Climate Change in Guam

PIRCA 2020

Indicators & Considerations for Key Sectors

Report for the Pacific Islands Regional Climate Assessment (PIRCA)

EAST-WEST CENTER

pirca PACIFIC ISLANDS REGIONAL CLIMATE ASSESSMENT

EAST-WEST CENTER

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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 Guam: 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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Mt Lamlam Summit, Guam
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Key Issues for Managers and Policymakers

Increasing air temperatures — Daytime and nighttime temperatures have risen in Guam. The annual number of hot days has increased, while the frequency of cool nights has decreased.

Stronger tropical storms and typhoons — Tropical cyclone intensity is expected to increase. Tropical cyclones are expected to decrease in number in the future, but those that do form are more likely to be intense (higher category), delivering higher wind speeds and more rainfall.

Declining total rainfall amounts — Guam is expected to become drier overall in the long term, with a projected island-wide decrease in rainy season precipitation.

Coral reef bleaching and loss — Oceans are warming, causing coral reef bleaching that is already severe and is expected to worsen in the next few decades. Coral reefs and ocean ecosystems contribute hundreds of millions of dollars annually to Guam's economy and provide natural protection from floods and storms.

Threats to infrastructure from sea level rise — Sea level is rising in Guam and is expected to damage natural and built assets by exacerbating high tide and wave flooding, storm surge, and coastal erosion. More frequent and intense coastal flooding and coastal erosion are anticipated to affect coastal properties and infrastructure in the coming decades as sea level rise accelerates.

Equity considerations — Climate change is expected to disrupt many aspects of life in Guam, and some groups will be affected disproportionately. Those who are already vulnerable, such as children, elderly people, and low-income communities, are harmed more by extreme weather and climate shifts.

Human health — The prevalence of heat-related illness is expected to increase with rising temperatures. Heatwaves and more extreme storms exacerbate pre-existing health issues and increase risk of wildfire and transmission of disease.

Risks to fresh water — Hotter temperatures increase the demand for water and decrease supply. Already, droughts can deplete surface water in southern Guam, causing dependence on well water. The combination of possible increased pumping, more frequent drought, and sea level rise threaten to bring saltwater contamination into wells in the Northern Guam Lens Aquifer. Water conservation, particularly during dry spells, may be necessary more often in the future.

Threats to ecosystems and biodiversity — Changes in temperature, rainfall, and tropical cyclone characteristics promote the spread of invasive species and reduce the ability of terrestrial habitats to support rare and protected species. Measures that enhance biodiversity and improve ecosystem resilience support communities in adapting.

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.


Photo: David Burdick

Climate Change in Guam: Indicators and Considerations for Key Sectors

Report for the Pacific Islands Regional Climate Assessment (PIRCA)

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Andersen Air Force Base
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Guam International Airport
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Agana Heights
Sinajana
Piti
Apra Harbor
Chalan Pago-Ordot
Mangilao
Pago Bay
Yona
Santa Rita
Agat
Fena Valley Reservoir
Talofofo
Umatac
Inarajan
Merizo
Original map by Laura Brewington

Inside this Report

Tumon Bay, Guam
Photo: shutterstock.com

Global Climate Change: Causes and Indicators

The causes of climate change

Scientists have researched the physical science of climate change for almost 200 years. Carbon dioxide and other greenhouse gases that naturally occur in the atmosphere keep the planet habitable by ensuring that some of the Sun's energy that radiates from Earth's surface is kept from escaping to 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 gas 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 last century (USGCRP 2018, Ch. 2, Key Message 1; IPCC 2014, SPM.1.2). The largest contributor to human-caused warming has been carbon dioxide (a greenhouse gas). 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 a warming trend in the climate system and the effects of increasing greenhouse gas concentrations in the atmosphere. The factors observed to be changing are known as **indicators** of change. Data collected from around the world show, for example:

- Globally, annual average temperatures over land and oceans have increased over the past 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, Ch. 1: Overview, Fig. 1.2, and Ch. 2, Key Messages 3–7; IPCC 2014, SPM.1.1; also see USGCRP Indicators—https://www.globalchange.gov/browse/indicators—and EPA Indicators—https://www.epa.gov/climate-indicators—websites).

