the western barrier reef of Palau. Depths shown to 500 m. (lower left) Bleached deepwater plate-like *Leptoseris* sp. coral at 60 m depth, August 2010, western barrier reef of Palau. (lower right) Vertical mosaic of a highly diverse coral reef about 3 × 5 m, 6 m depth, with many tabulate *Acropora* corals as well as smaller coral heads and branching species (courtesy NASA CORAL, E. Hochberg).

"ocean stations" by instrumenting them to examine ocean temperature, warming on reefs in particular. The central-western Pacific has many islands/reefs suitable for this purpose, and some efforts are already underway at Palmyra Atoll (the Line Islands Palmyra Atoll Research Station), Moorea (French Polynesia's Gump South Pacific Research Station), Pohnpei (in the Federated States of Micronesia; Sonia Rowley, University of Hawaii, *pers. comm.*, 2018), and Palau (reported here). More locations are needed.

The island nation of Palau, the westernmost island in the Caroline chain, lies within the western Pacific warm pool (Figure 1a). This article examines ocean thermal conditions there over the last two decades. Palau is known for its coral reefs and for a high diversity of marine habitat types in a relatively small area (Colin, 2009). Numerous islands in the main group at 7°N all occur within a barrier/fringing reef margin where healthy reef systems have differentially recovered from 1998 and 2010 bleaching events (Golbuu et al., 2007; van Woesik et al., 2012). The main islands/reefs (Figure 1b) are located at the interface between the westward-flowing North Equatorial Current (north of Palau) and the eastward-flowing North Equatorial Countercurrent (south of the main islands). The two currents move north to south relative to one another seasonally and also shift latitude with changes in El Niño-Southern Oscillation (ENSO; Hsin and Qui, 2012). Several small oceanic islands and one atoll belonging to Palau, collectively called the "southwest islands," lie in the area between the main group and the northern coast of New Guinea. They can serve as additional ocean stations for monitoring temperatures in current regimes that are different from those in the main island group.

Attempts to examine coral-reef warming on a worldwide scale have relied almost solely on satellite data (Heron et al., 2016; Hughes et al., 2018), which provide a global perspective of conditions relative to coral bleaching at intervals of a few days. These remote measurements of the infrared or microwave spectrum radiating from the ocean's "skin" provide satellite sea surface temperatures (SSST). However, they do not provide information regarding thermal conditions below the surface layer, and reefs and their corals can occur to depths of 100 m or more (Baker et al., 2016). Below the ocean/atmosphere interface, the effects of day/night and solar/atmospheric cooling and heating diminish, varying by location and weather, and the temperature where there is no diurnal change can only be measured with in situ instruments. In Palau, temperatures at depths of 10–15 m on outer reefs were found to be diurnally stable (Figure 2),

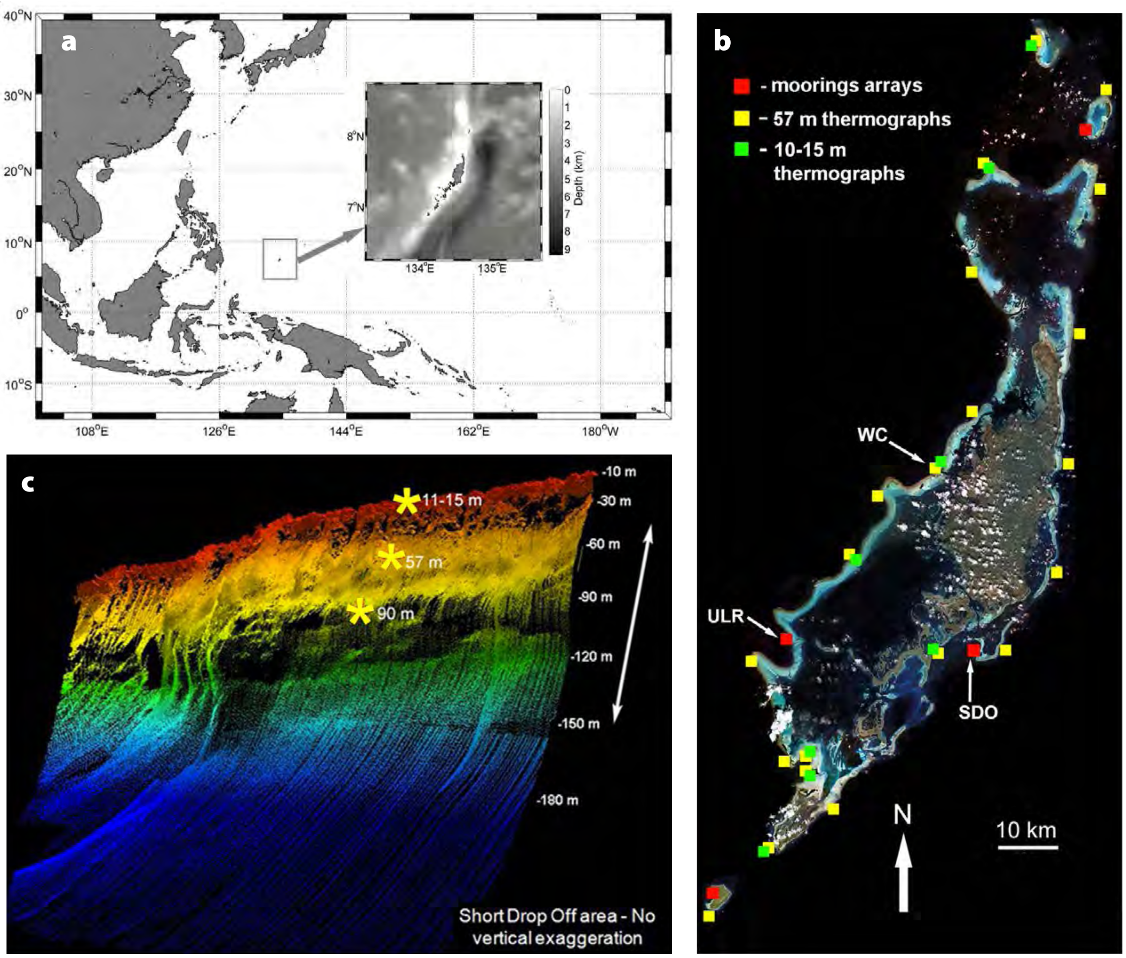


FIGURE 1. (a) Location and general bathymetry of Palau. (b) Satellite image of Palau showing locations of the outer reef thermograph network throughout the main reef tract. Vertical arrays of instruments (2–90 m depth) are shown by red squares, 57 m stations by yellow squares, and other outer reef 10–15 m stations by green squares. SDO = Short Drop Off. ULR = Ulong Rock. WC = West Channel. (c) Multibeam sonar image (no vertical exaggeration) of the SDO slope showing near vertical profiles with locations of thermographs at 15, 57, and 90 m depths indicated.

and therefore are considered to represent local "foundation" values.

When comparing remote-sensing data with those collected from in situ instruments, particularly recording thermographs placed directly on the reef for long periods, differences are often apparent for specific locations (Stobart et al., 2008; Castillo and Lima, 2010; Safaie et al., 2018). Data collected by in situ instruments provide a level of detail critical to understanding how different thermal regimes affect various reef habitats. These data also inform the broad applicability to bleaching considerations of remote-sensing information, which only offers average surface temperatures over kilometer scales. Within large reef tracts, temperatures are variable, and the sensitivity of individual coral species and communities are "spatially heterogeneous within reef scales (<1 km), and [are] therefore not predictable using conventional remote sensing products" (Safaie et al., 2018). A significant challenge is to obtain more detailed thermal data so the relationships between temperature and bleaching can be more clearly understood.

CORAL BLEACHING EVENTS IN 1998 AND 2010 SPUR AND VALIDATE TEMPERATURE MONITORING

Research at the Coral Reef Research Foundation (CRRF) in Palau began in 1995 with collection of marine invertebrates for screening by the US National Cancer Institute and documentation of the country's biodiverse marine environments. Palau's coral was extensively bleached during the 1998 La Niña, part of the 1997–1998 global ENSO event (Bruno et al., 2001; Colin, 2009), which was a shock as Palau had no prior record of significant bleaching. Earlier, very cool (for Palau) water (~17°–18°C) was found in deep reef areas during the late 1997 El Niño, but only nine months later, during La Niña, the same sites had temperatures of ~30°C from the surface to 90 m depth. Bleached and dying corals were observed throughout the water column, and on outer reef slopes mortality was 90% or more (Bruno et al., 2001). Surprisingly, at the same time, very shallow outer reef flats and many inshore reefs had much lower bleaching occurrence/mortality, with some communities appearing unaffected (*pers. obs.*).

The 1998 event prompted the installation of vertical arrays of calibrated thermographs (±0.1°C accuracy) to sample at 30-minute intervals from 2 m to 90 m depth along the east- and west-facing ocean reef slopes during 1999–2000 (Figure 1b,c). By the end of 2000, the warm oceanic conditions associated with bleaching had swung back toward cooler, slightly stratified ENSO neutral (Figure 3a). Starting in late 2001, water at depths below 35 m had major swings in temperature over timescales of minutes to weeks. At the deepest stations (90 m), temperature often changed 4°–8°C in half an hour, with individual values ranging between 8.6°C and 30.9°C. A year later (late 2002), the weekly mean temperatures at 57 m depth were 20°C, near the lower limit of reef growth, while at 90 m they were 15°–16°C, far below the lower limits of most reef coral survival (Kleypas et al., 1999). Adding to the general temperature stress were rapid shifts of several °C in minutes, exposing corals to even lower temperatures for varying periods.

A preliminary report by Wolanski et al. (2004) showed general agreement in mean values between the east and west outer reefs and attributed much of the rapid temperature fluctuations to "island-generated" internal waves. Based on coral temperature tolerances, we suggested the lower limit of reef growth occurred at 60–70 m, with the stress of rapidly fluctuating temperatures potentially producing a "depauperate" zone in the 60–120 m depth range.

Over the next decade, the thermograph network was expanded throughout Palau to include some 60 sites and 145 instruments. It is now thought to be the most comprehensive temperature monitoring network on any single coral reef area. Stations address specific questions, such as upwelling, mixing, and advection, while still documenting thermal regimes in all environments (Figure 1b). The present 18-year record (Figure 3a) provides detailed quantification of the remarkable variations in temperature conditions relative to depth, habitats, and timescales. Such detailed data on variation for specific areas within single habitats are needed, as the variation may be the most critical factor for assessing coral bleaching risk within large reef systems (Safiae et al., 2018).

In 2010 another bleaching event

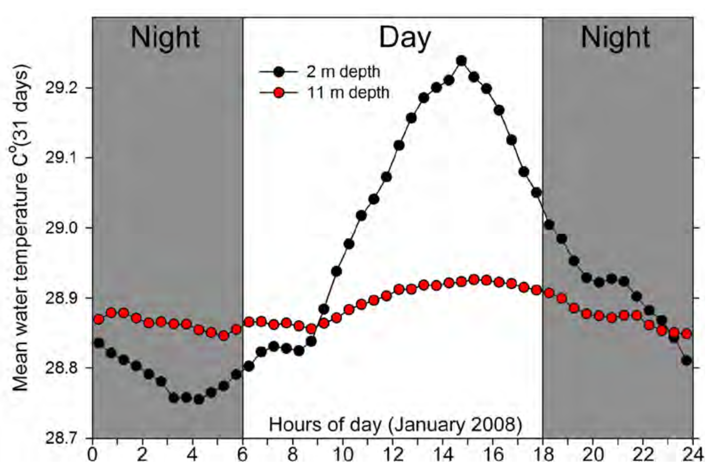


FIGURE 2. Validation of a "foundation" temperature depth (11 m) on the outer slope, Ulong Rock (western barrier reef). Data at 30-minute intervals from all days of January 2008. The nominal 2 m station is subject to diurnal variation as evidenced by increases during the day, peaking in the late afternoon, and decreasing below the 11 m temperature after midnight.

occurred (van Woesik et al., 2012), and with instruments in place, the shift from El Niño to La Niña over six months (February–August) was well documented (Figure 3d). Profiling data from Spray ocean gliders (Rudnick, 2016) near Palau (Figure 3b,c) at the same time documented temperature conditions identical to the outer slope, while also providing additional information on salinity and primary production (Figure 3b) in the water column. February 2010 (El Niño) chlorophyll *a* data indicated dense phytoplankton at 40–60 m depths associated with mesophotic reefs, something previously undocumented in Palau. By August (La Niña), the chlorophyll *a* maximum decreased greatly and returned to more typical depths of 100–120 m.

Although shallow temperatures exceeded 30°C in June and July 2010, bleaching became more common in August when daily mean temperatures were highest at 90 m depth (*pers. obs.*; Figure 3d,e). While remaining near the temperature observed to induce bleaching, temperature increases stalled in August and increased slightly in September and during half of October, but reef conditions did not move into a bleaching event comparable to 1998. The 2010 La Niña is considered only moderate, not strong like the 1998 event (NOAA Climate Prediction Center ENSO), so the reduced occurrence/mortality from bleaching in 2010 is not surprising (van Woesik et al., 2012; *pers. obs.*). The daily mean values for nine outer reefs at 10–15 m depth (which are not affected by the tidal flow from the warmer lagoon) never exceeded 30.5°C. Bleaching was limited to sensitive habitats and species, such as the temperature sensitive *Acropora* table corals, but overall the mortality was limited and localized (*pers. obs.*). After mid-October, temperatures decreased slightly and then remained close to the 30°C level (Figure 3d).

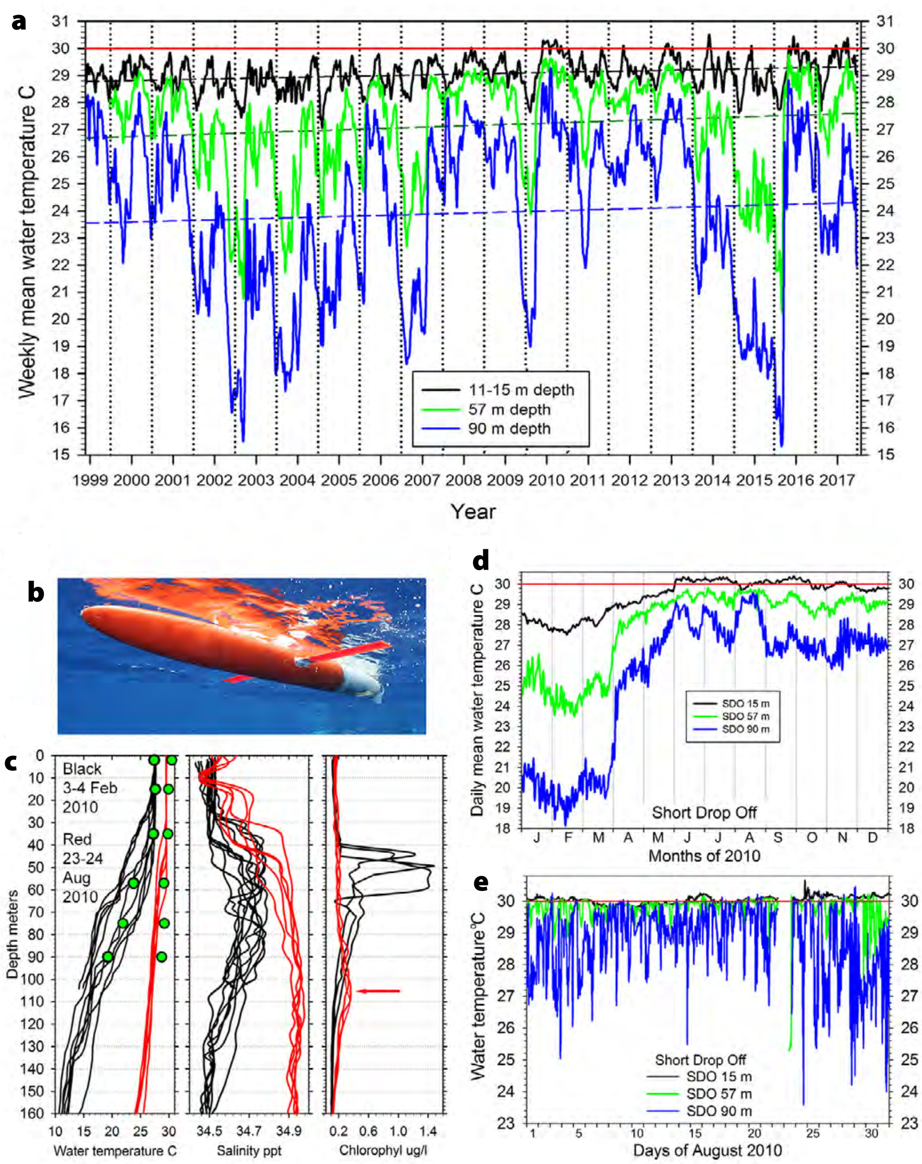


FIGURE 3. (a) Pattern of weekly mean water temperatures (MWT) on the outer slope of Palau, 1999–2017 at 15 m (black), 57 m (green), and 90 m (blue) depths. Straight-line regressions for all data at each depth are shown as dashed lines in respective colors. (b) View of the Spray glider used for profiling near the reef slope. (c) Spray glider profiles from February (El Niño) and August (La Niña) 2010 showing shifts in water column properties at that time. Mean temperatures over the same days at Short Drop Off and Ulong Rock stations (green circles) during the same time periods are shown. The red arrow indicates a faint peak in chlorophyll *a* in August. (d) Daily MWT at Short Drop Off (SDO) and Ulong Rock (ULR) during 2010. Red line indicates 30°C level beyond which bleaching may occur. (e) Detailed pattern of 30-minute water temperature measurements at Short Drop Off during bleaching event in August 2010.

THE QUASI-BLEACHING EVENT OF 2016

In mid-2013, deeper temperatures on outer slopes started decreasing rapidly (Figure 4a) while, concurrently, mean sea level (MSL) also dropped (Figure 4c,d), and by February 2016 the temperatures reached levels probably not seen since the 1997–1998 El Niño. Thermoclines were extremely shallow, and internal waves caused rapid daily temperature fluctuations at 15–57 m depth (Figure 4b). Temperatures were far below those associated with bleaching, and comfortably within the range for coral growth and survival. However, corals in very shallow and deep water did not fare well. Poorly understood "cold-water bleaching" was observed on the deep slope (Colin and Lindfield, in press). Conversely, on the shallowest reefs, the uppermost tips of branching corals, having grown ever upward during the relatively high MSL since 1998, were aerially exposed by a combination of low spring tides and low MSL (Figure 4c,d). Their upper reaches died and quickly become covered in algae (Figure 4e,f). The low monthly MSLs measured during El Niño, with values of 1,200-1,250 mm (Figure 4c), occur at intervals of several years and can stop or slow upward growth of reefs that were otherwise thought to be growing sufficiently to counter general sea level rise (van Woesik et al., 2016).

In early March 2016, both seawater temperatures and sea level dramatically and rapidly shifted in Palau, with temperatures rising at all depths (Figure 4a) and MSL rising rapidly (Figure 4c,d). Over the next 10 weeks, daily MSL rose at 7.5 mm per day and temperatures were racing toward levels that had the potential to induce massive coral bleaching and that could repeat the summer of 1998. However, in early June, the rise slowed as temperatures in shallow waters climbed just above the 30°C level, inducing bleaching only among sensitive corals. Temperatures then decreased, and bleached corals, rather than dying, quickly recovered. Modest thermal stratification had resumed by late summer. The extreme variation in 2016 provided a lesson in the variable and unpredictable conditions on western Pacific reefs, even in near-equatorial areas.

PALAU TEMPERATURE AND REEFS: WHAT HAVE WE LEARNED?

The temperature-monitoring network provides data throughout the geographic, habitat, and depth ranges of the reefs of Palau (Figure 1) over a timescale that allows some consideration of trends (Figure 3). Combined with other types of information (currents, wind shifts, other weather conditions, storm disturbance), the detailed breakdown of temperature is important when evaluating the actual thermal environments where reefs exist, and provides a needed counterbalance to and accuracy check on SSST observations. What we have learned from network data includes the following:

1. Annual patterns of temperature at different depths and locations are variable, but indicate a possible increase in temperature. The 18-year record of weekly mean temperatures on the outer slope shows the occurrence of a thermally dynamic environment (Figure 3a). Although the time frame is relatively short for climate change determinations, simple regressions (dashed lines in Figure 3a) indicate decadal upward trends of 0.29°C at 15 m, 0.49°C at 57 m, and 0.42°C at 90 m.

