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

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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.

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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

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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)

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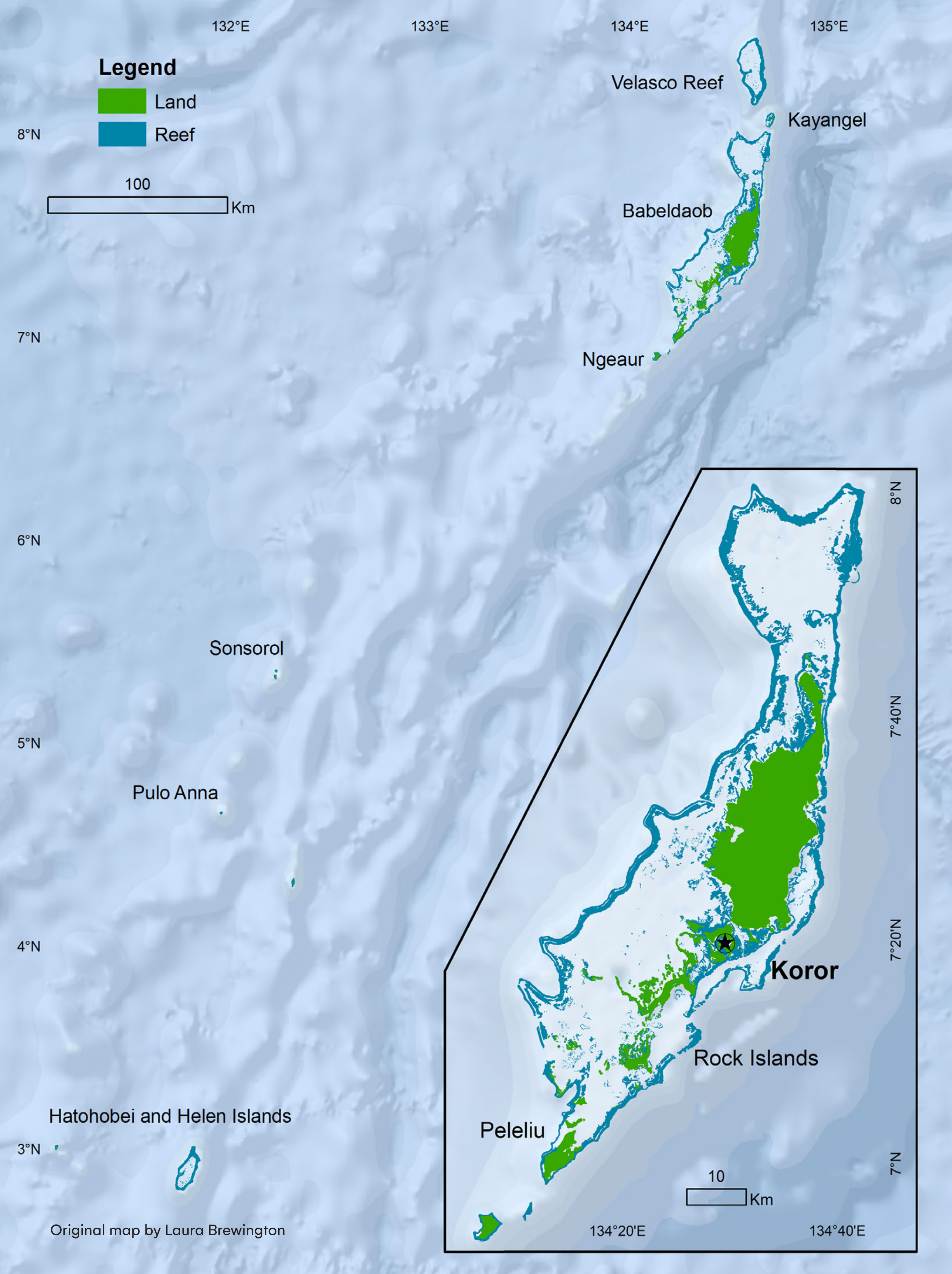
A bird's-eye view of the city of Koror.
Photo: Norimoto (Getty Images)

Inside this Summary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134°40'E
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.)