▶ **Global Climate Change:** Causes and Indicators

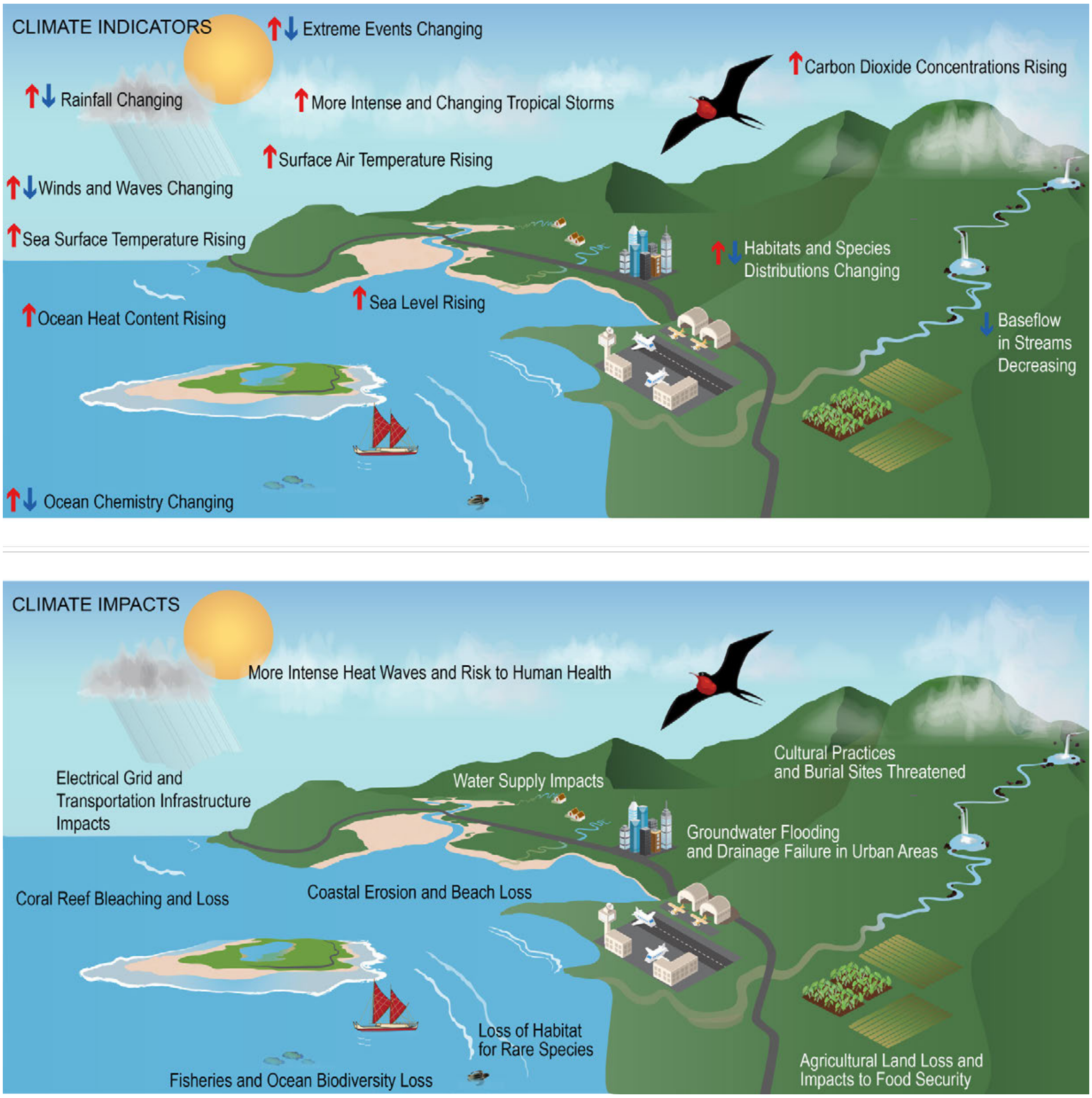


Figure 1. Observed changes in key climate indicators (top) in the Pacific Islands, such as carbon dioxide concentrations, sea surface temperatures, and species distributions result in impacts (bottom) to multiple sectors and communities, including built infrastructure, natural ecosystems, and human health. 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: From 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 (Fig. 1, 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 the future levels of greenhouse gas emissions (USGCRP 2018, Ch. 2, Key Message 2; IPCC 2014, SMP.2.1). Those emissions could vary widely depending on the actions that human society takes 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). In this summary, the "high scenario" (RCP8.5) represents a future where reliance on fossil fuels and annual greenhouse gas emissions continue to increase thoughout this century. The "low scenario" (RCP4.5) is based on reducing greenhouse gas emissions (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 Guam. Later sections describe: climate-related issues affecting families and households in Guam; extreme weather and climate change risks and considerations for managers and decision-makers; and identified needs for information and research. The findings are drawn from published literature on climate science, climate-related risks in the Pacific Islands, and risk management approaches. The Guam Climate Change Resiliency Commission, the University of Guam, the Pacific RISA, and the PI-CASC held a workshop in October 2019 that gathered knowledge that informed the report content and identified needs for information and research.

Indicators of Climate Change in Guam

These indicators of climate change in Guam build on previous work that includes the report *State of Environmental Conditions in Hawaii and the U.S. Affiliated Pacific Islands under a Changing Climate: 2017* (Marra and Kruk, NOAA NCEI, 2017). Indicators included in this foundational effort were derived through a series of 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 