Annual patterns of temperature on shallow (10–15 m depth) outer reefs

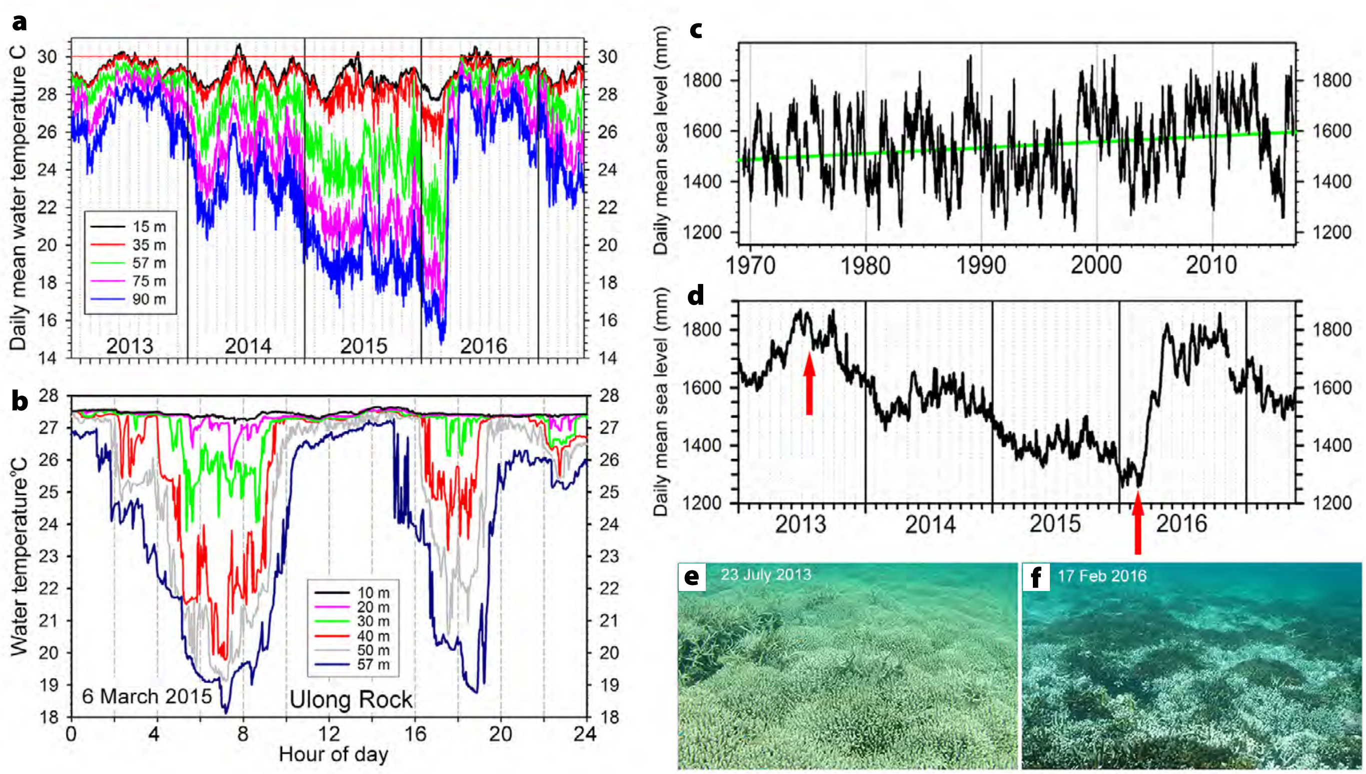


FIGURE 4. (a) Daily mean water temperatures at Short Drop Off from 2013 to mid-2017 at five depths. The red line indicates the 30°C bleaching level. (b) Water temperatures at one-minute intervals at Ulong Rock over 24 hours, March 6, 2015, during El Niño conditions with rapid changes in temperatures at given depths. (c) Daily mean sea level (MSL) as measured at Malakal Harbor tide gauge 1969–2017. Low and high peaks generally correspond with El Niño (low) and La Niña (high) in Palau. The green line shows the straight-line regression of daily MSL since 1969 with a very slow upward trend of 3 mm yr^{-1}. (d) Expanded view of daily MSL, Malakal Harbor tide gauge from 2013 to mid-2017. Red arrows indicate stage of MSL when photos (e) and (f) below were taken. (e,f) Shallow reef flat area on the north side of West Channel (Figure 1b-WC) prior to and after coral death (sections covered in brown algae) due to aerial exposure during the 2015 El Niño low sea levels.

are now well documented (Figure 5). Lagoon areas exhibit similar patterns, but are warmer by about 0.5°C. Climbing from the winter low, the highest annual temperatures occur around early June. Shortly after that peak, temperatures decrease by 0.5°–1.0°C over the next two months. The drops usually occur in concert with strong west to southwest monsoon winds that often persist for many days. During autumn, temperatures again climb slowly to a second lower peak in mid-November, then start falling toward the next annual low in February. The relative forces driving the observed patterns, particularly the summer decrease, remain to be fully determined. Also, this shallow-water pattern does not extend onto reefs at or deeper than 35 m.

The summer decrease in temperature, while usually associated with monsoon storms, does not always occur. In June 2010 as temperatures reached the level where coral bleaching had previously been observed to start (30°C), the west and southwest monsoon winds failed to occur. Shallow temperatures continued to climb when they normally would have dropped (Figure 5), and bleaching occurred. From 1999 to 2017, 2010 was the only year in which this anomalous pattern occurred, but it may be typical of what occurs during bleaching years.

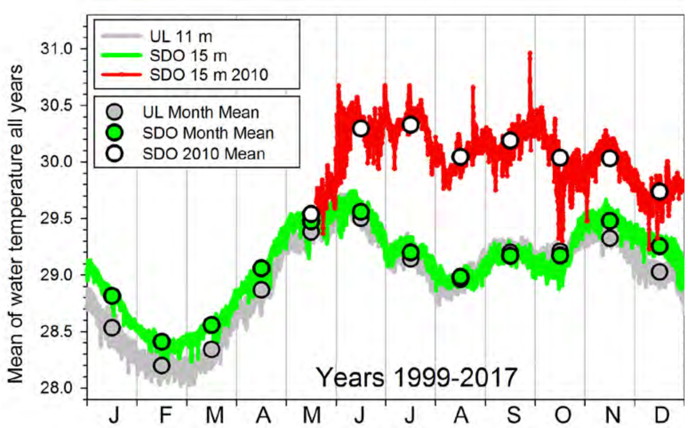


FIGURE 5. Annual pattern of water temperature at Ulong Rock (ULR) and Short Drop Off (SDO) for the period 1999–2017 from temperatures measured at 30-minute intervals averaged for all years, except 2010. Monthly mean values are shown as circles. The red curve shows all 30-minute 2010 data, including June–October bleaching, from May 20 to the end of the year, with monthly means indicated by circles.

2. There is no deep reef refuge from bleaching conditions. It has been suggested that deeper ("mesophotic") reefs may serve as refugia from conditions that negatively impact shallow reefs (Baker et al., 2016), allowing survival of reef organisms/communities eliminated by unfavorable conditions in shallow areas. However, the experience in Palau has been that bleaching also impacts deep reefs, and this observation, as well as other factors (Colin and Lindfield, in press), question their potential as climate change refugia. The occurrence of rapid shifts in outer slope temperatures due to internal waves/tides, first described for Palau by Wolanski et al. (2004), has proven to be the dominant condition on reef faces from 35 m to 90 m. Their interactions with steep slopes imply that water is regularly upwelled during El Niño periods when thermoclines are shallow (Figure 4b) and there are phytoplankton blooms in the mesophotic reef zone (Figure 3c). During La Niña induced coral bleaching, internal waves may still occur, but much deeper (below 100 m depth), so they are not detected by thermograph arrays in shallower reef waters.

There is no question now that temperatures associated with bleaching (near 30°C) can occur in Palau to depths at the lower limits of coral growth. The often unithermal profile from surface to 90 m depth during the bleaching event of 2010 (Figure 3d,e) indicates that the normal stratification in the water column disappears. While there may be mechanisms operating during El Niño and ENSO neutral periods that potentially provide cooling to reef waters through upwelling, these break down during La Niña, preventing any cooling potential to reefs from deeper waters.

3. The comparison of SSST with in situ records over years indicates a need to recalibrate their relationships. Long-term in situ temperature monitoring provides the data sets necessary to fully evaluate the accuracy of SSST and its relationship to deeper reef environments. If the assumption is made that in situ data are accurate within the limits of their precision and their calibration, this allows the critical comparison with remote-sensing-derived values. A preliminary analysis indicates that the accuracy of SSST compared to in situ values decreases with increasing depth (Figure 6). Comparing daily mean temperatures for three years with different ENSO conditions (2010 – La Niña, 2015 – El Niño, 2013 – neutral) provides an informative perspective. During 2010 (a bleaching year), daily means to 35 m were highly correlated with SSST (Figure 6), understandable since the water column was nearly unithermal much of the time. However, 2015 with its El Niño and cool water relatively shallow, did not have a close correlation, reflecting the cooler temperatures found at 15 m and 35 m depth. The ENSO neutral year (2013) was intermediate, but still demonstrated a decreasing correlation between in situ and daily SSST with depth. Although there can be a significant correlation between daily SSST and daily mean in situ measurements, it should also be remembered that there are often errors of some magnitude on any single day between SSST and in situ values. Efforts are needed to understand why these differences occur and what steps can be taken to modify SSST processing to reduce errors and thus increase the accuracy of heat estimates used in predicting bleaching conditions.

4. Monthly mean temperatures and sea level are closely correlated for deeper reefs. Monthly mean sea level (MMSL) has a close relationship with monthly mean water temperature at 90 m depth (Figure 7), with decreasing correlation as depth decreases. It provides a way to look into the heat content found on deeper reefs by measuring sea surface height (SSH) through remote-sensing or tide gauge data. Use of MMSL has been proposed (Travis Schramek, Scripps Institution of Oceanography, *pers. comm.*, 2018) as an additional metric (in combination with SSST) for developing predictions of coral bleaching conditions on reefs where there is no temperature monitoring at depth.

5. Temperature monitoring networks are important tools for examining both reef environments and their surrounding ocean waters. The present network shows the value in having many permanent thermograph stations at different depths and habitats to thoroughly document conditions within an island/reef system. With changing climate, the need for longer and more comprehensive temperature monitoring stations directly on reefs is critical. Gathering extensive data, which might seem excessive and unneeded at present, ensures that when and if such data are needed to help explain unanticipated events, the data will be there. Compared to the costs of doing many types of oceanographic monitoring, those related to starting and maintaining a water temperature monitoring network are relatively low.

Vertical arrays of thermographs can be installed on outer reef areas with steep slopes at specific depths, ideally in holders attached permanently to the reefs, with each station marked by subsurface floats for easy relocation. Instruments can be exchanged at intervals of months to years. If properly set up, it only requires a few seconds for a diver to exchange instruments at a given depth. The quick-exchange capability allows installation at deeper depths, including those accessible by mixed gas rebreather diving, for improved collection of data on internal waves and ENSO thermal shifts.

FUTURE DIRECTIONS AND EFFORTS

1. There is a need for enhanced understanding of the relationship between remote-sensing and in situ temperature data. Since the 1980s, perhaps no group of environmental researchers has

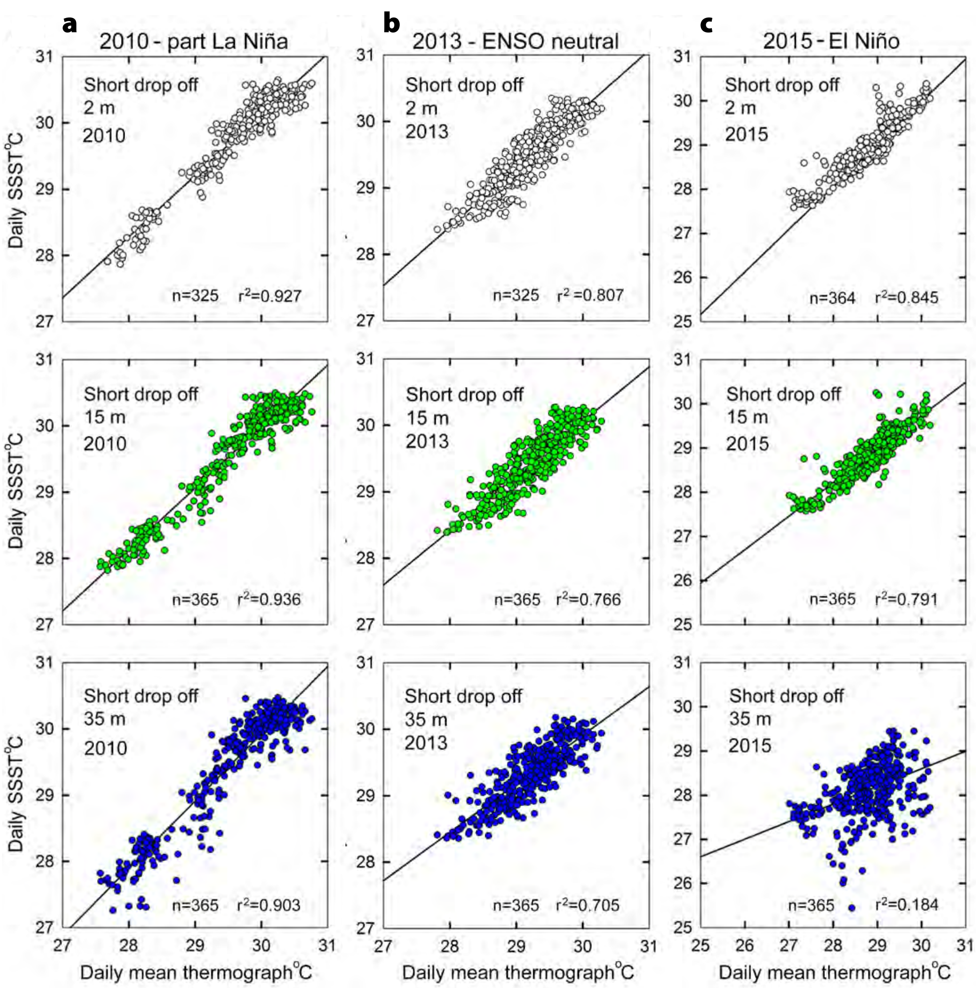


FIGURE 6. Comparisons of daily satellite sea surface temperature (SSST) from NOAA Coral Reef Watch and daily mean values from 30-minute thermograph temperature data from Short Drop Off at 2 m, 15 m, and 35 m depths. Values for r^2 are shown in lower right corners. (a) Values from the 2010 partial La Niña coral bleaching year, with close relationships between SSST and thermograph data at all depths. (b) Values from the 2013 ENSO neutral year with relationships between SSST and thermograph data decreasing with depth. (c) Values from the 2015 El Niño year with relationships between SSST and thermograph data decreasing with depth, particularly compared to 2013.

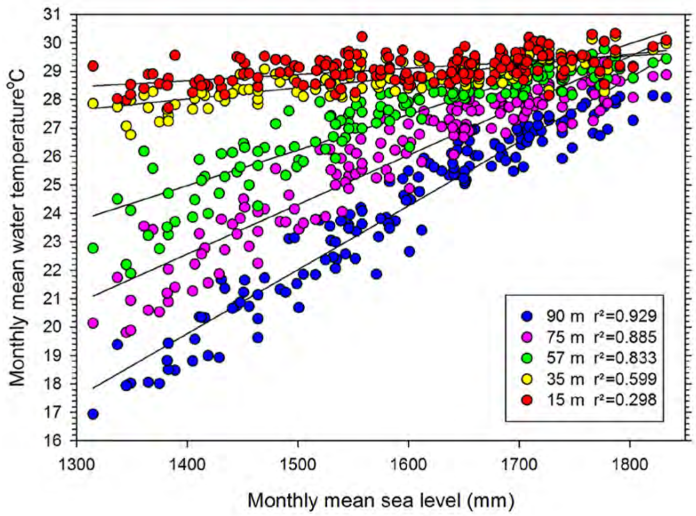


FIGURE 7. Comparison over 15 years of monthly mean sea level with monthly mean water temperature at five depths in Palau, from Short Drop Off 2000–2014.

more thoroughly embraced the globality of SSST measurements than coral reef scientists (Mumby et al., 2004), with numerous bleaching studies relying almost exclusively on SSST data (e.g., Peñaflor et al., 2009; Guest et al., 2012; Ainsworth et al., 2016). Despite this acceptance, there are some important caveats with regard to using SSST values.

Data from established in situ reef stations using accurate calibrated instruments are the gold standard temperature records for coral reefs, and increased in situ monitoring on coral reefs at all depths is needed. Other types of new oceanographic technology, such as profiling gliders, can provide additional important thermal data not available from instrument arrays. Sea level data from tide gauges and satellite-derived SSH information holds promise for improving understanding of remotely monitored coral bleaching conditions and should be incorporated into the systems in place for assessing bleaching risk. The relationships between remote-sensing and in situ instrument temperature data need to be reexamined, with the goal of increasing accuracy of remote data to reflect thermal conditions throughout the water column where reefs exist. To truly understand the implications of a warming ocean on coral reefs and other tropical marine habitats requires more attention to gathering baseline information and understanding present-day thermal dynamics. Given global trajectories, the preliminary indication of increasing temperatures on shallow and deep reefs in Palau is not surprising, yet the large and unpredictable variations there produce uncertainty about the reliability of trends.

2. The thermal conditions on shallow-flat reefs need more attention. Shallow reef areas generally have elevated temperature regimes and need increased attention to determine whether they have the potential to be the drivers of evolution and/or adaptation toward increased temperature tolerance through a combination of symbiont-host factors. Shallow reefs are very important locations where "greater high-frequency temperature variability may represent particularly important opportunities to conserve coral ecosystems against the major threat posed by warming ocean temperatures" (Safaie et al., 2018). Studies looking at areas with highly elevated temperatures in isolated pools along island shores, a relatively rare habitat, have found evidence for adaptation on several levels (Thomas et al., 2018). Shallow reef areas are a much more widespread habitat, found along the thousands of kilometers of barrier reefs of Indo-West Pacific reefs, and need more attention in this regard, as they are a nearby potential source for new propagules if deeper outer slope coral communities are devastated by bleaching.

3. The importance and effects of upwelling on coral reef futures need attention. It has been suggested that the upwelling of cool water from deeper environments may produce areas where coral bleaching is less likely in a given reef area (Skirving et al., 2010; Guest et al., 2012). Identifying such areas as "resistant" to bleaching conditions, potentially to be preserved as marine protected areas, is appealing, but relies on the upwelling of cool water during bleaching events. Our data show this is unlikely in Palau. Prior to the 2010 bleaching event, the occurrence of ~30°C water at 60–90 m depth had never been quantified on Indo-Pacific reefs, and now there is a need to examine other locations for similar attributes.

In addition to long-term vertical arrays and extensive lagoon deployments, we now have a network of 28 thermograph stations (Figure 1b) covering the entire outer slope of the main island group and sampling once per minute at 57 m depth. That depth was chosen because initial studies indicated 57 m was the depth of near maximal thermal dynamics and was a feasible depth for diving deployments. The network was installed in 2014 and is now generating around 15 million data points per year, providing the data to answer questions concerning the existence of island-trapped internal waves, the effects of storm passage, and the relationship between ENSO and thermal activity. We have also extended the 57 m network to all six of the southwest islands of Palau, with one array at each island group, giving the network a latitudinal expanse of over 500 km and crossing the main flow of the North Equatorial Countercurrent.

4. New approaches to measuring thermal stress are needed. In Palau, the relationship between SSST and temperature regimes on deeper areas breaks down starting at 10–15 m depth (Figure 6). MMSL from tide gauges or SSH from satellite measurements may provide needed insight into reef temperatures below the surface. Data from Palau support using SSH, along with SSST, to remotely measure thermal conditions associated with coral bleaching (Travis Schramek, Scripps Institution of Oceanography, *pers. comm.*, 2018).

The realization that temperatures inducing bleaching extend into deep water during La Niña events is important; in many locations, deeper reefs may have already been severely degraded by undetected bleaching. Unquestioned use by some of SSST data for most considerations of thermal regimes on reefs needs to be reexamined. There is also a risk in assuming that relatively short data collection periods provide information that is representative of temporal dynamics. Experience in Palau indicates periods of a year or less provide little understanding of the longer-term conditions found on reefs. This is particularly true for deeper reef areas.