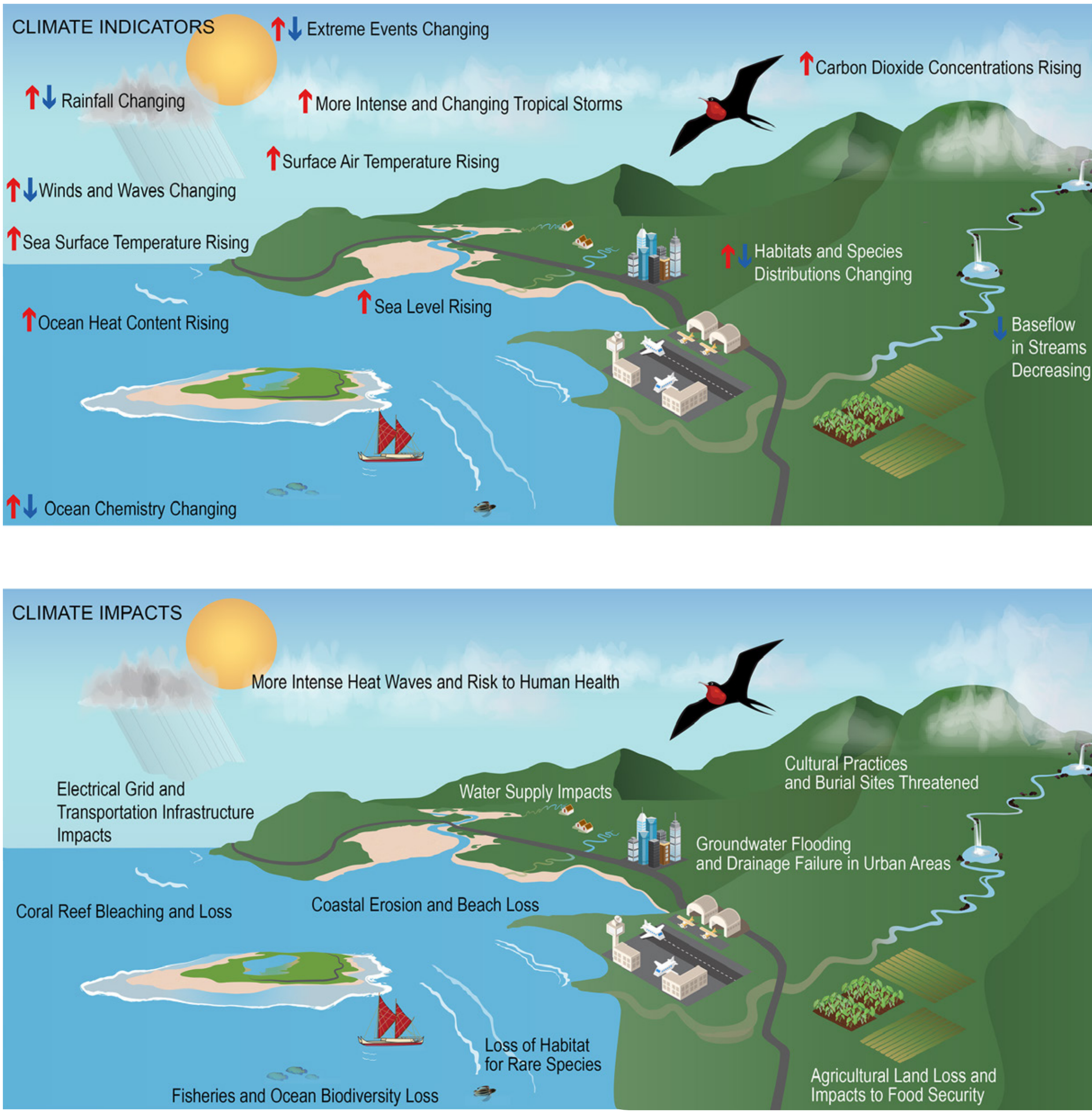


Figure 1. Observed changes in key climate indicators in the Pacific Islands, such as carbon dioxide concentration, sea surface temperatures, and species distributions result in impacts to multiple sectors and communities, including built infrastructure, natural ecosystems, and human health. In the top 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 Hawaiʻi 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