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AUTHOR

Patrick L. Colin (crrfpalau@gmail.com) is Director, Coral Reef Research Foundation, Koror, Palau.

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TAB 3

Climate Change in Palau

PIRCA 2020

Indicators & Considerations for Key Sectors

Report for the Pacific Islands Regional Climate Assessment (PIRCA)

EAST-WEST CENTER

pirca PACIFIC ISLANDS REGIONAL CLIMATE ASSESSMENT

EAST-WEST CENTER

The East–West Center promotes better relations and understanding among the people and nations of the United States, the Pacific, and Asia through cooperative study, research, and dialogue. Established by the US Congress in 1960, the Center serves as a resource for information and analysis on critical issues of common concern, bringing people together to exchange views, build expertise, and develop policy options.

The Center's 21-acre Honolulu campus, adjacent to the University of Hawai'i at Mānoa, is located midway between Asia and the US mainland and features research, residential, and international conference facilities. The Center's Washington, DC, office focuses on preparing the United States for an era of growing Asia Pacific prominence.

The East–West Center hosts the core office of the Pacific RISA grant, providing administrative and research capabilities for the program. The Pacific RISA is one of the 11 National Oceanic and Atmospheric Administration (NOAA) Regional Integrated Sciences and Assessments (RISA) teams that conduct research that builds the nation's capacity to prepare for and adapt to climate variability and change. This work is supported by funding from NOAA. The Pacific RISA provided primary oversight of this and the 2012 PIRCA report.

EastWestCenter.org
PacificRISA.org

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About PIRCA and this Report

Climate Change in Palau: Indicators and Considerations for Key Sectors is a report developed by the Pacific Islands Regional Climate Assessment (PIRCA). It is one in a series of reports aimed at assessing the state of knowledge about climate change indicators, impacts, and adaptive capacity of the US-Affiliated Pacific Islands (USAPI) and the Hawaiian archipelago. PIRCA is a collaborative effort engaging federal, state, and local government agencies, non-governmental organizations, academia, businesses, and community groups to inform and prioritize their activities in the face of a changing climate.

The initial phase of PIRCA activities was conducted during June–October 2019 and included meetings and workshops in American Sāmoa, the Republic of Palau, the Commonwealth of the Northern Mariana Islands (CNMI), and Guam. Draft PIRCA reports were developed and refined through engagement with the PIRCA network. The material presented in this report is based largely on published research and insights from participants in PIRCA activities. The PIRCA Advisory Committee reviewed this report. Workshop participants and reviewers independent of the PIRCA workshops who made contributions are recognized as Technical Contributors.

The Pacific Regional Integrated Sciences and Assessments (Pacific RISA) program has primary oversight of the 2020 PIRCA. The Pacific RISA is funded by the US National Oceanic and Atmospheric Administration (NOAA) and supported through the East-West Center. Key partners and supporters are NOAA's National Centers for Environmental Information (NCEI), the Department of the Interior's Pacific Islands Climate Adaptation Science Center (PI-CASC), and the US Global Change Research Program (USGCRP).

This series represents the latest assessment in a sustained process of information exchange among scientists, businesses, governments, and communities in the Pacific Islands region that began with the 2012 PIRCA (which produced *Climate Change and Pacific Islands: Indicators and Impacts,* Island Press). We anticipate that in conjunction with other collaborative regional assessment efforts, the PIRCA reports will provide guidance for decision-makers seeking to better understand how climate variability and change impact the Pacific Islands region and its peoples.

The PIRCA Advisory Committee

Keith Bettinger, East-West Center; **Kristie Ebi,** University of Washington Environmental and Occupational Health Sciences; **Yimnang Golbuu,** Palau International Coral Reef Center; **Jamie Gove,** NOAA Fisheries; **Mari-Vaughn V. Johnson,** Pacific Islands Climate Adaptation Science Center; **Heather Kerkering,** Pacific Islands Climate Adaptation Science Center; **William Kostka,** Micronesia Conservation Trust; **Darren T. Lerner,** University of Hawaiʻi Sea Grant College Program; **Karena Lyons,** East-West Center; **John J. Marra,** NOAA National Centers for Environmental Information; **Dan Polhemus,** US Fish and Wildlife Service

Aerial view of the Rock Islands
Southern Lagoon World Heritage Site.
Photo: Stuart Westmorland

Key Issues for Managers and Policymakers

Increasing air temperatures — Hot days have increased in Palau, while the frequency of cool nights has declined.

Coral reef bleaching and loss — Oceans are warming, causing coral bleaching events to become more common and severe. Widespread coral bleaching is projected to occur annually in Palau by 2040.

Stronger storms and typhoons — Tropical cyclone intensity is projected to increase, with a greater frequency of intense (higher category) tropical cyclones. However, the total number of cyclones is expected to decrease or remain the same.

Sea level rise — Palau experiences large fluctuations in sea level from year to year due to the El Niño—Southern Oscillation and Pacific Decadal Oscillation. Despite this natural variability, sea level is rising in Palau and will exacerbate high tide flooding, storm surge, and coastal erosion.

Changing rainfall patterns — Average rainfall is projected to increase, especially in the wet season, while the frequency and duration of drought is expected to decrease in Palau.

More extreme rainfall and flooding — Extreme rainfall events are projected to become more frequent and intense for Palau, increasing runoff and the risk of flooding.

Risks to freshwater — Hotter temperatures increase the demand for water and decrease freshwater availability. Saltwater intrusion during storms and tidal flooding and over-extraction from wells endanger local aquifers.

Threats to ecosystems and biodiversity — Increased air and ocean temperatures, changes in ocean chemistry, more intense storms, and changing rainfall patterns are expected to impact Palau's ecosystems.

Community safety during and after storms — More powerful tropical cyclones are projected. Health risks increase with storms when infrastructure and housing are damaged, and electricity, sanitation, food/water supplies, communication, and transportation are disrupted.

Human health and warming temperatures — More frequent extreme heat events are expected to increase heat-related illness and death. People who work outdoors, children, older adults, and individuals with chronic illnesses are at greater risk to heat-related illnesses.

Threats to infrastructure — The majority of Palau's population and infrastructure are in low-lying coastal areas. Most rural schools in Palau are built in locations identified as vulnerable to climate change. The potential vulnerability of critical infrastructure like the national hospital and main port need to be assessed.

Food security — Warming air and ocean temperatures, changes in ocean chemistry and rainfall patterns, and the increased intensity of storms are all expected to impact human food systems both in Palau and globally.

Equity considerations — Social, economic, and geographic factors shape people's exposure to climate-related impacts and how they are able to respond. Those who are already vulnerable—including children, the elderly, low-income communities, and individuals with disabilities—are at greater risk in extreme weather and climate events, in part because they are often excluded from planning processes.

Palau is home to some of the best managed
and most pristine reefs in the world.
Photo: Getty Images

Climate Change in Palau: Indicators and Considerations for Key Sectors

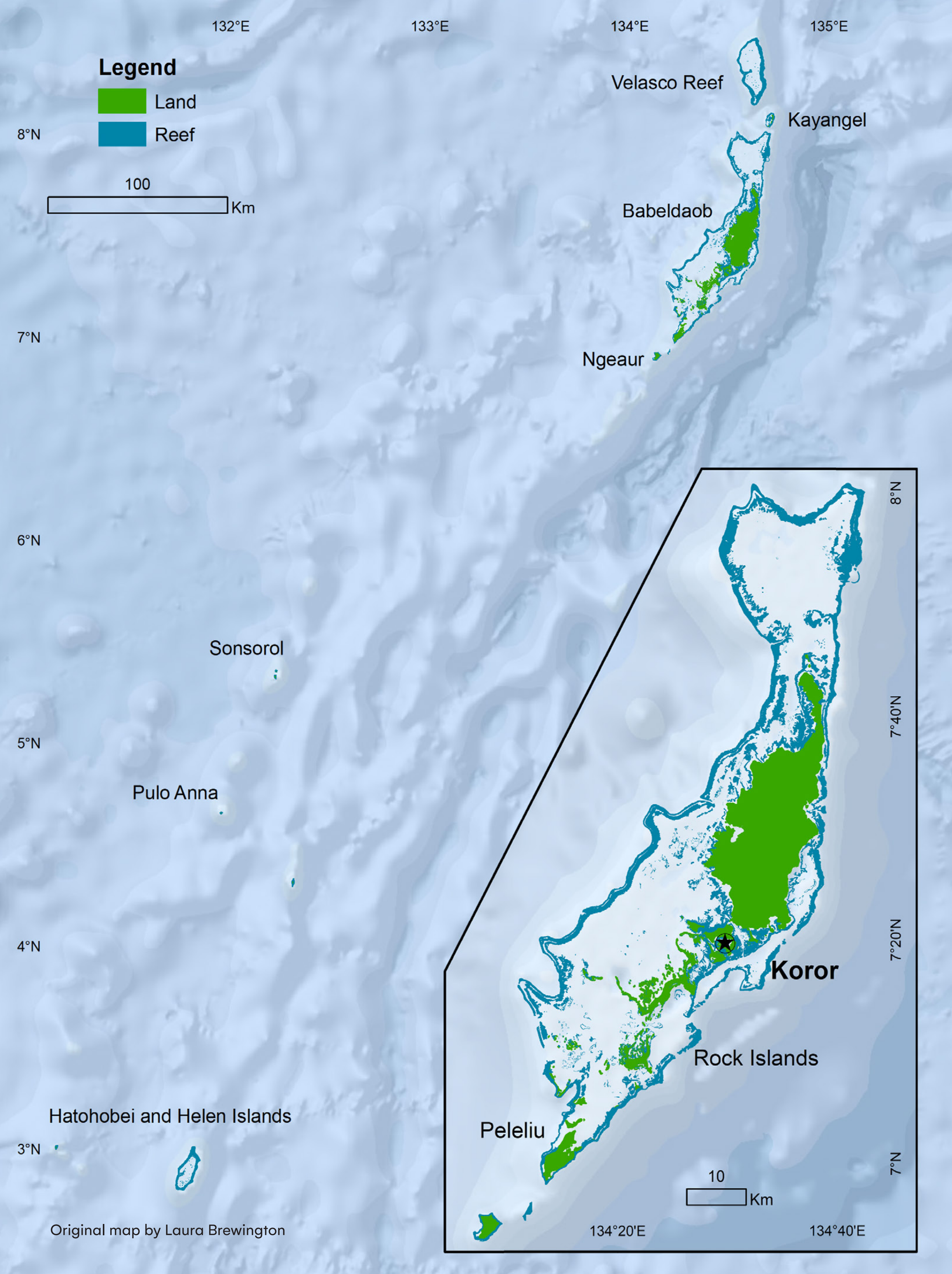
Report for the Pacific Islands Regional Climate Assessment (PIRCA)

Coordinating Authors: Wendy Miles, East-West Center; **Zena Grecni,** East-West Center; **Erbai Xavier Matsutaro,** Office of Climate Change; **Patrick Colin,** Coral Reef Research Foundation; **Victoria Keener,** East-West Center; **Yimnang Golbuu,** Palau International Coral Reef Center

Technical Contributors: Joseph Aitaro, Office of Climate Change; **Eunice Akiwo,** Bureau of Domestic Affairs, Ministry of State; **Hefflin Bai,** Palau National Communications Corporation; **Umai Basilius,** Palau Conservation Society; **Meked Besebes,** Bureau of Aging, Disability and Gender, Ministry of Community and Cultural Affairs; **Dennis Blaluk,** Palau Public Lands Authority; **Laura Brewington,** East-West Center; **Tutii Chilton**, Palau Energy Administration; **Calvin Emesiochel,** Bureau of Cultural and Historical Preservation, Ministry of Community and Cultural Affairs; **Omar Faustino,** Palau Protected Areas Network; **Abby Frazier,** East-West Center; **Skilang Harold,** Airai State Government; **Adelle Lukes Isechel,** Ministry of Natural Resource, Environment, and Tourism; **Charlene Mersai,** Palau National Environmental Protection Counsel; **Kevin Mesebeluu,** Palau Ministry of Natural Resources, Environment, and Tourism; **Metiek K. Ngirchechol,** Palau Environmental Quality Protection Board; **Tessy Nobuo,** Omekesang; **Celine Oiterong,** Palau Public Lands Authority; **Sharon Patris,** Coral Reef Research Foundation; **Victor Tyson Philip,** Airai State Government; **Richard Ruluked,** Palau National Communications Corporation; **Klouldil Singeo,** Palau Bureau of Aging, Disability and Gender, Ministry of Community and Cultural Affairs; **Kiblas Soaladaob,** United Nations Development Program Small Grants Programme; **William V. Sweet,** NOAA National Ocean Service; **Gerald Tulop,** Palau Energy Administration; **Darlynne Takawo,** Palau Automated Land and Resource Information System (PALARIS); **John Takesy,** Omekesang; **Eden Uchel,** Division of Environmental Science, Bureau of Public Health, Ministry of Health; **Matthew Widlansky,** University of Hawaiʻi Sea Level Center; **Wayne Wong,** Palau Red Cross Society

A bird's-eye view of the city of Koror.
Photo: Norimoto (Getty Images)

Inside this Summary



132°E
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Kayangel
Babeldaob
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Pulo Anna
Hatohobei and Helen Islands
8°N
7°40'N
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10
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134°20'E
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Original map by Laura Brewington

Global Climate Change: Causes and Indicators

The causes of climate change

Scientists have investigated the physical science of climate change for almost two centuries. Carbon dioxide and other greenhouse gases in the atmosphere capture some of the heat from the Sun's energy that radiates from Earth's surface, preventing it from escaping back into space (USGCRP 2018, Ch. 1, Overview). Known as the "greenhouse effect," this process keeps Earth habitable for life. However, human activities have emitted an increasing amount of greenhouse gases into the atmosphere since the late 1800s through burning fossil fuels (such as oil, gas, and coal) and, to a lesser extent, through changes in land-use and global deforestation. As a result, the greenhouse effect has intensified and driven an increase in global surface temperatures and other widespread changes in climate. These changes are now happening faster than at any point in the history of modern civilization (USGCRP 2018, Ch. 1, Overview; USGCRP 2017, Ch. 2, Physical Drivers of Climate Change; IPCC 2014, SPM.1.2).

Although natural climate cycles and other factors affect temperatures and weather patterns at regional scales, especially in the short term, the long-term warming trend in global average temperature documented over the last century cannot be explained by natural factors alone (USGCRP 2018, Ch. 2, Key Message 1). Human activities, especially emissions of greenhouse gases, are the only factors that can account for the amount of warming observed over the past century (USGCRP 2018, Ch. 2, Key Message 1; IPCC 2014, SPM.1.2). The largest contributor to human-caused warming has been carbon dioxide emissions. Natural factors alone would have actually had a slight cooling effect on climate over the past 50 years (USGCRP 2018, Ch. 2, Key Message 1).

How is climate changing?

Long-term scientific observations show the effects of increasing greenhouse gas concentrations in the atmosphere on the climate system. The factors observed to be changing are known as **indicators** of change. Data collected from around the world show, for example:

- Globally, the Earth has experienced a warming trend over the last century.
- Oceania's five warmest years in the past century have occurred since 2005, with the warmest year on record being 2019 (NOAA 2020a).
- Seas are rising, warming, and becoming more acidic.
- Some ocean species are moving toward cooler waters.
- Ice sheets and sea ice are decreasing, and glaciers and snow cover are shrinking.

These and many other changes are well-documented and are clear signs of a warming world (USGCRP 2018, Ch1, Overview, Fig. 1.2, and Ch. 2, Key Messages 3-7; IPCC 2014, SPM.1.1; also see USGCRP Indicators and EPA Indicators websites.)

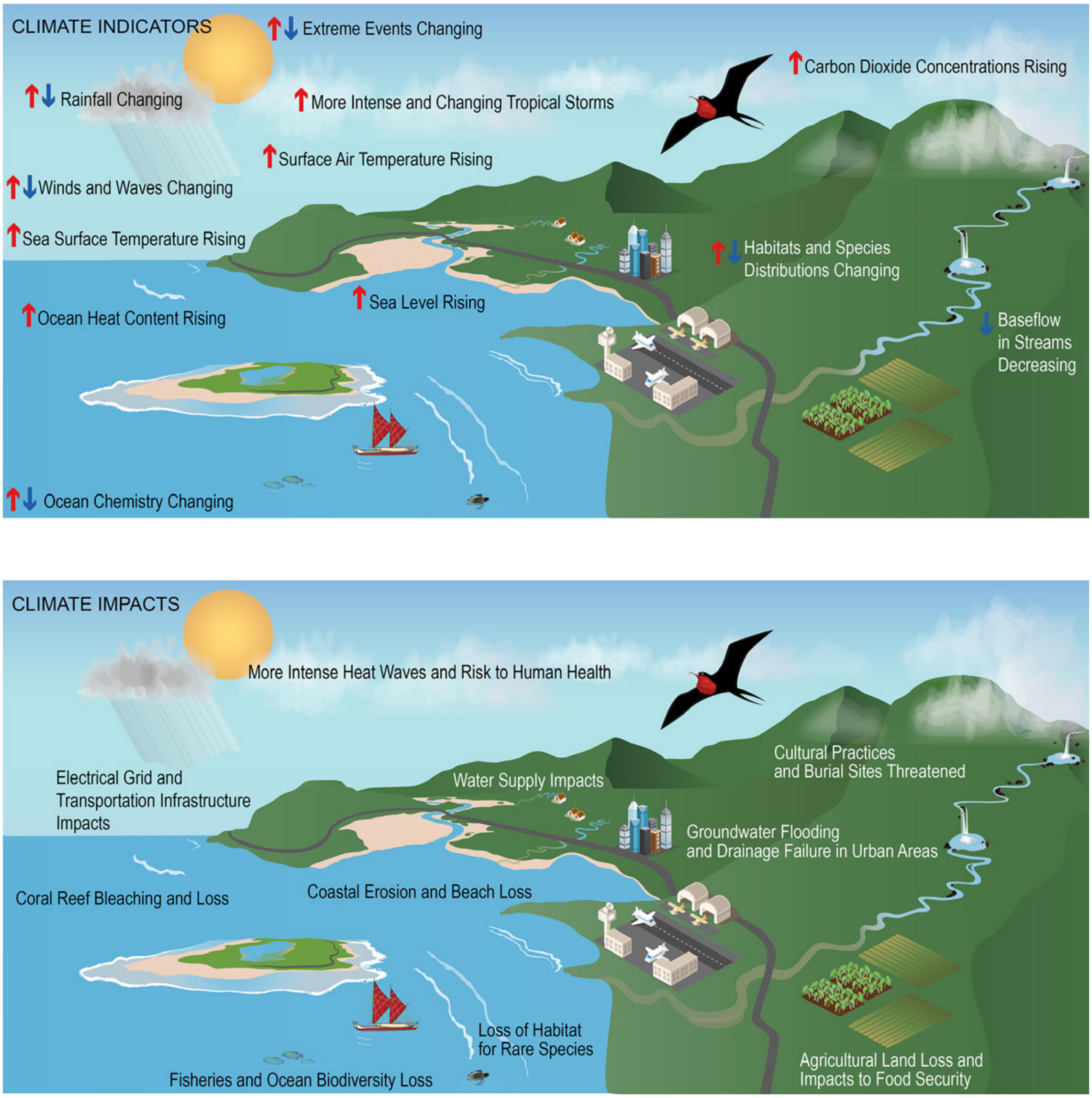


Figure 1. Observed changes in key climate indicators in the Pacific Islands, such as carbon dioxide concentration, sea surface temperatures, and species distributions result in impacts to multiple sectors and communities, including built infrastructure, natural ecosystems, and human health. In the top panel, red arrows signify an indicator is increasing, while blue arrows show the indicator is decreasing. A red and blue arrow appear together for an indicator that is changing and the direction of change varies. Source: Keener et al. 2018.

As in all regions of the world, the climate of the Pacific Islands is changing. The top panel of Figure 1 summarizes the changes that have been observed by scientists through several key indicators. The impacts of climate change (lower panel) are already being felt in the Pacific Islands, and are projected to intensify in the future (Keener et al. 2018).

Future changes

Greenhouse gas emissions from human activities will continue to affect the climate over this century and beyond; however efforts to cut emissions of certain gases could help reduce the rate of global temperature increases over the next few decades (USGCRP 2018, Ch. 1, Overview and Ch. 2, Key Message 2).

The largest uncertainty in projecting future climate conditions is predicting the actions that human society will take to reduce greenhouse gas emissions in the coming years (USGCRP 2018, Ch. 2, Key Message 2; IPCC 2014, SMP.2.1). Climate models representing our understanding of historical and current climate conditions are often used to project how our world will change under future conditions. To understand how different levels of greenhouse gas emissions could lead to different climate outcomes, scientists use plausible future scenarios—known as Representative Concentration Pathways (RCPs)—to project temperature change and associated impacts (USGCRP 2018, Guide to the Report). The "high scenario" (RCP8.5) represents a future where reliance on fossil fuels and annual greenhouse gas emissions continue to increase throughout this century. The "low scenario" (RCP4.5) is based on reducing greenhouse gas emissions (to about 85% lower emissions than the high scenario by the end of the 21st century).

Current greenhouse gas emissions far outpace lower emissions pathways and are currently tracking higher than the high scenario (RCP8.5). Human activities have caused approximately 1.0°C of warming above pre-industrial levels (IPCC 2018, A.1). Limiting global warming to 1.5°C, while physically possible, would require rapid and far-reaching transitions in energy, land, cities, transportation, and industrial systems (IPCC 2018, C.2).

This report summarizes the long-term changes and future projections for key climate indicators in the Republic of Palau. Later sections describe: climate change issues facing families and households in Palau; extreme weather and climate-related risks and considerations for managers and decision-makers; and identified needs for information and research. The findings draw from published literature on climate science, climate risks in the Pacific Islands, and risk management approaches. A workshop held in Palau in July 2019, collaboratively by the Palau Office of Climate Change and Pacific RISA, gathered knowledge that informed the report content and identified needs for information and research.

Indicators of Climate Change in Palau

The indicators of climate change in Palau build upon the *State of Environmental Conditions in Hawai'i and the U.S. Affiliated Pacific Islands under a Changing Climate: 2017* (Marra and Kruk 2017), *Climate Variability, Extremes and Change in the Western Tropical Pacific: 2014* (Australian BOM and CSIRO 2014), and work of the Intergovernmental Panel on Climate Change (IPCC). These indicators were derived through formal and informal discussions with a variety of stakeholders in the public and private sectors and members of the scientific community. Criteria for indicator selection included regional and local relevance and an established relationship to climate change and variability.

Air Temperature

Indicator	How has it changed?	Projected future change
Hot days	↑	↑
Cool nights	↓	↓
Average air temperature	↑	↑

Air temperature factors into many realms of decision-making, from public health to utilities and building construction, and air temperature is also a key indicator of climate change.

The number of **hot days** (above 90°F/32°C) in Koror has increased from an average of about 46 days per year in the first decade records were kept (1952–1961) to 100 days per year in the last decade (2009–2018) (NOAA 2020c) (Fig. 2).

The number of **cool nights** (below 74°F/23.5°C) has decreased. Koror experienced an average of about 40 cool nights per year in the first decade on record (1952–1961), versus only 13 nights per year in the last decade (2009–2018) (NOAA 2020c) (Fig. 3).

In Palau, average **air temperature** has increased (Australian BOM 2020; NOAA 2020c) (Fig. 4). At Koror, an increase in maximum daily temperatures of 0.36°F (0.2°C) per decade on average since 1951 makes up much of the increase in average air temperature (Australian BOM and CSIRO 2014). Only the minimum daily temperature warming trend in the dry season (November–April) is statistically significant at the 5% level (Australian BOM and CSIRO 2014).

Fig.2

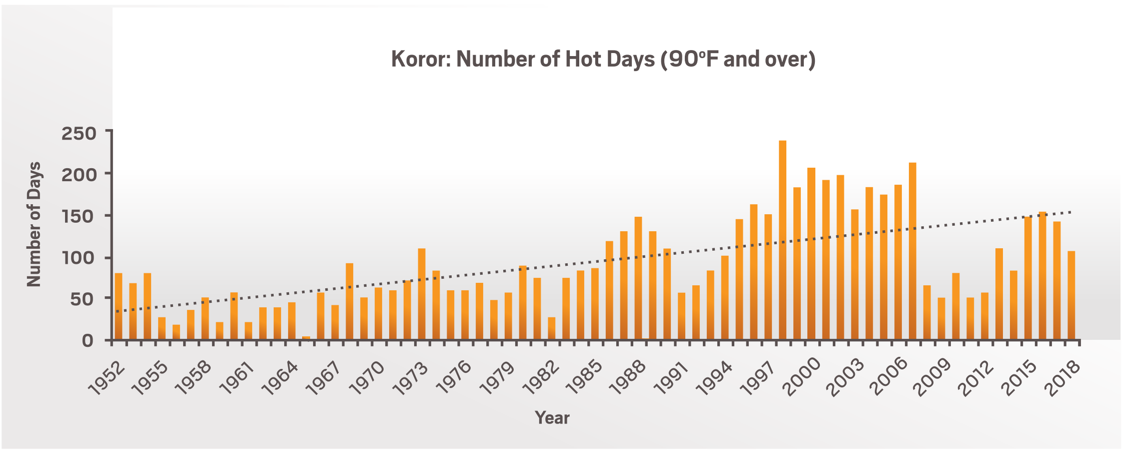


Figure 2. Annual count of days with maximum temperature of 90ºF (approximately 32ºC) or hotter (temperatures at or above the 90th percentile). Over the period of 1952 to 2018, the number of hot days increased at a rate of 1.81 days per year on average (black dotted line). Original figure by Abby Frazier, using data from the NOAA GHCN-Daily database for 1952–2018 (NOAA 2020c; Menne et al. 2012).

Fig.3

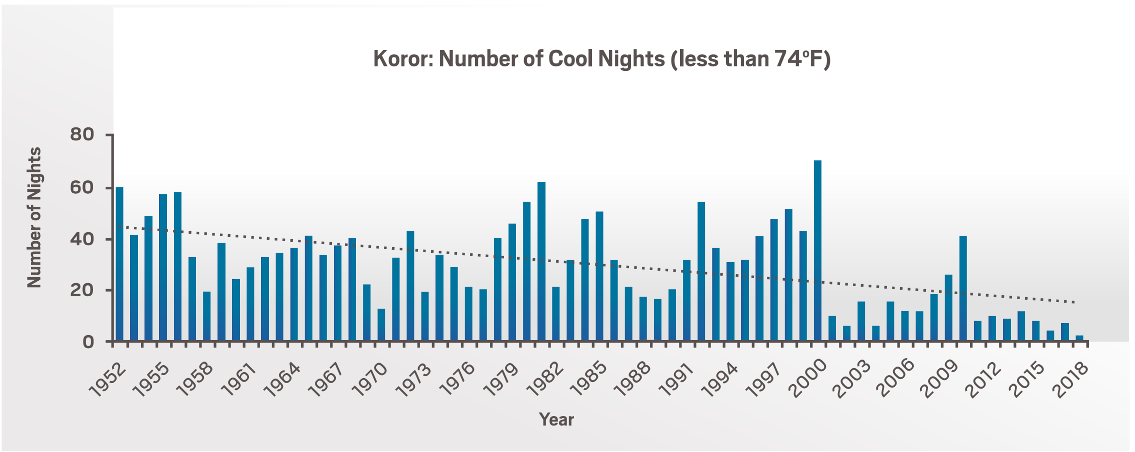


Figure 3. Annual count of nights with minimum temperature less than the 10th percentile (roughly 74ºF or 23.5ºC) for the entire record at Koror. Over the period of 1952 to 2018, the number of cool nights decreased at a rate of 0.42 nights per year on average (black dotted line). Original figure by Abby Frazier, using data from the NOAA GHCN-Daily database for 1952–2018 (NOAA 2020c; Menne et al. 2012).

Fig.4

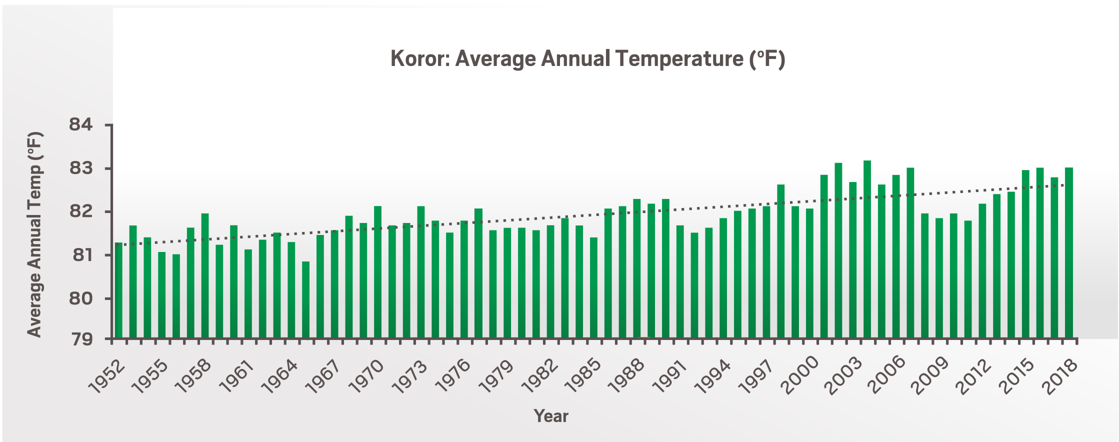


Figure 4. Average annual temperature in Koror, Palau (ºF). During the period of 1952 to 2018, average annual temperatures increased at a rate of 0.02ºF per year (black dotted line). Original figure by Abby Frazier, using data from the NOAA GHCN-Daily database for 1952–2018 (NOAA 2020c; Menne et al. 2012).

Surface air temperature is expected to continue to increase this century (Table 1). Compared to the period of 1986 to 2005, under the high scenario (RCP8.5) annual average air temperature in Palau is projected to rise 1.1–1.8°F (0.6–1.0°C) by 2030, 1.8–3.4°F (1.0–1.9°C) by 2050, and as much as 3.8–7.2°F (2.1–4.0°C) by 2090 (Australian BOM and CSIRO 2014). Increases in average air temperatures will result in a rise in the number of hot days and warm nights and a decrease in cooler weather.

	2030		2050		2070		2090	
	ºF	ºC	ºF	ºC	ºF	ºC	ºF	ºC
Low Scenario (RCP4.5)	0.9–1.8	0.5–1.0	1.3–2.5	0.7–1.4	1.6–3.2	0.9–1.8	1.8–3.8	1.0–2.1
High Scenario (RCP8.5)	1.1–1.8	0.6–1.0	1.8–3.4	1.0–1.9	2.9–5.6	1.6–3.1	3.8–7.2	2.1–4.0

Table 1. Projected increases in annual average air temperature in Palau, compared to the period of 1986 to 2005. Source: Adapted from the Pacific-Australia Climate Change Science and Adaptation Planning Program's "Current and future climate of Palau" (Australian BOM and CSIRO 2014).

Rainfall

Indicator	How has it changed?	Projected future change
Average rainfall	No change	↑
Extreme rainfall frequency	No change	↑

On islands, rainfall is the primary source of all fresh water, making it essential to human communities and ecosystems. Rainfall patterns across Palau are strongly linked to El Niño–Southern Oscillation (ENSO) events, the location of the Intertropical Convergence Zone, and seasonal monsoons (NOAA 2015). As a result, Palau's rainfall is highly variable from year to year. The driest periods on record have been correlated with strong El Niño events, occurring in 1982–1983, 1997–1998, and 2015–2016. During each of these periods, Palau experienced droughts and acute water shortages which resulted in water rationing (Polhemus 2017; Rupic et al. 2018).

Fig.5

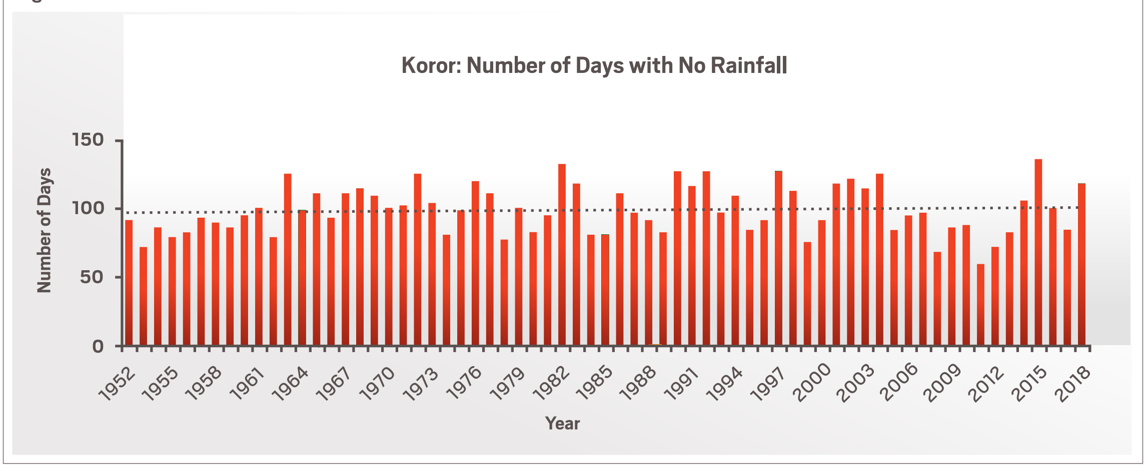


Figure 5. Annual count of days with no rainfall (0 inches) for the entire record at Koror (1952–2018). The black dotted line indicates the linear trendline, showing no measurable long-term change in number of days with no rainfall. Original figure by Abby Frazier, using the NOAA GHCN-Daily database for 1952–2018 (NOAA 2020c; Menne et al. 2012).

At Koror, **average daily and annual rainfall** trends show no long-term change since record keeping began. The number of days with no rainfall has varied year to year, but has not significantly changed since 1952 (Fig. 5). Average rainfall is expected to increase, especially in the wet season. This is consistent with the projected increase in intensity of the West Pacific Monsoon and the Intertropical Convergence Zone over Palau (Australian BOM and CSIRO 2014).

Palau will most likely experience more frequent and intense **extreme rainfall events** in the future with global warming. Extreme daily rainfall has changed little on average since the 1950s (Fig. 6). However, in the future, a 1-in-20 year event is anticipated to become, on average, a 1-in-8 year event under the low scenario and a

Fig.6

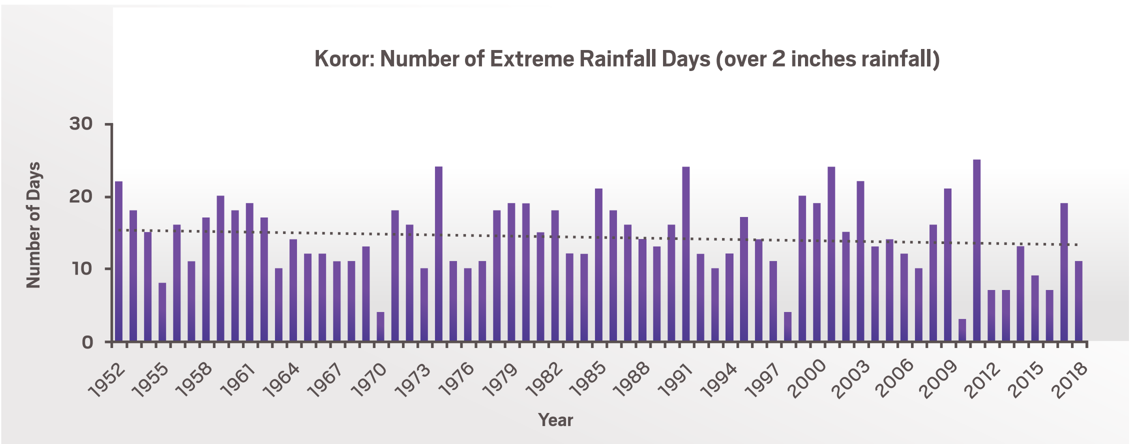


Figure 6. Annual count of days with rainfall greater than 2 inches (51 mm) at Koror (corresponding approximately to the 95th percentile of daily rainfall). For comparison, about 2.7 inches (69 mm) of rain fell in 24 hours at Koror during Typhoon Bopha on December 3, 2012. The black dotted line indicates the linear trendline, showing little change amidst considerable annual variation. Original figure by Abby Frazier, using the NOAA GHCN-Daily database for 1952–2018 (NOAA 2020c; Menne et al. 2012).

Indicator	How has it changed?	Projected future change
Frequency of drought	No change	↓
Duration of drought	No change	↓

1-in-4 year event under the high scenario by 2090 (Australian BOM and CSIRO 2014). Increased heavy rainfall events would result in increased runoff and increased potential for flooding.

Palau is expected to spend less time overall in drought under all future warming scenarios. The **frequency of drought** is projected to decrease, and the **duration** of moderate, severe, and extreme droughts is projected to decrease in the future under the high scenario. The duration of mild drought events is projected to remain stable in the future under the high scenario (Australian BOM and CSIRO 2014).

Typhoons and Storms

Indicator	How has it changed?	Projected future change
Tropical cyclone frequency	No change	?
Tropical cyclone intensity	No change	↑

Typhoons and tropical storms can bring intense winds, torrential rainfall, high waves, and/or storm surge, and can have a range of impacts on lives and property when they strike.

Tropical cyclones (also known as tropical storms or typhoons depending on their strength) are not uncommon to Palau historically (CRRF 2014). Past typhoons have resulted in wave-driven inundation, destruction of coral reefs, and extensive infrastructure damage due to wind (Merrifield et al. 2019). The number of named storms, typhoons, and major typhoons has remained constant on average, with a roughly equal number of above- and below-normal seasons of cyclone activity in the western Pacific since 1980 (Marra and Kruk 2017; Knapp et al. 2010).

The annual frequency of **gale-force winds** remained relatively constant from 1981 to 2015 in the western North Pacific (Marra and Kruk 2017; Kanamitsu et al. 2002). Gale-force winds (greater or equal to 34 knots) are an indicator of storminess, and are responsible for moderate to high waves which impede boating (Marra and Kruk 2017).

There is scientific consensus that **tropical cyclone intensity** is likely to increase in a warmer climate for most regions, including around Palau (USGCRP 2017; Marra and Kruk 2017; Knutson et al. 2015; Sobel et al. 2016; Zhang et al. 2016; Widlansky et al. 2019). The change in tropical cyclone intensity is projected to affect stronger storms the most (that is, increased maximum intensities), which would amplify the potential for severe damage (Widlansky et al. 2019).

Globally, **tropical cyclone frequency** shows a slow downward trend since the early 1970s. Fewer tropical cyclones are projected to occur by the end of this century, both globally and around Palau. The overall decrease in tropical cyclones is expected because climate models suggest that the atmosphere will become more stable with continued greenhouse warming (Kossin et al. 2016; Zhang et al. 2016; Wang et al. 2016; USGCRP 2017; Widlansky et al. 2019). The Australian Bureau of Meteorology and CSIRO project a decrease in tropical cyclone formation in the northern Pacific basin, however the confidence in the projection is low since results vary across global climate models (Australian BOM and CSIRO 2014).

Kayangel Island's village center and dock—as well as the island's primary area of taro production—before (left) and after (right) Super Typhoon Haiyan. Photos: Patrick L. Colin, Coral Reef Research Foundation.

Sea Level

Indicator	How has it changed?	Projected future change
Sea level	↑	↑
Tidal flood frequency	↑	↑

Sea level rise poses many challenges to island communities and infrastructure because it brings more frequent and extreme coastal erosion, coastal flooding, and saltwater intrusion into coastal aquifers.

Palau experiences large fluctuations in sea level over variable time periods (ranging from a few weeks to years) under the influence of the El Niño–Southern Oscillation (ENSO), as well as longer-term fluctuations via the Pacific Decadal Oscillation (Qiu et al. 2019; Chowdhury et al. 2010). While overall sea level in Palau has risen since 1969, these changes have been non-linear and Palau actually experienced decreasing sea levels during the 2010s (Caldwell, Merrifield, and Thompson 2015; UHSLC 2020). Sea level in Palau varies; sometimes by as much as 1.6–2.0 feet (0.5–0.6 m) due to El Niño and La Niña events (CRRF 2020; UHSLC 2020). Despite dramatic short-term variability, **mean sea level** in Palau increased on average 0.095 inches (2.42 mm) per year from 1969 to 2016 (NOAA 2020b).