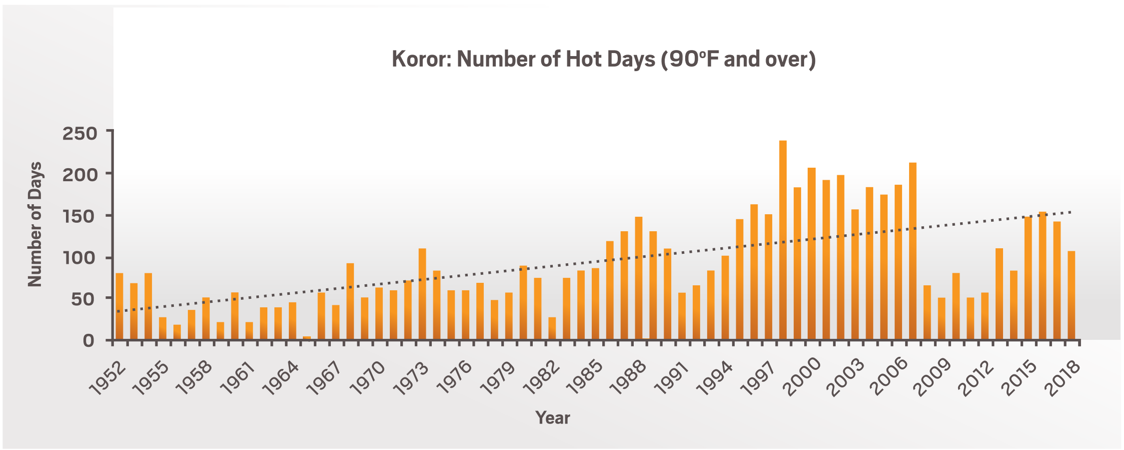


Figure 2. Annual count of days with maximum temperature of 90ºF (approximately 32ºC) or hotter (temperatures at or above the 90th percentile). Over the period of 1952 to 2018, the number of hot days increased at a rate of 1.81 days per year on average (black dotted line). Original figure by Abby Frazier,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

Fig.3

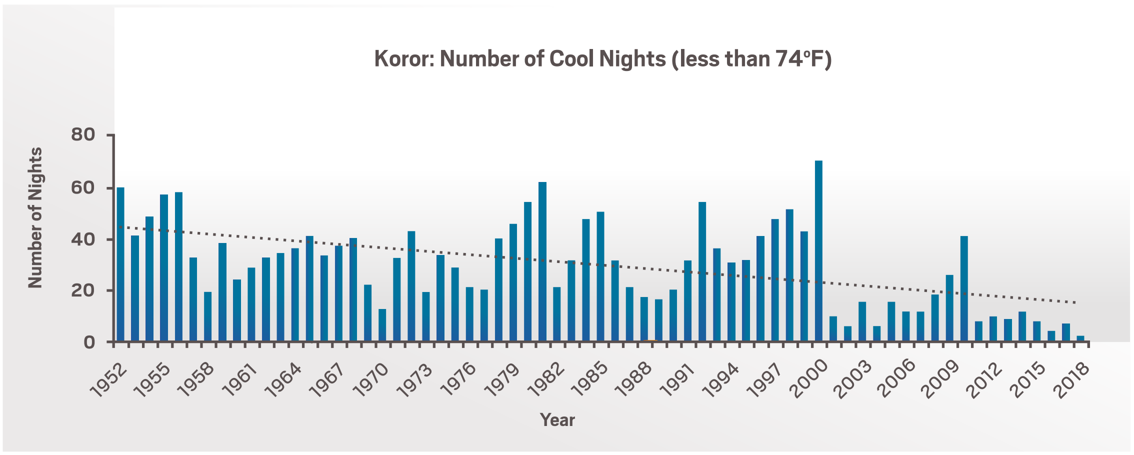


Figure 3. Annual count of nights with minimum temperature less than the 10th percentile (roughly 74ºF or 23.5ºC) for the entire record at Koror. Over the period of 1952 to 2018, the number of cool nights decreased at a rate of 0.42 nights per year on average (black dotted line). Original figure by Abby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

Fig.4

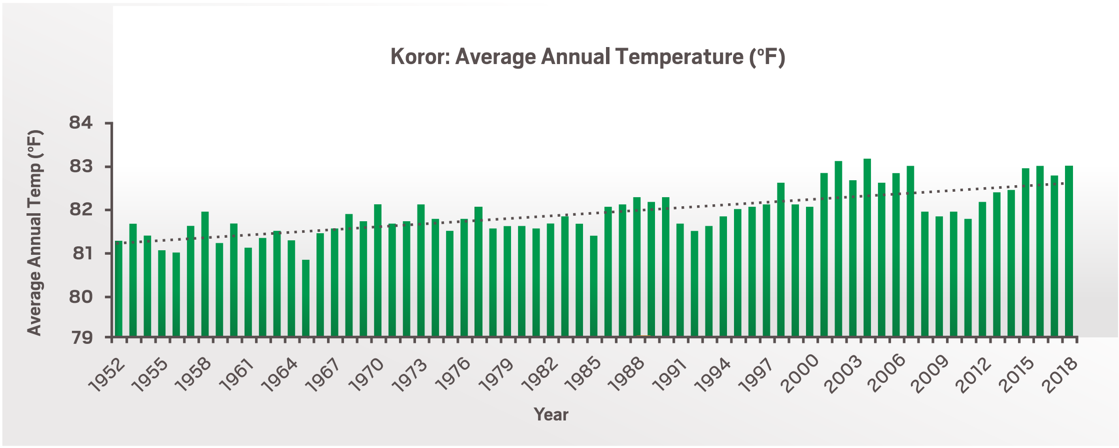


Figure 4. Average annual temperature in Koror, Palau (ºF). During the period of 1952 to 2018, average annual temperatures increased at a rate of 0.02ºF per year (black dotted line). Original figure by Abby Frazier, using data from the NOAA GHCN-Daily database for 1952–2018 (NOAA 2020c; Menne et al. 2012).