Increases in mean sea level will affect **tidal flood frequency** and magnitude. Palau's natural shifts in mean sea level will be accentuated by global sea level rise, causing high tide flooding (also known as nuisance coastal flooding) to become more common in the long term (Marra and Kruk 2017).

Fig.7

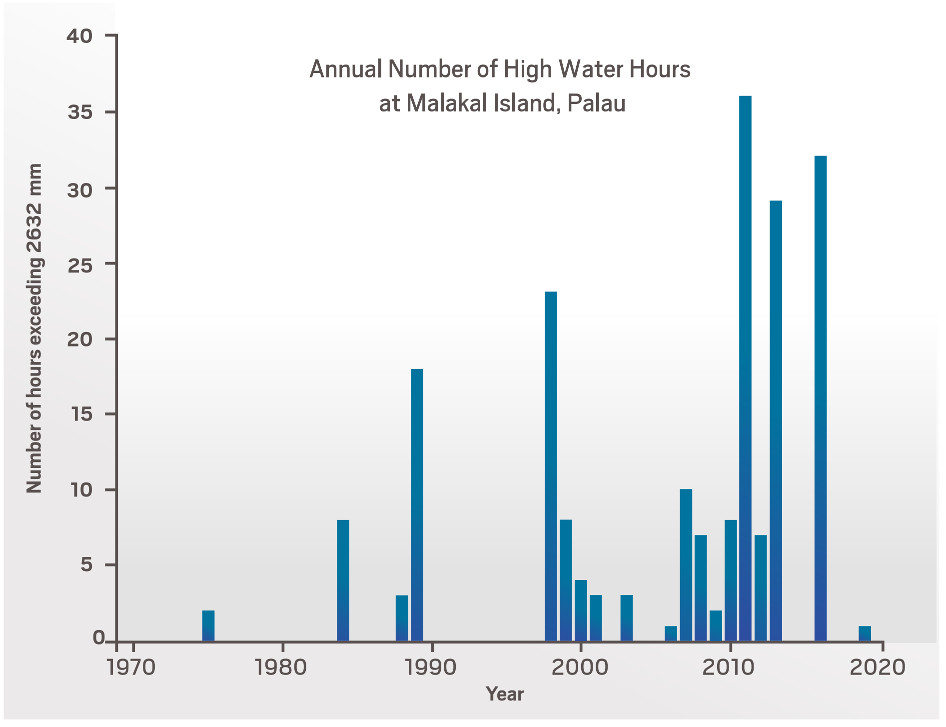


Figure 7. Number of high water hours per year at Malakal Island in Palau from 1970 to 2019. The high water threshold (2632 mm) is defined as the Mean Higher High Water level plus one-third of the difference between that and the Mean Lower Low Water level at the tide gauge (that is, water levels above the daily average highest tide plus a factor of the typical tidal amplitude). Original figure by Matthew Widlansky, using data from the University of Hawai'i Sea Level Center Station Explorer (https://uhslc.soest.hawaii.edu/stations/?stn=007#datums).

Sea level rise will continue in Palau. Compared to the year 2000, Global Mean Sea Level is projected to rise 0.3–0.6 feet (0.09–0.18 m) by 2030, 0.5–1.2 feet (0.15–0.38 m) by 2050, and 1.0–4.3 feet (0.3–1.3 m) by 2100 (USGCRP 2017; Sweet et al. 2017a). Emerging climate research indicates that by 2100, it is physically possible for Global Mean Sea Level to rise 8 feet (2.4 m) (USGCRP 2017), although the probability of this extreme outcome cannot currently be assessed and is considered low (Sweet et al. 2017a). There is *very high confidence* in the lower bounds of these projections, and it is *extremely likely* that global sea levels will continue to rise after 2100 (USGCRP 2017; Sweet et al. 2017a).

Although the world's oceans are connected, sea level is not uniform across the globe. There are variations in sea level due to winds and ocean currents, temperature changes, and changing ice and water distribution. Palau and other tropical Pacific Islands experience amplified relative sea level rise due to several of these factors (Sweet et al. 2017b). As a result, under the 2100 Intermediate-High Global Mean Sea Level Rise Scenario of 4.9 feet (1.5 m), Palau could experience another 1–1.7 feet (0.3–0.5 m) of rise for a total of 5.9–6.6 feet (1.8–2 m) by the end of the century (Sweet et al. 2017b). This effect is accounted for in Figure 8, which shows six different Global Mean Sea Level Rise scenarios applied to Koror. The probability of exceeding each of these six scenarios by 2100 is provided in Table 2.

Fig.8

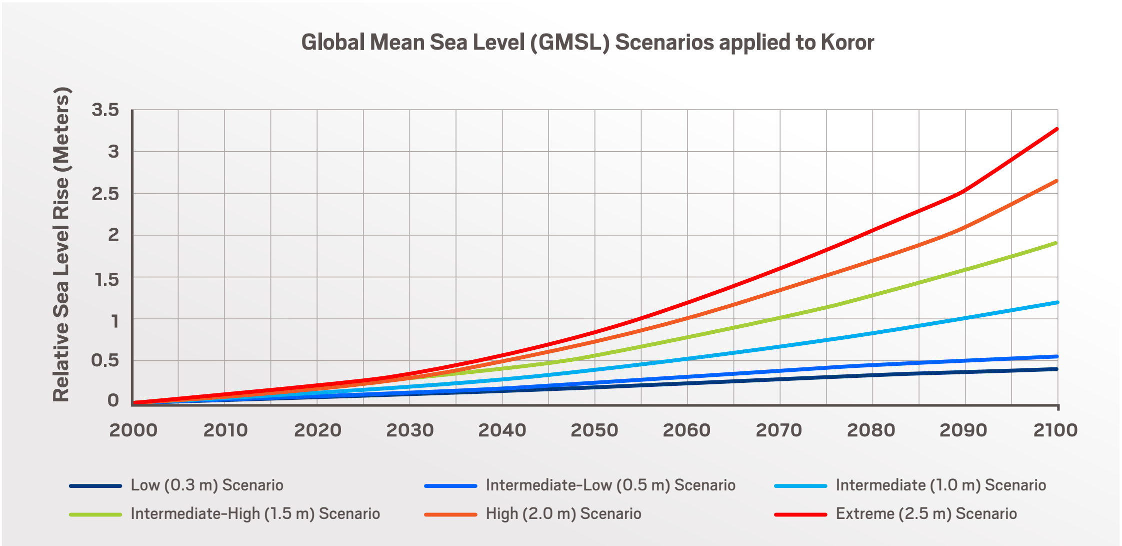


Figure 8. Six representative Global Mean Sea Level scenarios (6 colored lines) applied to Koror, Palau. The probability of exceeding each of these GMSL rise scenarios by 2100 is shown in Table 2. Sea level rise scenarios for Palau post-2100 can be found at: https://geoport.usgs.esipfed.org/terriaslc/. Source: USGS TerriaMap of Sea Level Change 2020 for Malakal B Tide Gauge in Koror (7.33ºN, 134.470ºE) and Sweet et al. 2017b.

GMSL Rise Scenario	RCP4.5	RCP8.5
Low (0.3 m)	98%	100%
Intermediate-Low (0.5 m)	73%	96%
Intermediate (1.0 m)	3%	17%
Intermediate-High (1.5 m)	0.50%	1.30%
High (2.0 m)	0.10%	0.30%
Extreme (2.5 m)	0.05%	0.10%

Table 2. Probability of exceeding Global Mean Sea Level rise scenarios in 2100. New evidence from research on the Antarctic Ice Sheet supports higher probabilities of exceeding the Intermediate-High, High, and Extreme scenarios than provided here (Sweet et al. 2017b). Source: Adapted from Sweet et al. 2017b, based on Kopp et al. 2014.

As global mean sea level continues to rise, variations in local mean sea level values related to ENSO will continue to influence the number of coastal floods in Palau each year. While a general increase in coastal floods is expected with sea level rise, the frequency and extent of extreme flooding associated with individual tropical cyclones and storms will be closely associated with the ENSO sea level state and timing of high/low tides.

In order for Palau's coral reefs to 'keep up' with sea level rise, they will need to grow vertically at rates associated with sea level rise (which might not be feasible under higher sea level rise scenarios) (van Woesik, Golbuu, and Roff 2015; van Woesik and Cacciapaglia 2018; Hongo, Kurihara, and Golbuu 2018), while also compensating for periods of lower mean sea level associated with El Niño conditions which limit upward growth (Colin and Schramek 2020).

Ocean Changes

Indicator	How has it changed?	Projected future change
Ocean water temperature	↑	↑
Accumulated heat stress	↑	↑
Ocean acidification	↑	↑

Human-caused greenhouse gas emissions are resulting in changes in the chemical composition, temperature, and circulation of oceans, which have ramifications for marine ecosystems.

Changes in **sea surface and sub-surface water temperature** can dramatically alter marine ecosystems and affect circulation patterns in the ocean. Sea surface temperature has increased globally since 1880 (NOAA 2020d).

Palau has one of the most comprehensive temperature monitoring networks on any single coral reef area in the world (Colin 2018). Ocean temperatures at different depths have been documented for the past 20 years. Although local ocean water temperatures are variable through time (Schönau et al. 2019), data shows that Palau has experienced an average rise in ocean temperature of 0.36°F (0.2°C) per decade since 1999 (Colin 2018; Schramek et al. 2018) (Fig. 9).

Fig.9

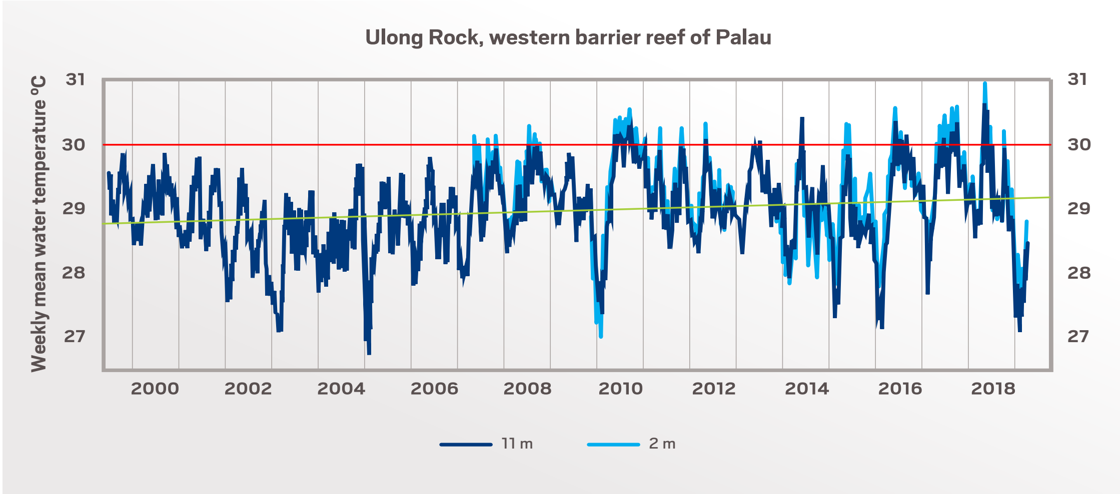


Figure 9. Water temperatures at Ulong Rock on the western barrier reef of Palau have shown a rise of about 0.36ºF (0.2ºC) per decade since 1999 (green line). The shallower areas of the barrier reef (average depth 2 m, but with high variation due to the 1–2 m tidal amplitude) are subject to higher variation in temperature than deeper areas (11 m) without tidal influence on temperature. A 30ºC threshold for coral bleaching is indicated (red line) and temperature often exceeds that threshold for short periods during summer. Graph courtesy of the Coral Reef Research Foundation.

In Palau, 86°F (30°C) is considered the threshold for initiation of coral bleaching (red line in Fig. 9), and coral bleaching occurs if temperatures remain above 86°F (30°C) for sustained periods of time. Prior to 1998, Palau had no records of significant bleaching events (Colin 2009). Palau's corals were exposed to intense heat stress during the first global bleaching event in 1998 when a strong El Niño event followed by a La Niña event brought warmer waters to Palau. Prolonged high temperatures during this period led to significant coral death in Palau. Bleaching was widespread and affected both shallow and deeper corals (Bruno et al. 2001), but Palau's reef recovered to levels of high coral cover and diversity in most areas impacted by the event (Colin 2009). By comparison, Palau experienced minor coral bleaching during the global bleaching events of 2010 and 2014–2017 (van Woesik et al. 2012; Colin 2018; Gouezo et al. 2019).

There is *very high confidence* that average sea surface water temperature will continue to increase in the western North Pacific, but only *medium confidence* in the rate of sea surface temperature change in the region (Australian BOM and CSIRO 2014). Palau is expected to continue experiencing high interannual variability in sea surface temperature due to the El Niño–Southern Oscillation (Australian BOM and CSIRO 2014).

Widespread coral bleaching is projected to occur annually in Palau by 2040 (van Hooidonk et al. 2016). Unless coral species adapt to ocean warming, coral reef areas in Palau are currently projected to experience annual severe bleaching conditions by 2048, and some areas are expected to experience these conditions beginning in about 2035 (van Hooidonk et al. 2016) (Fig. 10). A conservative model by Storlazzi et al. (2020) indicates that the semidiurnal temperature fluctuations

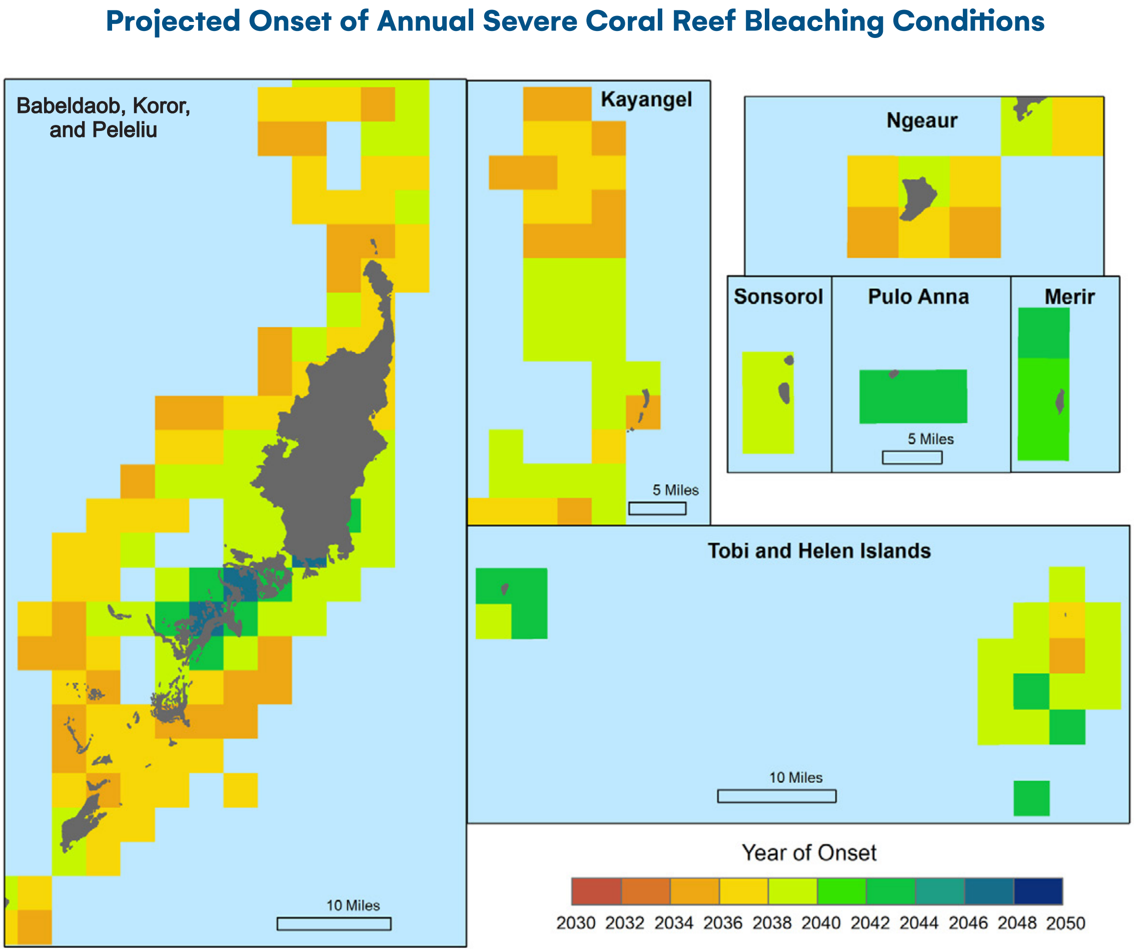


Figure 10. Projected year of onset of annual severe bleaching conditions for corals in Palau's waters (RCP8.5). Original figure by Laura Brewington, using data from van Hooidonk et al. 2016.

around Palau might delay the onset of annual severe bleaching on the order of a decade under RCP4.5, but this delay becomes negligible for RCP6.0 and RCP8.5.

Palau's waters experience large temporal, horizontal, and vertical variability of temperatures, which has implications for thermal stress on the reef (Colin and Shaun Johnston 2020), and might provide relief to some areas in the near term. More localized research is needed to improve projections for coral reef bleaching and loss in Palau due to climate change.

Data show that **ocean acidification** has been slowly increasing in the waters off of Palau and throughout the Pacific (Australian BOM and CSIRO 2014; Feely et al. 2012; Kuchinke et al. 2014). As extra carbon dioxide in the atmosphere reacts with sea water, the ocean becomes slightly more acidic. Ocean chemistry will continue to change and under the high scenario, all coral reefs are projected to exist in acidified conditions that will impede their ability to grow by the end of the century (Australian BOM and CSIRO 2014).

Managing Climate Risks in the Face of Uncertainty

Climate change impacts are often difficult to predict, leading to uncertainties in the timing, magnitude, or type of impacts. Resource managers are responding with various risk management approaches that can be used to plan for uncertainty. Risk management typically involves identifying, evaluating, and prioritizing current and future climate-related risks and vulnerabilities (even those with uncertainties that are difficult to characterize with confidence), and assigning effort and resources toward actions to reduce those risks (USGCRP 2018, Ch. 28, Key Message 3). Future economic and social conditions are considered alongside climate risks. Often risk management allows for monitoring and adjusting strategies to risks and vulnerabilities as they evolve. Addressing equity, economics, and social well-being are important parts of effective climate risk management efforts (Fatorić and Seekamp 2017).

Two approaches to climate risk management, which can be used either separately or together, are: (i) **scenario planning**, which involves the creation of several potential scenarios that might develop in the future, based upon a set of variables or projections; and (ii) **adaptive management**, in which resource managers monitor, evaluate, and adapt management practices to changing environmental conditions, such as rising sea levels and temperatures. Scenarios are used to assess risks over a range of plausible futures that include socioeconomic and other trends in addition to climate. Adaptive management approaches can benefit from technical analysis of hazards (CSIWG 2018), such as critical infrastructure vulnerability assessments and incorporating climate change considerations into land-use planning.

Comprehensive risk management can help to avoid adaptation actions that address only one climate stressor, such as sea level rise, while ignoring other current or future climate impacts. **Maladaptation** arises when actions intended to address climate risks result in increased vulnerability. For example, if a city builds new infrastructure designed to address the impacts of increased mean sea level, but then sea level rises more than anticipated, their infrastructure may exacerbate flooding if stormwater and sewer systems are unable to handle the additional water. To avoid maladaptation, policymakers and managers can consider a range of future scenarios and projected impacts over the lifetime of a project and communicate across sectors when designing solutions.

What Do Extreme Weather and Climate Change Mean for Palau's Families, Households, and Vulnerable Populations?

Climate change is anticipated to disrupt many aspects of life. More intense extreme weather events, flooding, the transmission of disease, and failing ecosystem health all threaten the health and well-being of families and communities (USGCRP 2018, Summary of Findings). Additionally, climate-related risks to energy and food production and to the global economy are projected to cause large shifts in prices and availability of goods and lead to price shocks and food insecurity (USGCRP 2018, Ch. 16, Key Message 1 and 3).

Although climate change is expected to affect all people in Palau, some populations are disproportionately vulnerable. Social, economic, and geographic factors shape people's exposure to climate-related impacts and how they are able to respond. Those who are already vulnerable, including children, the elderly, low-income communities, those facing discrimination, and those with disabilities are at greater risk in extreme weather and climate events, in part because they are excluded in planning processes (USGCRP 2018, Ch. 14, Key Message 2; Ch. 15, Key Messages 1-3; Ch. 28, Introduction).

Vulnerable populations are expected to be affected in the following ways, for example:

- Hot days are increasing, and children have a higher rate of heat stroke and heat-related illness than adults (USGCRP 2016; EPA 2016).
- Older adults and persons with disabilities are more vulnerable to extreme events, such as storms, that cause power outages or require evacuation (USGCRP 2016; EPA 2016).
- Some of the first to be exposed to the effects of heat and extreme weather are people who work outdoors, such as tourism and construction workers, fisherpeople, farmers, and other outdoor laborers (USGCRP 2016; Schulte and Chun 2009).
- People who live, work, go to school, or otherwise spend time in locations that are more directly affected by climate risks (such as coastal and other flood-prone areas) are more likely to experience higher risks to health and safety (USGCRP 2016).
- Foreigners can sometimes be at greater risk during natural disasters because they do not have the same local networks and resources as nationals. Palau's agriculture and tourism sectors are heavily comprised of foreign workers, who made up 27% of the population as of 2015 (NEPC 2019).
- There is disparity between urban areas (Koror and the suburb of Airai) and rural communities. On average, rural households have an income of $13,340 versus $16,670 for urban households (Republic of Palau 2014), and rural households are more likely to depend on marine resources to meet their subsistence food needs (NEPC 2019). Such differences can influence the ability of communities to adapt to extreme weather events and decreased natural resource availability.

Certain populations may also be affected more than others by actions to address the causes and impacts of climate change, if these actions are not implemented in ways that consider existing inequalities (USGCRP 2018, Ch. 11, Key Message 4 and Ch. 28, Key Message 4). Plans that incorporate local knowledge into decision-making can lead to better outcomes for communities at risk (Corburn 2003). Furthermore, emergency response plans that include specific accommodations for more vulnerable groups can save lives (USGCRP 2016; EPA 2016).

Global action to significantly cut greenhouse gas emissions can reduce climate-related risks in the long term. For example, the health-related impacts and costs across the United States are projected to be 50% lower under a lower warming scenario (RCP4.5) than a higher warming scenario (RCP8.5) (USGCRP 2018).

What Do Extreme Weather and Climate Change Mean for Palau's Key Sectors?

The ad hoc Climate Change Committee of the Government of Palau identified "priority risks" in ten sectors based on the probability, frequency, and severity of impacts associated with climate change and disaster events (Republic of Palau 2015a). A table from the Palau Climate Change Policy lists the top three priority risks for the assessed sectors and appears here as an appendix. The Pacific Islands Regional Climate Assessment suggests the following considerations for managers working in these ten sectors and adds detail to the priority risks based on a comprehensive review of published literature on climate science, climate-related risks in the Pacific Islands, and risk management approaches.

If you are involved in farming and agroforestry...

- ***Expect climate change to negatively impact agriculture and agroforestry production.*** In Palau the value of locally grown agricultural goods accounts for $9.3 million annually, or 3.2% of GDP and 3.8% of the nation's work force (World Bank 2019). Subsistence crop production is the predominant agricultural activity in Palau (FAO 2019), and Palau's Bureau of Agriculture promotes agroforestry. Farms and agroforests are already exposed to impacts from soil erosion, flooding, drought, winds, diseases and pests, and clearing for development. Climate change will exacerbate these impacts for some crops and locations. Changing rainfall and higher temperatures, for example, are expected to increase pest and disease problems in staple crops such as bananas (Taylor et al. 2016). The planting and harvesting times for traditional food crops depend on factors such as rainfall, temperature, and the seasons, and may need to be adjusted due to climatic shifts (Iese et al. 2018). Saltwater intrusion will put low-lying agriculture and taro patches at risk. Resilience to climate change is expected to require changes in farming methods and cultivars (Bell and Taylor 2015).
- ***Plan for warmer weather.*** Rising temperatures will increase evapotranspiration, affecting the amount of water crops require. Warmer temperatures will enable some crops to be cultivated in locations currently unsuitable for them; however, warming temperatures can increase the incidence and spread of disease, as higher nighttime temperature does for taro leaf blight. Rising temperatures can also increase the demand on available freshwater resources, which in turn can lead to water shortages, impacting the local economy and food security.
- ***Monitor research and development of farming methods that improve food security and ecosystem resilience.*** Traditional farming systems enhance resilience to external shocks and help to bolster food security (McGregor et al. 2009). For example, cultivated wetland taro in Palau has been shown to control erosion, improve soil health and reduce the impact of sediment pollution on nearshore coral reefs (Koshiba et al. 2014). Low-lying taro fields are at increasing risk of saltwater intrusion, making research into salt-tolerant taro varieties important. The Agriculture Division at Palau Community College's

Cooperative Research and Extension Department conducts wide-ranging research on Palau's staple root crops, including taro (Del Rosario et al. 2015).

A taro field in Palau slows runoff from rainfall events and reduces erosion by trapping sediment. Photo: Faustina K. Rehuher-Marugg.

If you are involved in fisheries or managing ocean resources…

- ***Expect declining coral reef health. Watershed conservation measures can help protect refugia for coral populations.*** In the next few decades, more frequent coral bleaching events and ocean acidification will combine with other stressors such as erosion and sedimentation to threaten coral reefs and the livelihoods they support. Widespread coral bleaching is projected to occur annually in Palau by 2040 (van Hooidonk et al. 2016). Nearshore reefs in Palau's bays have demonstrated more resistance to heat stress than patch and outer reefs, and could be refugia for corals from climate change (Golbuu et al. 2007; van Woesik et al. 2012). However, these nearshore reefs are threatened by local impacts such as pollution and soil erosion from land-use change (Golbuu et al. 2011), and overexploitation of fish stocks (Muller-Karanassos et al. 2020). Ridge to reef management approaches emphasize the linkages between terrestrial and marine ecosystems, and can help to address the negative impacts of land-based activities on coral reef health.

- ***Expect reduced available catch for subsistence and commercial fishing.*** Fish is important for food security in Palau, with an estimated 80% of the population consuming wild foods (FAO 2019), and wild reef fish comprising a major part of local diets (Dacks et al. 2020). Reef fish are primarily caught and consumed by local residents, while offshore fisheries are dominated by foreign-owned vessels and the majority of catch is exported (Oleson et al. 2019). Climate change and ocean acidification could result in 20% declines in coral reef fish by 2050 (Bell et al. 2013). Rapidly changing conditions also affect open ocean fisheries. Under a business-as-usual scenario for 2100, maximum potential catch is projected to decline by more than 50% for most islands in the central and western Pacific including Palau (Asch et al. 2018).

- ***Monitor research and development of aquaculture methods, while keeping biosecurity risks of imported species in mind.*** Palau's current aquaculture species include giant clam, milkfish, shrimp, reef fish, mangrove crab, grouper, rabbitfish, sea cucumber, coral, and ornamental marine aquarium fish (NEPC 2019; Pickering et al. 2011). Palau's focus on native species for aquaculture has helped minimize the introduction of transboundary aquatic animal diseases that can accompany imported species, threatening both aquaculture and wild stocks (FAO 2018). Research on the impacts of climate change on aquaculture identify the potential for increased aquatic animal diseases and harmful algal blooms, infrastructural damage from floods and storms, and decreasing availability of freshwater and wild seed (Barange et al. 2018; Bell et al. 2013).

- ***Be alert to potential health risks on hot days.*** With warming temperatures, fishers will be at increased risk of heat illnesses and heat stroke while at sea. Precautions include bringing extra drinking water, consuming sufficient fluids and electrolytes, finding ways to stay cool while at sea, and avoiding exposure to extreme heat conditions.

If you work in public health or disaster management...

- ***Account for the consequences of climate change at multiple levels across the health sector***. Climate change and extreme events are anticipated to affect individuals and communities, and also affect healthcare facilities and public infrastructure. Adaptation actions at multiple scales are needed to prepare for and manage health risks in a changing climate (USGCRP 2018, Ch. 14, Key Message 3).

- ***Prepare for more frequent extreme heat events that are expected to increase heat-related illness and death.*** Even small increases in seasonal average temperatures can increase extremes, and in some places are observed to result in illness and death. People working outside on hot days are at greater risk to heat stress, including fishers, farmers, and construction workers. Some groups have a higher risk of becoming ill or dying due to extreme heat, including people with chronic illnesses, older adults, and children (Sarofim et al. 2016). To assess the risks of rising air temperatures and other climatic changes on local health, the United States Center for Disease Control and Prevention developed the "Building Resilience Against Climate Effects" (BRACE) framework (CDC 2019; Marinucci et al. 2014), which could be used to inform local climate and health strategies in Palau.

Sechemus Hamlet is regularly flooded during king tides. Photo: O. Obechad.

- ***Expect stronger typhoons and storms.*** Although they might occur less frequently in the future, the tropical cyclones that do affect Palau are expected to bring stronger winds, storm surge, and greater precipitation amounts. Coral reefs protect the shoreline by weakening wave energy. Projected sea level rise and a decline in coral cover would reduce Palau's protection from storms.
- ***Prepare for disaster response and recovery from stronger storms.*** Injuries, fatalities, and mental health impacts are associated with strong storms, especially in coastal populations vulnerable to storm surge. Health risks increase after a storm when infrastructure and housing is damaged, and electricity, sanitation, safe food and water supplies, communication, and transportation are disrupted. Communication systems are important for quick response

leading up to, during, and after natural disasters. Government and non-governmental organizations can increase adaptive capacity, for example by providing early warning systems, evacuation assistance, and disaster relief (McIver et al. 2016; Bell et al. 2016). They can also build resilience through ecosystem-based adaptation, for example by revegetating coastal areas with mangroves to reduce flooding and erosion, thereby helping to protect coastal communities from storm surge and high winds (Förster et al. 2019). Pre-planning for disaster recovery can help communities to seize opportunities and funds to improve resilience to future disasters during the recovery and rebuilding phase (FEMA 2017).

- ***Prepare for climate change to disrupt "lifeline" infrastructure.*** Storms can disrupt sewage and water lines. Both storms and heatwaves can impact electrical supply. Extended disruptions to these services carry human health and safety risks (Mora et al. 2018).

- ***Prepare for more food insecurity in Palau's households.*** Palau's Climate Change Policy identified disruption of food supply and food production systems as a key risk in the health sector (Republic of Palau 2015a). In Palau, an estimated 81–84% of food consumed is imported (McGregor et al. 2012). Recent data suggests that local agricultural production is beginning to increase (NEPC 2019). A heavy dependence on imported foods can increase Palau's vulnerability, since it is highly likely that climate change will drive up the prices of imported foods (USGCRP 2018). Palau's narrow economic base also increases its vulnerability to economic shocks, which if severe enough could impact food security.

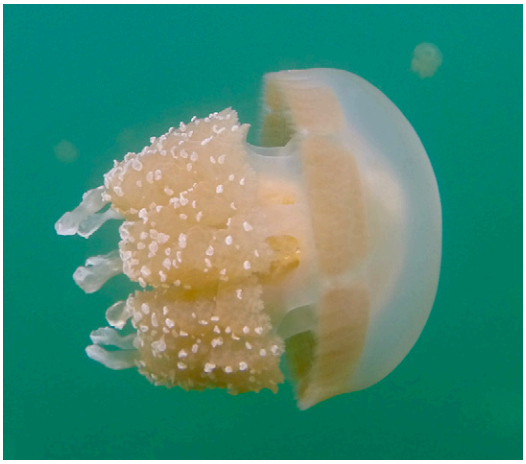
- ***Prepare for increasing frequency of tidal flooding events.*** The public health and disaster management sector will be faced with the combined impacts of sea level rise, storm surge inundation, and king tide flooding. During flood events, travel along the coast and access to medical services may be jeopardized. The Belau National Hospital, Palau's only secondary care facility, is located on the coast. Further research is needed to assess if the hospital and/or access routes to it are vulnerable to extreme weather and climate change.

- ***Monitor emerging research on climate and vector-borne diseases.*** Palau experienced a sharp rise in cases of dengue in 2016 and a dengue outbreak was announced in December 2018. Mosquito-borne pathogens like dengue have increased as global health threats in recent years (Beard et al. 2016). Researchers are concerned that future warming and precipitation changes will increase the suitable habitat for pathogens and vectors, thereby increasing the instances of dengue fever, malaria, diarrhea, salmonellosis, and other diseases (Mora et al. 2018). Community-level adaptation and public health measures can reduce human vulnerability to water-borne and vector-borne disease (Beard et al. 2016; Radke et al. 2012; Reiter et al. 2003).

If you manage ecosystems and biodiversity...

- ***Monitor and prepare for changes in temperature, rainfall, and storminess that reduce the ability of marine habitats to support native species.*** Long-term ecological monitoring conducted by the Palau International Coral Reef Center has shown that Palau's coral reefs took a minimum of 10 to 12 years to recover from the 1998 El Niño mass bleaching event (Gouezo et al. 2017). By the time the Global Reef Expedition surveyed Palau's coral communities in 2015, the reefs were in excellent condition and had the highest overall live coral cover observed by the expedition during their five-year worldwide assessment (Carlton et al. 2020). However, unprecedented changes in temperatures along with intensifying storms, extreme rainfall, and sea level rise bring new threats to the fringing and barrier reefs, marine lakes, seagrass beds, estuaries, and other ecosystems. Continued and expanded monitoring can aid in tracking ecosystem health and developing appropriate and timely responses, as described in the inset on Palau's Jellyfish Lake. There is also experimental research underway on the trade-offs of breeding increased thermotolerance traits into coral species, which could inform coral bleaching response and preparedness (www.coralassistlab.org).

- ***Monitor and prepare for changes in temperature, rainfall, storminess, and fire that exacerbate the spread of invasive species, pests, and disease and reduce the ability of terrestrial habitats to support native species.*** Current threats to Palau's native ecosystems include fire, tree disease, typhoons and storms, and invasive species introduced by global trade and tourism (NEPC 2019). Palau's forests have high plant diversity and species that exist nowhere else. This includes two bats,



The golden jellyfish. Photo: Wendy Miles

Monitoring and Management of Jellyfish Lake

Jellyfish Lake is a biologically unique ecosystem that is home to millions of golden jellyfish, *Mastigias papua etpisoni*. Marketed heavily in the Palau tourist industry and generating millions in revenue, Jellyfish Lake is an important economic resource for Palau. However, Jellyfish Lake is sensitive to changes in ocean and weather patterns brought on by climate change—severe droughts, excessive rainfall, variation in wind patterns, and extremes in ocean temperatures all play a role in the lake's water conditions and the golden jellyfish population. Strong ENSO events, such as the 1997—1999 El Niño—La Niña and the 2015/2016 El Niño, have a more pronounced impact on Jellyfish Lake, with both events leading to the disappearance of the golden jellyfish. With ocean and weather patterns that promote a return to favorable physical lake conditions (specifically, cooling temperatures that are conducive to jellyfish production through polyps and their growth), the golden jellyfish population will return to "normal." This resilience is facilitated by a healthy ecosystem; however, management of the lake is especially important to prevent degradation through tourist use. Furthermore, ecological long-term monitoring of the lake and further studies on the hydrology of the water table that feeds into Jellyfish Lake will increase our knowledge and understanding of this significant area of biodiversity.

By Sharon Patris and Patrick L. Colin
Coral Reef Research Foundation, Koror, Palau

two snails, and a handful of bird species that are threatened (NEPC 2019; IUCN 2020). Current pressures on Palau's native forest species include habitat loss and degradation, invasive species, and in some cases poaching. Climate change poses new risks to Palau's forests and biodiversity, including changes in the seasonal patterns of fruiting trees and migrating birds, and increased soil erosion and slope failure with more frequent heavy rainfall events (NEPC 2019). Temperature rise can constrict island species' ranges (Raxworthy et al. 2008), while at the same time expanding the range of invasive species that threaten native flora and fauna (Fortini et al. 2015).

- ***Consider traditional ecological knowledge and management practices when developing adaptation strategies.*** Local customary knowledge has been crucial to conservation solutions in Palau (Pilbeam et al. 2019). For example, bul (traditional no-take zones) have been used in Palau to allow marine areas time to recover from non-climate stressors (Carlisle and Gruby 2019).

- ***Promote measures that enhance ecosystem services as a critical way to support communities in adapting to climate change.*** Palau already has a number of climate adaptation initiatives that enhance ecosystem services (Mcleod et al. 2019). In Melekeok State, community representatives identified nature-based policy options to address erosion, declines in water quality and quantity, and pollution (Förster 2018; Franco et al. 2017; ValuES 2018). The Melekeok State government then worked with local community representatives to design climate smart upland housing developments (Melekeok State Government 2016), and safeguard freshwater resources through improved watershed management and traditional soil conservation methods (*Island Times* 2016; Polloi 2018). These innovations can inspire nature-based adaptation dialogues elsewhere in Palau and the Pacific Islands region (Mcleod et al. 2019).

If you are a cultural or historical resources steward...

- ***Prepare for sea level rise, coastal erosion, and storm surge to impact low-lying cultural and historical sites on the coast.*** Palau has archaeological features at low elevations along the coast, including stone monoliths, pathways, piers, and platforms. Kukau El Bad in Ollei, Ngarchelong State, is a culturally important site for prayers and offerings for the health of mesei (taro fields) (Rehuher-Marugg and Tellei 2014). Local officials report that Kukau El Bad is already being inundated during coastal flooding events (Palau Bureau of Cultural and Historical Preservation, pers. comm. 2020; Forrest and Jeffery 2018). Research currently underway has found evidence that cultural and historical sites elsewhere in Palau are also being impacted by coastal inundation due to sea level rise, erosion, storm surge, and tropical cyclones (Palau Bureau of Cultural and Historical Preservation, pers. comm. 2020).

- ***Local and cultural knowledge is essential for adaptation planning.*** Traditional knowledge is derived from the sharing of environmental observations across generations, and is useful for defining environmental baselines (Nuuhiwa et al. 2016). An important role for cultural practitioners will be ensuring that place-based knowledge and community values are incorporated into climate resilience planning in Palau.

Kukau El Bad (meaning "Stone Taro") is an important historical site in Ngarchelong State where offerings are made for the health and bounty of mesei (taro fields). Inundated by salt water in this image, Kukau El Bad is threatened by sea level rise, storm surge, and inland erosion. Photo: Calvin Emesiochel, Bureau of Cultural and Historical Preservation, Republic of Palau.

If you are involved in recreation or tourism...

- ***Anticipate that coral reefs might support fewer tourism opportunities in the future.*** Visitors and residents of Palau enjoy significant recreational benefits from coral reefs, particularly snorkeling and diving. Tourism is the main industry in Palau, with coral reefs central to the tourism industry (IMF 2019; TNC 2019; Spalding et al. 2017; Vianna et al. 2012). The total value of coral reef tourism in Palau has been estimated at $92.5 million per year, or 43.2% of the GDP (Spalding et al. 2017). In the next few decades, more frequent coral bleaching events and ocean acidification will combine with other stressors to threaten coral reefs. In most of Palau's waters, widespread coral bleaching has been projected to occur by 2040 (van Hooidonk et al. 2016) (Fig. 10). The 2015 Palau Climate Change Policy identified climate change's potential "negative impacts on Palau's brand/image and tourism arrivals" as a "priority risk" that needs to be prepared for (Republic of Palau 2015a). The Palau Responsible Tourism Policy Framework supports emissions reductions in line with Palau's Climate Change Policy, and calls for actions to identify potential impacts from climate change. Furthermore, the Bureau of Tourism aims to incorporate efforts to mitigate the impacts of climate change into tourism development planning and management (Republic of Palau 2016).

- ***Prepare for the erosion of beaches and shoreline areas to increase.*** Beach loss and seasonal sand migrations are already issues in Palau, and certain erosion-control structures (such as seawalls) have the unintended consequence of exacerbating shoreline erosion nearby. This has implications for hotels along the shoreline as well as coastal destinations popular with tourists. Tourism planning can be strengthened by incorporating short- and long-term climate considerations (Scott et al. 2019).

T-Dock in Koror State flooded during a king tide in 2019. Palau's coastal infrastructure already experiences inundation during exceptionally high tide events. Photo: Bernardi Ngiraked.

If you are a coastal decision-maker...