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

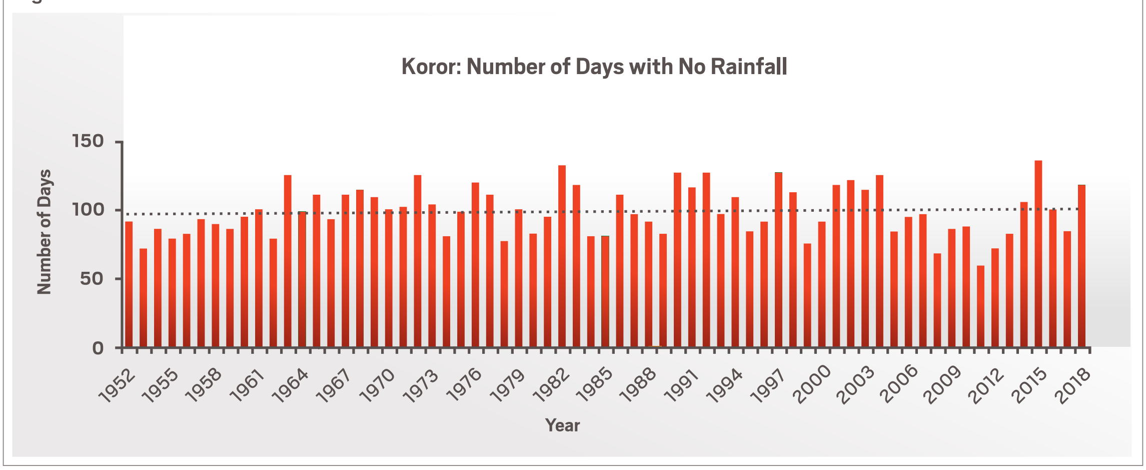


Figure 5. Annual count of days with no rainfall (0 inches) for the entire record at Koror (1952–2018). The black dotted line indicates the linear trendline, showing no measurable long-term change in number of days with no rainfall. Original figure by Abby Frazier, using the NOAA GHCN-Daily database for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

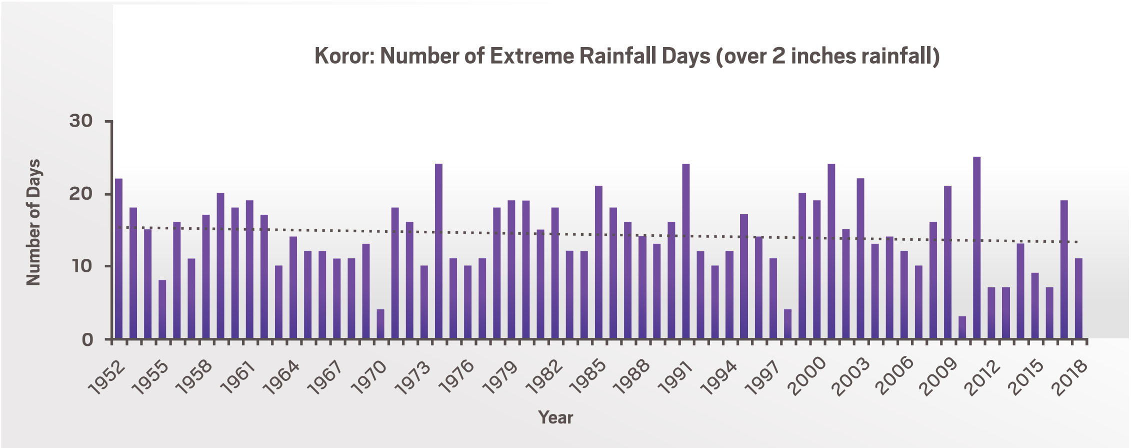


Figure 6. Annual count of days with rainfall greater than 2 inches (51 mm) at Koror (corresponding approximately to the 95th percentile of daily rainfall). For comparison, about 2.7 inches (69 mm) of rain fell in 24 hours at Koror during Typhoon Bopha on December 3, 2012. The black dotted line indicates 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).