- ***Prepare for more frequent flooding and increased erosion to affect coastal properties and infrastructure.*** Both sea level rise and more frequent and intense heavy rainfall events will produce flooding in coastal and urban areas in Palau. A significant component of Palau's population and infrastructure are located in low-lying coastal areas, including Koror. High tidal flooding already affects homes, businesses, and infrastructure. Furthermore, maladaptation is occurring. For instance, seawalls are built with the intention of reducing erosion, but often have the unintended consequence of causing beach loss at other locations along the shore, worsening the erosion problem. Land-use decisions can increase or decrease vulnerability to climate change, and should be considered in this context. Palau is particularly vulnerable to rapid coastal erosion on eastern shores during La Niña events. It is thus important to assess how climate-related hazards could impact current infrastructure as well as sites being considered for future development.

- ***Expect less frequent but more intense typhoons and storm surge.*** Combined with continued acceleration in global average sea level rise, the wind and wave climate during typhoons has the potential to destroy both natural and built infrastructure at the coast and severely disrupt communities. The geographic distribution of damage will vary with the storm tracks and features of Palau's diverse coastlines (Merrifield et al. 2019). Prioritizing reef and mangrove ecosystem protection has a range of benefits that include climate adaptation and protection from coastal hazards such as storm surge (Ferrario et al. 2014).

- ***Promote measures that enhance ecosystem services as a critical way to support coastal communities in adapting to climate change.*** Natural resources underpin the sustenance and resiliency of Palauan communities. For example, mangrove forests provide storm protection and building materials, and are productive estuaries relied on for food (Victor et al. 2004). Already threatened by clearing and sedimentation from development, mangroves are now additionally stressed due to sea level rise (Gilman et al. 2008; Gilman et al. 2006; NEPC 2019). Restoring mangrove forests can help to protect communities against storm surge and coastal inundation, enabling them to adapt, while also providing secondary benefits such as maintenance of fisheries (Hills et al. 2013).

- ***Monitor new scientific understanding of the timing and magnitude of future global sea level rise.*** Regular updates of management plans and engineering codes may be increasingly important as new information about sea level rise and shorter-term climate variability becomes available.

If you are a water or utilities manager...

- ***Expect hotter conditions to increase water demand.*** Rising temperatures will increase evapotranspiration, affecting both the amount of water available and the demand for water. The Ngerikill River and Ngerimel Dam system that provides the majority of the public water supply and other surface water sources are particularly vulnerable to shortage when hot, dry conditions persist for weeks or months, as they did during the 2016 drought. Due to the near absence of aquifers on Babeldaob, and the resulting reliance on riverine reservoirs, periodic episodes of water shortage during even moderate drought conditions will be a continuing vulnerability.

- ***Prepare for a decline in water quality during droughts and heavy rainfall events.*** Low water levels in sources for public water systems can increase turbidity and negatively affect water quality, posing a health risk to those relying on public water supply for drinking water and sanitation needs. Heavy rains can also increase turbidity levels of surface water, stressing public utilities and occasionally causing temporary closures.

- ***Prepare for increased instances of tidal flooding and saltwater intrusion, and be alert to the risks of over-extraction.*** Saltwater intrusion during storms and tidal

The Ngerikill River and Ngerimel Dam system provides the majority of the public water supply for Koror and Babeldaob. The drought of 2016 left water levels in Ngerimel Reservoir (pictured) dangerously low. Photo: Palau Public Utilities Corporation.

flooding and the continued risk of over-extraction from wells both endanger local aquifers. Angaur, Peleliu, and Kayangel already have filtration systems due to the levels of salinity in their freshwater aquifers. Long-term monitoring of Palau's freshwater resources will be important for stewardship and sustained supplies. Raising awareness among community members about how water systems may be impacted and increasing communication among agencies and sectors that manage water can boost resilience to climate change and other shocks and stressors.

- ***Energy consumption could increase, driven by a combination of hotter weather and increasing population.*** Energy is used to pump and distribute water for use in households, agriculture, and industries. A greater number of hot days will generally increase the need for water and the loss of water through evaporation. Meanwhile, if Palau's tourism industry and resident population increases, so will the demand for water and electricity. Thus a greater amount of energy may be required to pump and distribute water in the future (Gingerich et al. 2019).

- ***Monitor salt concentrations in groundwater wells that already have high chloride levels.*** Sea level rise will cause a rise in groundwater heads in nearshore developed areas. Buried utilities in these areas may be subject to subsurface inundation through exposure to the saturated zone. This could cause increased corrosion of utilities, increased inflow and infiltration of wastewater lines, and even potential contamination of drinking water lines (Habel et al. 2017). Increasing rainfall and groundwater recharge might compensate for this increase. Since it is uncertain exactly how these wells will change in the future, it is important to maintain a robust observation and monitoring network for wells near the coast.

- ***Consider proactive strategies to mitigate the impacts of drought, sea level rise, and stronger storms.*** Increasing knowledge and awareness among community members about how water systems may be impacted by climate change and variability could increase community resilience. Communication between agencies and sectors that manage water has the potential to boost the ability to effectively manage climate issues and other shocks and stressors (Gingerich et al. 2019). Given the absence of downscaled climate models for Palau, it is prudent to engage in scenario planning under different climate conditions (for example: wetter versus drier conditions, and slower versus faster sea level rise scenarios) (Spooner et al. 2017).

- ***Strive for energy security through renewable energy technologies to decrease dependence on imported fossil fuels.*** Palau currently meets the vast majority of its energy needs using imported fossil fuels. Palau is an excellent candidate for renewable energy technologies because the population is highly centralized, with over 99% of households connected to the public electric grid and only one public power company (Palau Energy Administration 2020; Spooner et al. 2017). Transitioning to renewable energy resources will decrease Palau's vulnerability to price volatility in the international energy market (Palau Energy Administration 2020). Palau's "Nationally Determined Contribution" outlines Palau's commitment to generate 45% of the nation's energy from renewable resources by 2025 (Republic of Palau 2015b; Republic of Palau 2017). Possible strategies for decreasing dependence on fossil fuels include developing policies for incorporating renewable energy sources into the existing power grid, expanding residential rooftop solar photovoltaic capacity, and improving energy efficiency across sectors (Spooner et al. 2017).

- ***Monitor ENSO and its effects on rainfall.*** El Niño–Southern Oscillation strongly influences rainfall amounts, which vary greatly from year to year in Palau. El Niño events bring high rainfall at first and later very dry weather to Palau (Fig. 11). A strong El Niño can cause severe drought, as it did in 1997–1998 and again in 2015–2016. Palau is highly vulnerable to hydrological drought due to the relatively impervious bauxite clay surface on Babeldaob, and the porous limestone nature of Palau's other islands, which limits water infiltration (Polhemus 2017). Seasonal forecasts can help water managers to prepare for potential water shortages during drought years.

Fig.11

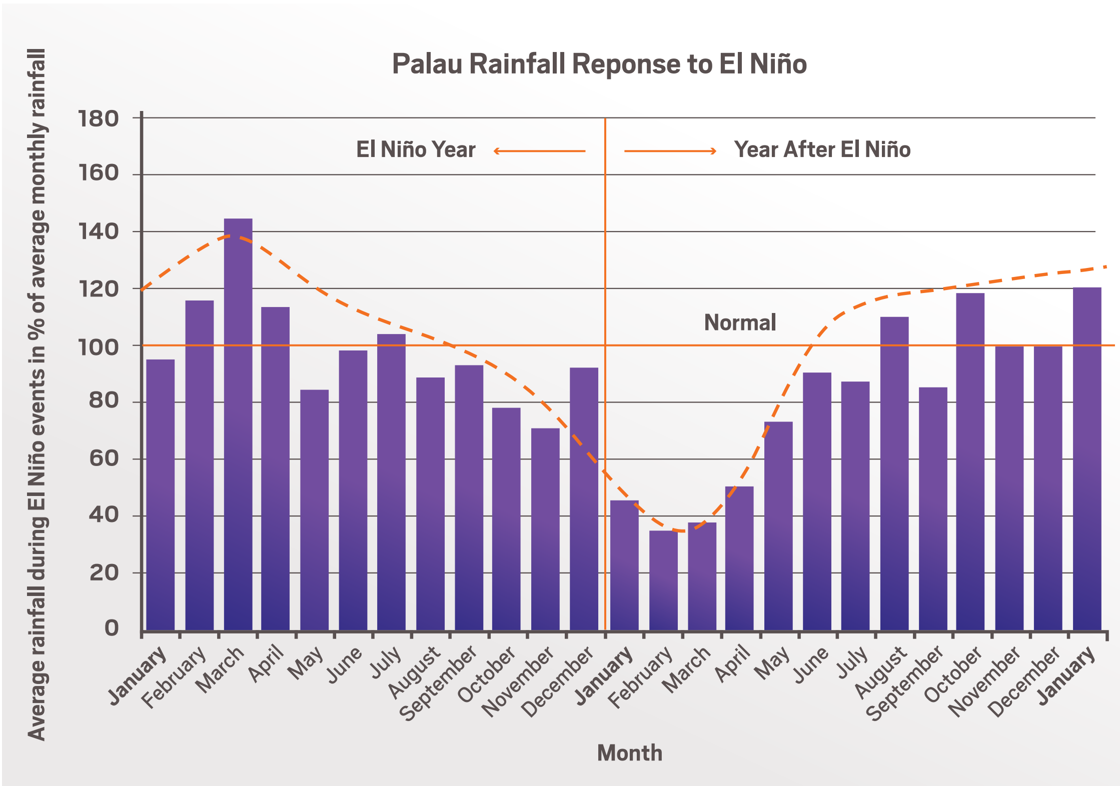


Figure 11. Average rainfall in Palau during El Niño events shown as the percent of average monthly rainfall. Source: Pacific ENSO Applications Climate Center 2018 (www.weather.gov/peac).

If you are involved in finance or economic development...

- ***Expect economic disruptions and increased costs from necessary disaster preparations, clean-up, recovery, and operation of essential services during disasters.*** The Palau Climate Change Policy (2015) identifies costs associated with disasters as a priority risk affecting the financial sector. Climate changes—both gradual and abrupt—disrupt the flow of goods and services that form the backbone of economies (Houser et al. 2015). Climate change impacts are expected to increasingly affect international trade and the economy, including import and export prices (Smith et al. 2018).

- ***Monitor and research innovative insurance mechanisms.*** The risks posed by climate change are often too great for companies, individuals, and local governments to cover on their own. Countries with greater insurance coverage across sectors are found to experience better GDP growth after weather-related catastrophes (Melecky and Raddatz 2011). There are an array of options to manage climate-related risks, such as weather-indexed insurance products and risk transfer-for-adaptation programs. Some cities and states have bought catastrophe bonds or parametric insurance policies.

For example, the government of Quintana Roo, Mexico, purchased a parametric policy that would provide up to $3.8 million to repair hurricane damage to their coral reef (Gonzalez 2019). This kind of policy provides a fast payout to quickly address impacts from a triggering event. The government could consider similarly innovative mechanisms for protecting Palau's significant ecological resources.

- ***Anticipate climate-related risks to local businesses***. Adaptation blind spots for businesses include the magnitude and costs of physical climate change impacts; anticipating second- and third-order consequences for their business (for example, risks to supply chains and customers); and the risk of climate-related tipping points (after which more sudden ecological and social change occurs) (Goldstein et al. 2019). In a survey of business adaptation strategies internationally, researchers found that ecosystem-based adaptation remains underutilized as a cost-effective approach for reducing climate risk, and many businesses continue to plan for incremental or reactive responses to climate change. To reduce risk, businesses can proactively research and prepare for the impacts of climate change on their customers, employees, communities, supply chain, and business model (Goldstein et al. 2019).

- ***Enhanced collaboration between the private sector, government, and academia***. Research collaborations to build Palau's economic resilience to climate change might stimulate new innovations in both the private and public sector (Surminski 2013).

If you are an educator or education decision-maker...

- ***Expect greater public health threats to students.*** Children are especially vulnerable to heat-related illness, including dehydration, heat stress, fever, and exacerbated respiratory problems. The increasing frequency and intensity of hot days, as well as stronger storms, could result in health impacts for students (Sarofim et al. 2016).

- ***Prepare for stronger typhoons and storm surge, and consider options for schools and educational facilities at the coastline.*** Most rural schools in Palau are built in locations identified as vulnerable to climate change (Republic of Palau 2019). Coastal areas will be affected by erosion, storm surge, and coastal inundation from sea level rise, and schools along the coast or in low-lying areas may be affected, causing temporary school closures, and the need for repairs or rebuilding. For instance, schools in Melekeok and Ngaraard were already inundated by storm surge during Typhoon Haiyan. Locating and designing buildings to accommodate sea level rise can avoid costs and protect students.

- ***Consider the potential impacts of hotter days on student learning and classroom design.*** Research has found that cumulative exposure to heat negatively impacts students' ability to learn (Goodman et al. 2018). Innovative school building designs that reflect local environmental conditions—including projected increases in air temperature—can benefit students' health and learning outcomes.

During Typhoon Haiyan in 2013, high winds heavily damaged public schools in Kayangel, as shown here. The year before, educational facilities on the east side of Babeldaob were flooded during a storm surge caused by Typhoon Bopha. Photo: Palau Ministry of Education.

Needs for Research and Information

This assessment identified the following needs for research and information, which if met could support responses to extreme weather and climate change:

- ***National vulnerability assessment using GIS-based mapping*** – A comprehensive GIS-based vulnerability study would help to visualize future risks. This information could support land-use planning and zoning improvements to minimize future climate impacts (Spooner et al. 2017).
- ***Development of a wave run-up model for Palau*** – Localized sea level research, projections, and mapping will provide decision-makers and communities with better information from which to plan for sea level rise (Gesch 2018; Gesch et al. 2020). When done alone, passive flood mapping of sea level rise (the so-called "bathtub" approach) underestimates the total land area exposed to flooding. For a robust SLR vulnerability assessment, it is recommended that multiple SLR stresses are modeled (Anderson et al. 2018).
- ***Economic loss from sea level rise scenario mapping*** – Research on the potential economic impacts of sea level rise—mapped in formats that can be used by policy makers and community planners—can inform climate adaptation planning and infrastructure development decisions (see the *Hawai'i Sea Level Rise Vulnerability and Adaptation Report* for examples).
- ***Research on freshwater supply and systems*** – With hotter temperatures reducing water supply while increasing demand, it will be important to research ways to improve the efficiency of Palau's freshwater management systems, while buffering freshwater resources and infrastructure from saltwater intrusion, extreme rainfall events, and typhoons. Given Palau's heavy reliance on surface water, a more extensive network of precipitation and stream gauges is a priority, including the re-establishment of former gauging stations (Polhemus 2017). An assessment of Palau's freshwater resources, particularly belowground aquifers, is needed to determine volume, recharge, capacity for use, and vulnerability to both climate change and non-climate threats.
- ***Strengthened long-term environmental monitoring programs*** – Ongoing environmental monitoring programs provide critical information in understanding how Palau's climate and environment are changing, which in turn improve planning and response.
- ***Strengthened programs in adaptation monitoring and evaluation*** – Monitoring progress made towards adaptation goals and evaluating climate change measures can reveal what is working and not, and over time strengthen climate resiliency efforts (learn more at: www.resiliencemetrics.org). PIRCA contributors identified "the ability to monitor progress of outputs and evaluation of their effectiveness" as an important institutional gap that requires capacity enhancement.
- ***Effective sharing of information across sectors and with the public*** – Addressing climate risks will require cross-sectoral coordination. This includes sharing real-time climate data, especially during extreme events and emergencies. There is also a need for regular management and information updates in the recently created Palau Climate Change Portal (http://climatechange.palaugov.pw/). Having this in place

will further strengthen the consolidation and accessibility of climate information for the public.

- ***Research on effective strategies for economic resilience in the context of climate change and renegotiation of the Compact of Free Association (COFA)*** – Palau's 2019 voluntary national review on progress towards the Sustainable Development Goals (SDGs) outlines the need for strengthened national fiscal policies and increased domestic financing for SDGs, in preparation for the renegotiation of the COFA agreement with the United States in 2024 (Republic of Palau 2019). Research that incorporates climate change considerations into assessments of program needs and financing strategies could be beneficial towards these aims. In recent years, over 70% of Palau's national gross domestic product was driven by international tourism (Kitalong et al. 2015). The COVID-19 pandemic has underscored the importance of a diversified and resilient economy.
- ***Research on "climate proofing" critical infrastructure*** – Governments and resource managers commonly use various forms of "vulnerability assessments" as a foundational tool to tailor solutions and policies that address the specific ways critical infrastructure is threatened. Assessing climate vulnerability involves technical analyses of changing hazards; often includes an evaluation of exposure, sensitivity, and adaptive capacity; and rankings of the seriousness of various climate risks. Decision-makers can utilize this information to explore climate proofing and relocation options. Climate resilience infrastructure projects could be piloted on a small/individual scale to demonstrate new concepts and support creative problem-solving.
- ***Research on the societal impacts of climate change interventions*** – Understanding the potential socioeconomic and cultural impacts of climate change interventions can help decision-makers avoid inadvertently causing harm, particularly for more vulnerable populations in Palau. One possible approach is transdisciplinary research, which involves building inquiries based on stakeholder-driven information needs, and learning from diverse knowledge systems. Another useful approach is evaluation research, which can help managers adapt their approaches through time to improve climate-related policies and programs.
- ***Research on emergency preparedness and vulnerable populations*** – Safeguarding vulnerable populations prior to, during, and after a natural disaster requires emergency plans that incorporate the needs of vulnerable populations including children, pregnant women, the elderly, those with disabilities, and marginalized groups. Social science research can help identify the specific needs of those at heightened risk in Palau, and share "best practices" from the emergency management literature (Phillips and Morrow 2007; Hoffman 2008). This information can save lives when incorporated into emergency planning and response.
- ***Sector-specific climate vulnerability assessments*** – Sector-specific vulnerability assessments could help to inform climate adaptation actions taken by Palau's public and private sector. Land-use policies and new infrastructure projects can increase or decrease local vulnerability to climate change, and should be considered in this context.
- ***Exploratory studies on tourism strategies*** – Studies that explore options for diversi-

fying Palau's tourism industry, sustainably managing popular tourism areas, and effectively communicating with tourists and tour operators can all support climate-smart strategies in the tourism sector.

- ***Research supporting food security*** – Furthering the ongoing research on new farming methods and cultivars in Palau, in combination with experimentation and expansion of traditional food cultivation practices, can increase the resiliency of Palau's food systems. For example, low-lying taro fields are at risk of saltwater intrusion, making research into salt-tolerant taro varieties important. New farming, aquaculture, food storage, and processing techniques are already being experimented with in Palau, with the need for continued work in this vein (SPREP 2013; Del Rosario et al. 2015; Iese et al. 2018).
- ***Safeguarding ecological resources*** – Further research on the interplay between Palau's unique ecosystems and climatic factors is needed to inform management practices. The continued monitoring of bleaching events and reef health is important and will help identify reef areas with greater resilience (Spooner et al. 2017). Land management practices also affect marine ecosystem health. Local fishers have requested studies on the transition zone between mangroves and reef, an important habitat for marine species during their reproductive stage. The aim of this research would be to better understand how nearshore fisheries are impacted by coastal development, mangrove expansion, and a changing climate.
- ***Safeguarding cultural resources and practices*** – Research on potential climate change impacts to archaeological sites in Palau can inform planning processes for these areas with the histories and knowledge they represent. This research should extend beyond the economic and tourism impacts, to better understand the importance of these resources for local culture and heritage.
- ***Exchange of adaptation experiences with other Pacific Islands*** – Peer-to-peer exchanges that enable the sharing of lessons learned between climate adaptation efforts can assist decision-makers in understanding the benefits and risks of such measures.
- ***"Transformation" dialogues on climate change*** – The IPCC defines "transformation" as systemic changes that enable significant and rapid climate change mitigation and adaptation, while pursuing the SDGs (IPCC 2018). Research has found that people's values and worldviews are the most important lever enabling system change (Moser et al. 2019a). For policy makers and managers, this means that local values should guide transformative change (Moser et al. 2019b). Towards this aim, one approach is to hold dialogues for diverse community stakeholders to identify shared values, and define common goals.
- ***Community-based climate research and resilience building*** – PIRCA technical contributors identified the need for more holistic representation of community views in future climate change research in Palau. Incorporating the voices of local stakeholders, vulnerable groups, and marginalized populations is critical to effective climate resilience planning. Community-based research approaches, including community vulnerability assessments, can help to integrate local knowledge and community priorities into climate resilience planning. Social innovation can also be fostered through community-led climate resilience pilot initiatives, and lessons learned can then be shared between communities.

Palau Sources of Climate Data and Projections

Coral Reef Research Foundation's Water Temperature Catalogue: http://wtc.coralreef-palau.org/

NOAA Coral Reef Watch: https://coralreef-watch.noaa.gov/satellite/index.php

NOAA DigitalCoast Sea Level Change Curve Calculator: https://coast.noaa.gov/digital-coast/tools/curve.html

NOAA Downscaled Climate Model Projections of Coral Bleaching Conditions: https://coralreefwatch.noaa.gov/climate/projections/downscaled_bleaching_4km/index.php

NOAA Quarterly Climate Impacts and Outlook for Hawai'i and the US-Affiliated Pacific Islands: https://www.drought.gov/drought/climate-outlook/Pacific%20Region

Pacific Climate Change Data Portal: http://www.bom.gov.au/climate/pccsp/

Pacific-Australia Climate Change Science and Adaptation Planning Program: https://www.pacificclimatechangescience.org/

PacIOOS (Pacific Islands Ocean Observing System): http://www.pacioos.hawaii.edu/

PacIOOS Six-Day High Sea Level Forecast: https://www.pacioos.hawaii.edu/shoreline/highsea-malakal/

Palau Climate Change Portal: http://climatechange.palaugov.pw/

University of Hawai'i Sea Level Center's Sea Level Forecasts: https://uhslc.soest.hawaii.edu/sea-level-forecasts/

USGS, USGCRP, NOAA, and Terria Sea Level Change Map: https://geoport.usgs.esipfed.org/terriaslc/

Traceable Accounts

The findings in this report are based on an assessment of peer-reviewed scientific literature, complemented by other sources (such as gray literature) where appropriate. These Traceable Accounts document the supporting evidence, sources of uncertainty, and draw on guidance by the IPCC and USGCRP (2018), to evaluate the conclusions reported in the "Indicators of Climate Change" section in terms of:

- **Confidence** in the validity of a finding based on the type, quantity, quality, and consistency of evidence; the skill, range, and consistency of model projections; and the degree of agreement in literature.
- **Likelihood**, based on statistical measures of uncertainty or on expert judgment as reported in literature.

Indicator	How has it changed?	Source	Data Range	Projected future change	Source
Hot days	↑	NOAA Global Historical Climatological Network – Daily (GHCN-Daily) – PSW00040309, Koror	1952–2018	↑	Australian Bureau of Meteorology (ABM) and CSIRO 2014 (CMIP5)
Cool nights	↓	GHCN-Daily – PSW00040309, Koror	1952–2018	↓	ABM and CSIRO 2014 (CMIP5)
Average air temperature	↑	ABM and CSIRO 2014 – WMO No. 91408, Koror; GHCN-Daily – PSW00040309, Koror	1948–2011; 1952–2018	↑	ABM and CSIRO 2014 (CMIP5)
Average rainfall	No change	ABM and CSIRO 2014 – WMO No. 91408, Koror	1948–2011	↑	ABM and CSIRO 2014 (CMIP5)
Extreme rainfall days	No change	GHCN-Daily – PSW00040309, Koror	1952–2018	↑	ABM and CSIRO 2014 (CMIP5)
Frequency of drought	No change	GHCN-Daily – PSW00040309, Koror	1952–2018	↓	ABM and CSIRO 2014 (CMIP5)
Duration of drought	No change	GHCN-Daily – PSW00040309, Koror	1952–2018	↓	ABM and CSIRO 2014 (CMIP5)
Tropical cyclone frequency	No change	Marra and Kruk 2017; Knapp et al. 2010 – Western Pacific	1980–2016	?	Kossin et al. 2016; Zhang et al. 2016; Wang et al. 2016; Marra and Kruk 2017; US-GCRP 2017; Widlansky et al. 2019
Tropical cyclone intensity	No change	Marra and Kruk 2017 – Western Pacific	1980–2016	↑	USGCRP 2017; Marra and Kruk 2017; Knutson et al. 2015; Sobel et al. 2016; Zhang et al. 2016; Widlansky et al. 2019

Indicator	How has it changed?	Source	Data Range	Projected future change	Source
Sea level	↑	NOAA 2020b; UHSLR 2020 – Malakal B, Koror	1969–2019	↑	Sweet et al. 2017a and 2017b; USGCRP 2017; USGS TerriaMap 2020
Tidal flood frequency	↑	NOAA 2020b; UHSLR 2020 – Malakal B, Koror	1969–2019	↑	USGCRP 2017
Ocean water temperature	↑	NOAA 2020d – global sea surface temperature; CRRF 2020 – sub-surface water temperature at ULR mooring array, western barrier reef of Palau	1880–2019 (NOAA 2020d); 1999–2019 (CRRF 2020)	↑	USGCRP 2017
Accumulated heat stress on coral	↑	Colin 2018; Schramek et al. 2018; Coral Reef Research Foundation (pers. comm.) 2019 – ULR and SDO mooring arrays, Palau	1999–2019	↑	van Hooidonk et al. 2016
Ocean acidification	↑	Australian BOM and CSIRO 2014; Feely et al. 2012; Kuchinke et al. 2014 – various data sets, Pacific Ocean	Multiple data ranges (late 18th century to 2010s)	↑	Australian CSIRO and BOM 2014; USGCRP 2017

Temperature – Daily air temperature at Koror has been measured since 1951. Hot days are days for which maximum temperature exceeds the 90th percentile or 90°F (32°C). Cool nights are days for which minimum temperatures were colder than the 10th percentile of the distribution—roughly 74°F (23.5°C). Only the minimum daily temperature warming trend in the dry season (November–April) is statistically significant at the 5% level (Australian BOM and CSIRO 2014).

In 2014, the Australian government used general circulation model (GCM) simulations taken from the international Coupled Model Intercomparison Project Phase 5 (CMIP5) to project future climate conditions in the geographic region encompassing Palau. Projected increases in annual average air temperature (Table 1) represent 90% of the range of models, as compared to 1986–2005. There is *very high confidence* that air temperatures will rise, but *medium confidence* in the projected amount of average temperature change.

Rainfall – There is *medium confidence* that wet season, dry season, and annual average rainfall in Palau will increase in the 21st century (Australian BOM and CSIRO 2014). There is *high confidence* that the frequency and intensity of extreme rainfall events will increase because: (a) a warmer atmosphere can hold more moisture, so there is greater potential for extreme rainfall (IPCC 2012); and (b) increases in extreme rainfall in the Pacific are projected in all available climate models. However, there is *low confidence* in the magnitude of these changes (Australian BOM and CSIRO 2014).

Drought – The frequency of droughts and the overall time spent in all categories of drought are projected to decrease under the high scenario (RCP8.5). The duration of extreme, severe, and moderate drought events is projected to decrease under the high scenario while mild drought duration is projected to remain stable. ENSO will continue to play a large role in future droughts, but there is no consensus on how ENSO may change in the future. There is *medium confidence* in these drought projections (Australian BOM and CSIRO 2014).

Typhoons and Storms – The future is less certain for tropical cyclones than other elements. The environmental conditions to produce a cyclone are at timescales much shorter than global climate model simulations, for example, the state of ENSO and the intensity and phase of the Madden-Julien Oscillation (Diamond and Renwick 2015). There is *medium confidence* that globally tropical cyclone frequency will decrease (USGCRP 2017). For western North Pacific typhoons, increases are projected in tropical cyclone precipitation rates (*high confidence*) and intensity (*medium confidence*) (Knutson et al. 2015; USGCRP 2017). The frequency of the most intense of these storms is projected to increase in the western North Pacific (*low confidence*) (USGCRP 2017). Recent studies detect increasing trends in tropical cyclone intensity in observations from 1979 to 2016 and raise confidence in projections of increased tropical cyclone intensity with continued warming (Kossin et al. 2020). Model results vary around Palau, and confidence in the projected decrease in tropical cyclone frequency around Palau is *low* (Australia BOM and CSIRO 2014).

Fig.12

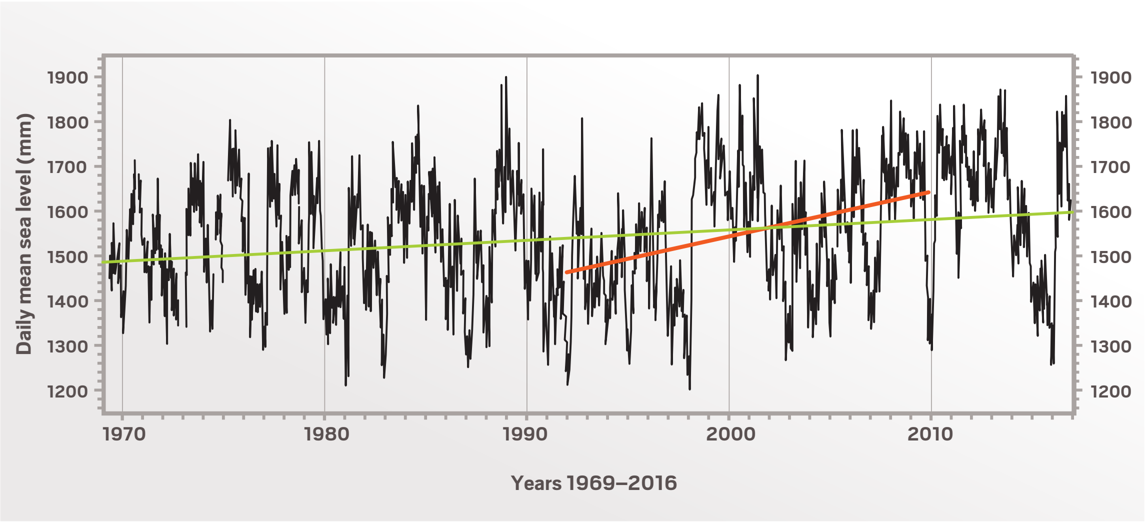


Figure 12. Mean Sea Level in Koror, Palau. From 1969 to 2016, average mean sea level in Palau increased (green line) but daily mean sea level (black line) fluctuated due to natural variability. These changes were particularly dramatic during shifts between El Niño and La Niña events. This resulted in higher rates of sea level rise reported for the period of 1992 to 2010 (red regression line of 90 mm/yr), versus for the 46-year period of 1969 to 2016 (2.42 mm/yr) (NOAA 2020b; CRRF 2020). Graph courtesy of Coral Reef Research Foundation (2020)'s Ocean Observations, https://coralreefpalau.org/research/oceanographyweather/ocean-observations/.

Sea Level Rise – From 1969 to 2016 the mean sea level trend documented at Malakal, Palau, was 2.42 mm/yr with a 95% confidence interval of +/- 2.55 mm/yr (NOAA 2020b). As Figure 12 shows, Palau experienced large fluctuations in mean sea level associated with El Niño and La Niña events during this period (CRRF 2020; UHSLC 2020; NOAA 2020b).

Scientific understanding of the timing and magnitude of future global sea level rise continues to evolve and improve. The *Fourth National Climate Assessment, Vol. 1: Climate Science Special Report* (USGCRP 2017), "Chapter 12: Sea Level Rise," Key Message 2, states:

"Relative to the year 2000, Global Mean Sea Level (GMSL) is *very likely* to rise by 0.3–0.6 feet (9–18 cm) by 2030, 0.5–1.2 feet (15–38 cm) by 2050, and 1.0–4.3 feet (30–130 cm) by 2100 (*very high confidence* in lower bounds; *medium confidence* in upper bounds for 2030 and 2050; *low confidence* in upper bounds for 2100). Future pathways have little effect on projected GMSL rise in the first half of the century, but significantly affect projections for the second half of the century (*high confidence*). Emerging science regarding Antarctic ice sheet stability suggests that, for high emission scenarios, a GMSL rise exceeding 8 feet (2.4 m) by 2100 is physically possible, although the probability of such an extreme outcome cannot currently be assessed. Regardless of pathway, it is *extremely likely* that GMSL rise will continue beyond 2100 (*high confidence*)" (USGCRP 2017).

Figure 13 shows the six representative Global Mean Sea Level rise scenarios for 2100, and Table 2 in the Sea Level section shows the probability of exceeding each of the six scenarios in 2100 under the Low Scenario (RCP4.5) and High Scenario (RCP8.5). New evidence from research on the Antarctic Ice Sheet supports higher probabilities of exceeding the Intermediate-High, High, and Extreme scenarios in 2100 (Sweet et al. 2017b).

Fig.13

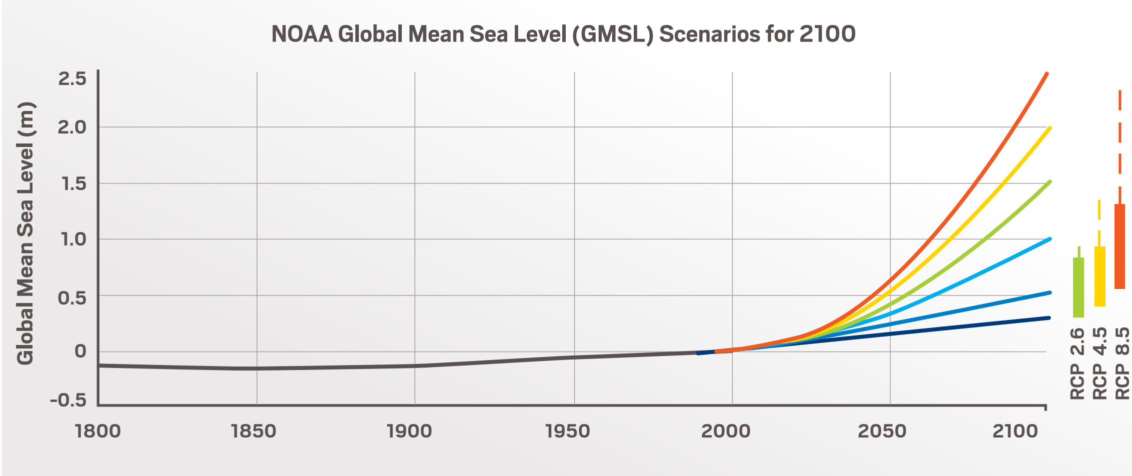


Figure 13. Six representative Global Mean Sea Level (GMSL) scenarios for 2100 (6 colored lines) relative to historical geological, tide gauge, and satellite altimeter GMSL reconstructions from 1800 to 2015. The colored boxes show central 90% conditional probability ranges of RCP-based GMSL projections from recent studies. Dashed lines extending from the boxes show the median contribution from Antarctic melt from recent studies. Source: Sweet et al. 2017b.

In Palau, relative sea level rise is amplified by static-equilibrium because the region is far from all sources of melting land ice (USGCRP 2017, 12.5.4; Sweet et al. 2017b; Slangen et al. 2014). This effect is accounted for in Figure 8 in the Sea Level section, which shows the GMSL scenarios applied to Koror. Under the 2100 Intermediate Global Mean Sea Level Rise Scenario of 3.3 feet (1.0 m), Sweet et al. (2017b) project that tropical Pacific Islands could experience an additional 0.7–1.3 feet (0.2–0.4 m) relative sea level rise, resulting in a total of 3.9–4.6 feet (1.2–1.4 m) sea level rise. Under the 2100 Intermediate-High Global Mean Sea Level Rise Scenario of 4.9 feet (1.5 m), Palau could experience another 1–1.7 feet (0.3–0.5 m) of rise for a total of 5.9–6.6 feet (1.8–2 m) by the end of the century (Sweet et al. 2017b: 30-31). As global mean sea level rises, Palau will continue to experience large fluctuations in relative sea level associated with El Niño and La Niña events. For local relative sea level change scenarios, see the NOAA Digital Coast Sea Level Change Curve Calculator (https://coast.noaa.gov/digitalcoast/tools/curve.html) or the Terria Sea Level Change Map from USGS, USGCRP, and NOAA (https://geoport.usgs.esipfed.org/terriaslc/).

Ocean Changes – Palau has experienced an average rise in ocean temperature of 0.36°F (0.2°C) per decade since 1999 (Fig. 9) (Colin 2018; Schramek et al. 2018). During the first global bleaching event in 1998, Palau's reefs experienced intense heat stress and significant coral reef death. Although the third global bleaching event in 2014–2017 caused more reefs in the Pacific to be exposed to heat stress than any time before, Palau did not have a high alert level for bleaching (Alert Level 2) during the event, implying that different oceanographic factors were present in the area during this time. Alert Level 2 was present only in two years historically: for up to 12 days in 1998 (during the first global bleaching event) and for three days in 2010 (during the second global bleaching event).

Average sea surface temperature is projected to increase in Palau. There is *very high confidence* in this warming trend (Australian BOM and CSIRO 2014). Palau is expected to continue experiencing high interannual variability in sea surface temperature due to the El Niño–Southern Oscillation (Australian BOM and CSIRO 2014).

Current conditions that cause severe coral bleaching are predicted to occur annually by 2035–2048 in Palau under RCP8.5 (van Hooidonk et al. 2016). Severe coral bleaching is defined by van Hooidonk et al. (2016) as "the annual exceedance of >8 DHW (Degree Heating Weeks) accumulating during any 3-month period." The potential for Palau's corals to adapt to warming temperatures is not incorporated into these projections. A conservative model by Storlazzi et al. (2020) indicates that the semidiurnal temperature fluctuations around Palau might delay the onset of annual severe bleaching on the order of a decade under RCP4.5, but this delay becomes negligible for RCP6.0 and RCP8.5.

There is *very high confidence* in the increased risk of coral bleaching as the ocean warms but only *medium confidence* in the rate of sea surface temperature change for the western North Pacific (Australian BOM and CSIRO 2014).

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Appendix: Priority Risks by Sector and Impact from the Palau Climate Change Policy

Sector	Priority Risks	Direct Impact				
		Sea level rise	Extreme weather	Rainfall change	Temperature change	Ocean acidification
Agriculture and Fisheries	1. Saltwater intrusion/inundation (particularly taro patches)	x	x			
	2. Changes in fish movement and spawning seasons, negative impacts on marine species, and disruption to the food chain				x	
	3. Erosion/sedimentation and changes in water quality impacting agricultural and marine resources and food security		x	x		
Health	1. Disruption of food supply/production systems, with increases in poor nutrition and non-communicable diseases	x		x		
	2. Damage or destruction of infrastructure (water, sewage, power, health, etc.), disruption in community health services	x	x			
	3. Increases in water-borne and vector-borne diseases		x			
Biodiversity Conservation and Natural Resources	1. Decreased resilience of marine resources and coral reef systems					x
	2. Destruction and transformation of forest ecosystems		x		x	
	3. Coral bleaching and loss of vulnerable marine species and habitats				x	
Society and Culture	1. Negative impacts on traditional and subsistence food production		x			
	2. Disruption of social units (families, clans, communities, cheldebechel, etc.)		x			
	3. Changes in social behavior and migration		x			
Tourism	1. Reduced food supply for visitors				x	
	2. Negative impacts on Palau's brand/image and tourism arrivals		x		x	
	3. Disruption of power and water supply and other essential services		x			
Critical Infrastructure	1. Damage or destruction to coastal infrastructure	x				
	2. Higher costs for development and maintenance of public infrastructure		x			
	3. Overloading and increased pressure on emergency response systems and damage to emergency response facilities		x			
Utilities	1. Damage to utilities leading to disruption of services		x			
	2. Damage to solid waste management systems with increased pollution and associated health impacts		x			
	3. Decrease in quantity and quality of water provided by utilities		x			
Finance, Commerce, and Economic Development	1. Damage and destruction to infrastructure, public facilities, and private and commercial facilities	x				
	2. Increased costs for prevention, clean-up, reconstruction, recovery, and operation of essential services during disasters		x			
	3. Increased costs of clean-up, loss of fishing income, and loss of tourism sector income		x			
Education	1. Damage or closing of schools and relocation of students		x			
	2. Increased costs of education		x			
	3. Science information used in curriculum rapidly becomes outdated	x		x	x	x

Source: Palau Climate Change Policy (2015)

Notes

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The **bai** is a traditional meeting house in Palau, adorned with artwork that depicts the history, stories, and values of Palau.

EastWestCenter.org
PacificRISA.org

For information,
please contact:

East–West Center
1601 East–West Road
Honolulu, Hawai‘i 96848–1601

Ph (808) 944–7111

info@PacificRISA.org

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