18 Sep 2013 | 8 Nov 2013

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

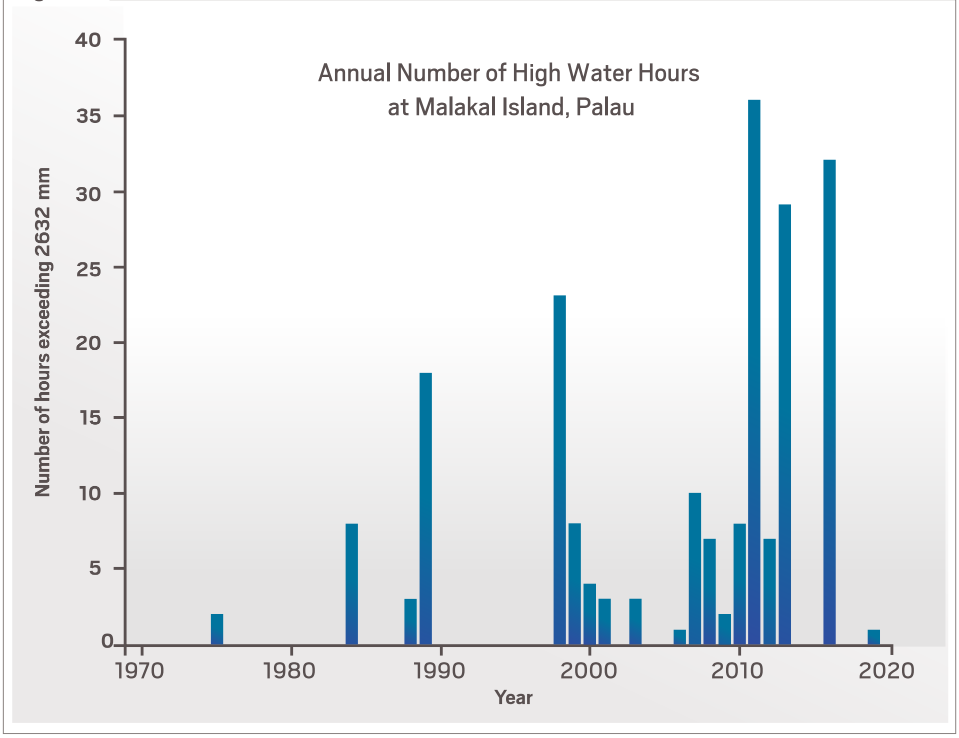


Figure 7. Number of high water hours per year at Malakal Island in Palau from 1970 to 2019. The high water threshold (2632 mm) is defined as the Mean Higher High Water level plus one-third of the difference between that and the Mean Lower Low Water level at the tide gauge (that is, water levels above 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

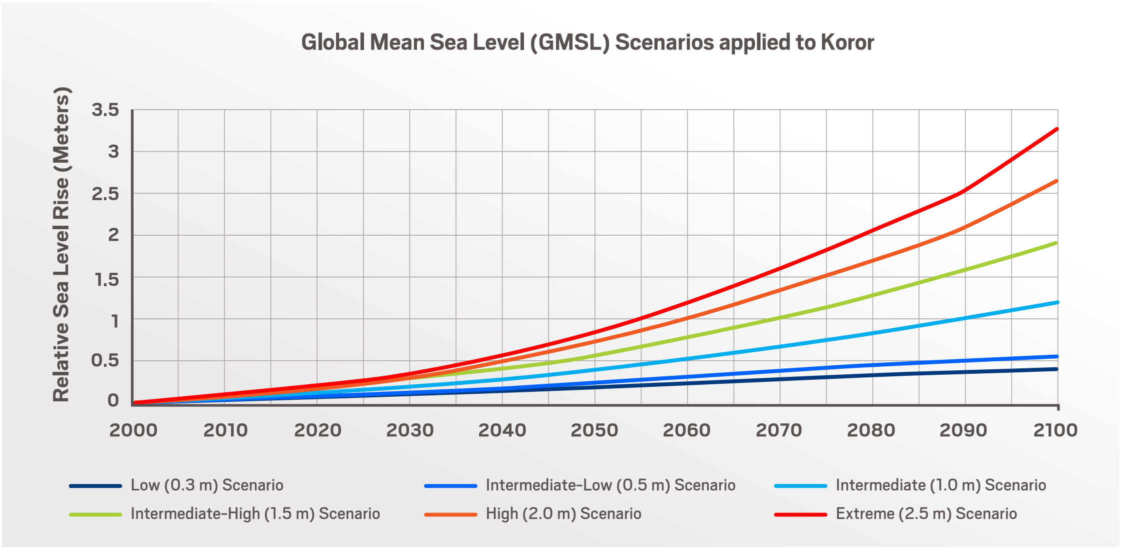


Figure 8. Six representative Global Mean Sea Level scenarios (6 colored lines) applied to Koror, Palau. The probability of exceeding each of these GMSL rise scenarios by 2100 is shown in Table 2. Sea level rise scenarios for Palau post-2100 can be found at: https://geoport.usgs.esipfed.org/terriaslc/. 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

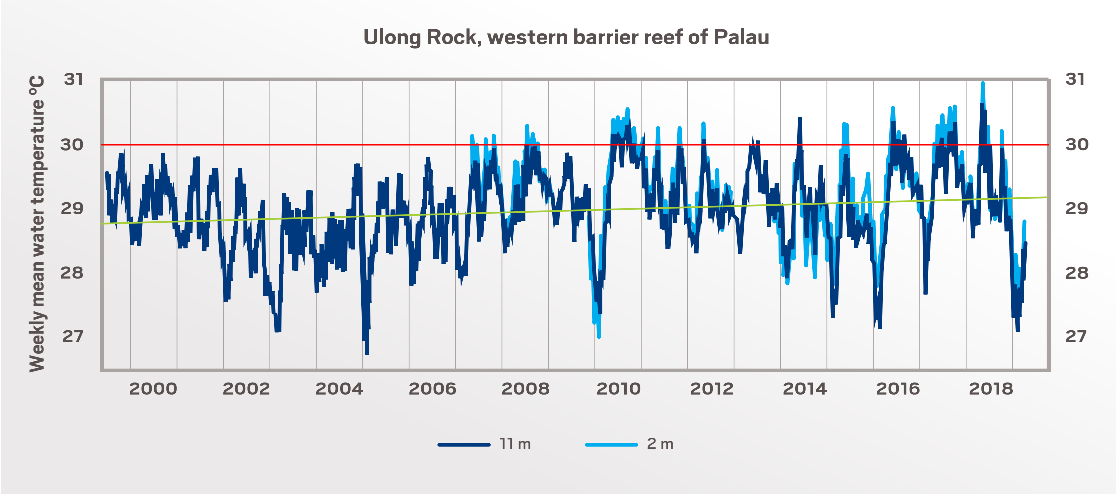


Figure 9. Water temperatures at Ulong Rock on the western barrier reef of Palau have shown a rise of about 0.36ºF (0.2ºC) per decade since 1999 (green line). The shallower areas of the barrier reef (average depth 2 m, but with high variation due to the 1–2 m tidal amplitude) are subject to higher variation 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

Projected Onset of Annual Severe Coral Reef Bleaching Conditions

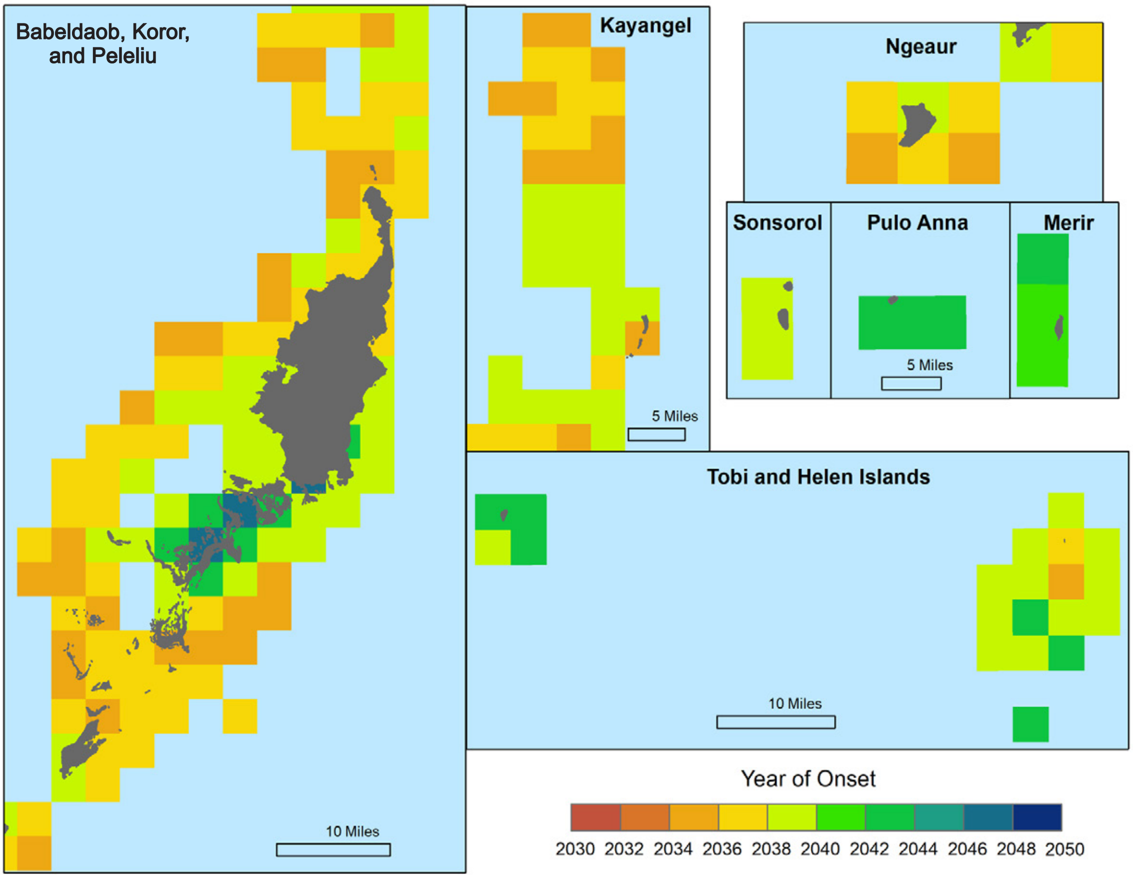


Figure 10. Projected year of onset of annual severe bleaching conditions for corals in Palau's waters (RCP8.5). Original figure by Laura Brewington, using data from van Hooidonk et al. 2016.

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.

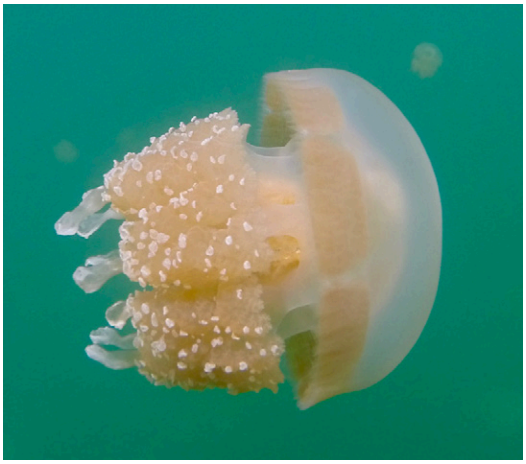
- ***Prepare for increasing frequency of tidal flooding events.*** The public health and disaster management sector will be faced with the combined impacts of sea level rise, storm surge inundation, and king tide flooding. During flood events, travel along the coast and access to medical services may 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.

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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

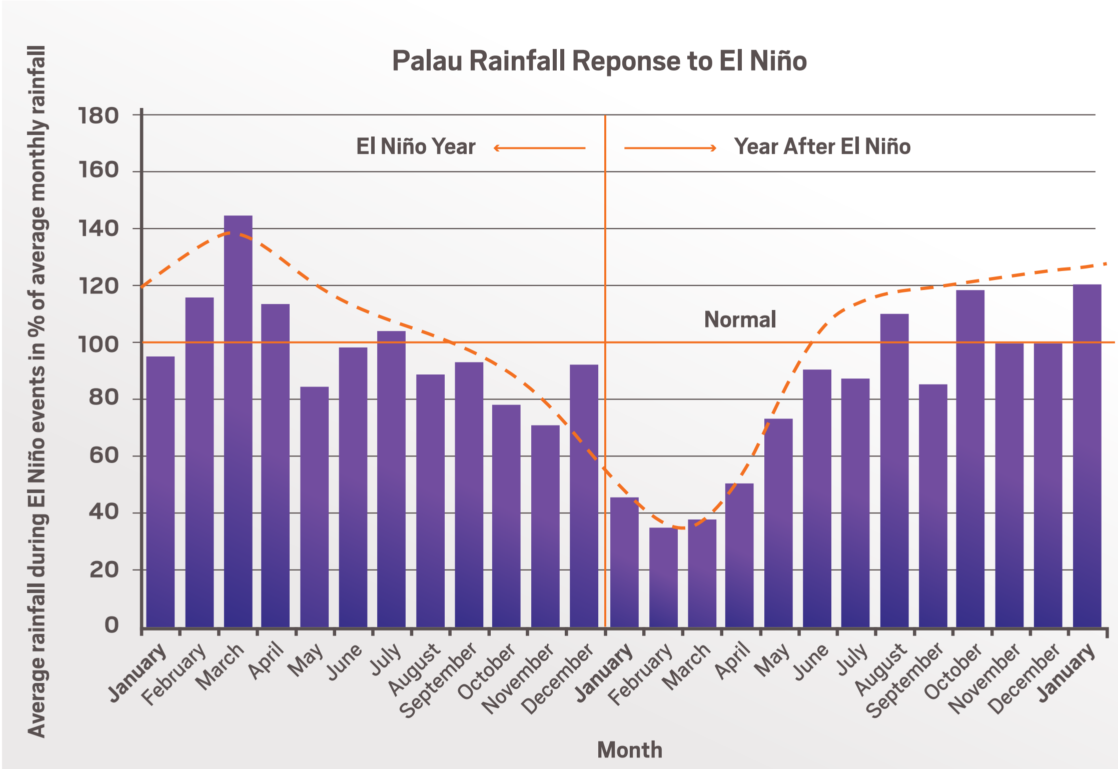

Figure 11. Average rainfall in Palau during El Niño events shown as the percent of average monthly rainfall. Source: Pacific ENSO Applications Climate Center 2018 (www.weather.gov/peac).

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; US-GCRP 2017; USGS Terria-Map 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

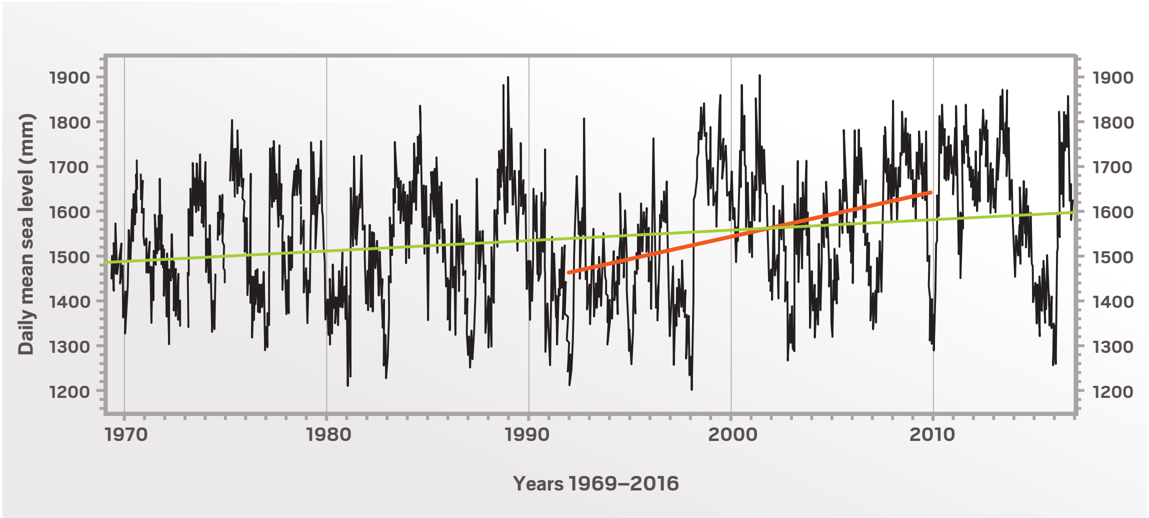

Figure 12. Mean Sea Level in Koror, Palau. From 1969 to 2016, average mean sea level in Palau increased (green line) but daily mean sea level (black line) fluctuated due to natural variability. These changes were particularly dramatic during shifts between El Niño and La Niña events. This resulted in 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

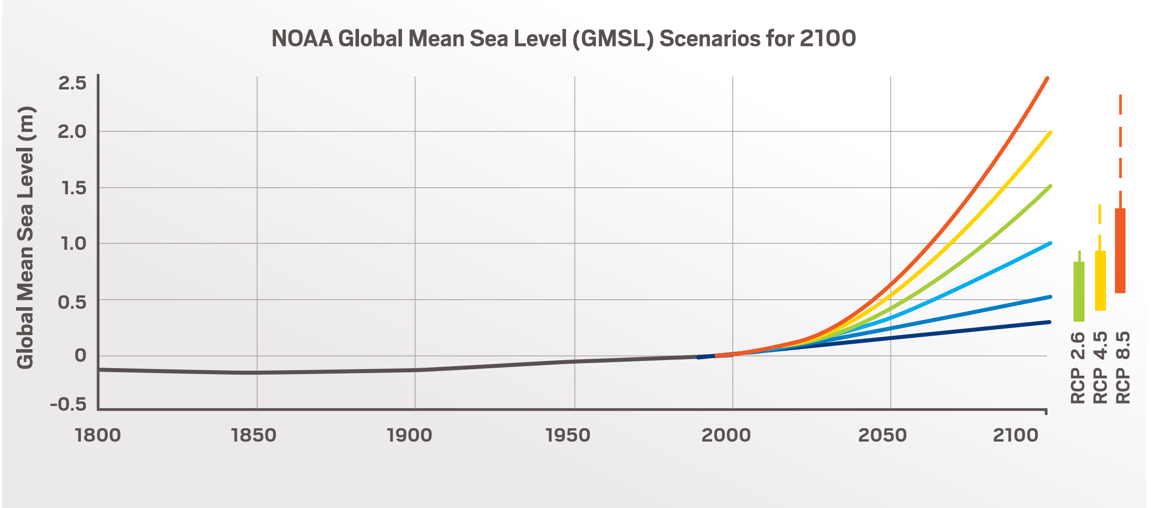

Figure 13. Six representative Global Mean Sea Level (GMSL) scenarios for 2100 (6 colored lines) relative to historical geological, tide gauge, and satellite altimeter GMSL reconstructions from 1800 to 2015. The colored boxes show central 90% conditional probability ranges of RCP-based GMSL projections 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.

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