annual number of **hot days** in Guam has increased. The number of days with temperatures above 88°F (31.1°C), measured at the weather station located at Andersen Air Force Base, has increased, with 5 days per year exceeding 88°F (31.1°C) on average in the 1950s, compared to 36 days per year on average in the 1990s (Fig. 2). Recent air temperature measurements at the Antonio B. Won Pat International Airport in Tiyan show an increasing trend in the annual number of hot days (over 90°F, 32°C) since 1999 (Fig. 3). The longest complete dataset for Guam available from NOAA is the Andersen Air Force Base record from 1953 to 2002. Since recent data (after 2002) are not available from NOAA for this station, data are also shown for the International Airport at Tiyan from 1999 to 2019. Data prior to 1999 at the International Airport were omitted as they are considered unreliable because of weather station location changes in the mid-1990s.

The number of hot days over 90°F (32°C) in Guam is projected to increase to 257 days per year under a high scenario by the end of this century. In other words, more than 70% of days in the year are projected to experience temperatures over 90°F (32°C) (Zhang et al. 2016).

There has been a decrease in the annual number of **cool nights** (below 74°F) observed at Andersen Air Force Base between 1953 and 2002 (Fig. 4) and at the International Airport in Tiyan from 1999 to 2019 (Fig. 5). Similarly, the 2017 NOAA NCEI report found that cold nights (below the 5th percentile of the data record) decreased from an average of 40 per year in 1950 to an average of zero cold nights annually since 2005 (Marra and Kruk 2017).

Average air temperature, as measured at Andersen Air Force Base, has risen overall since measurements started in 1953 (See Fig. 6, Marra and Kruk 2017). Average air temperature at the International Airport also has risen since 1999 (Fig. 7). Average daily temperatures in Guam are projected to rise by 2.7–3.6°F (1.5–2.0°C) under a low warming scenario and by 5.4–6.3°F (3.0–3.5°C) under a high scenario (RCP8.5) by 2080–2099 (Zhang et al. 2016; Wang et al. 2016).

Fig.2

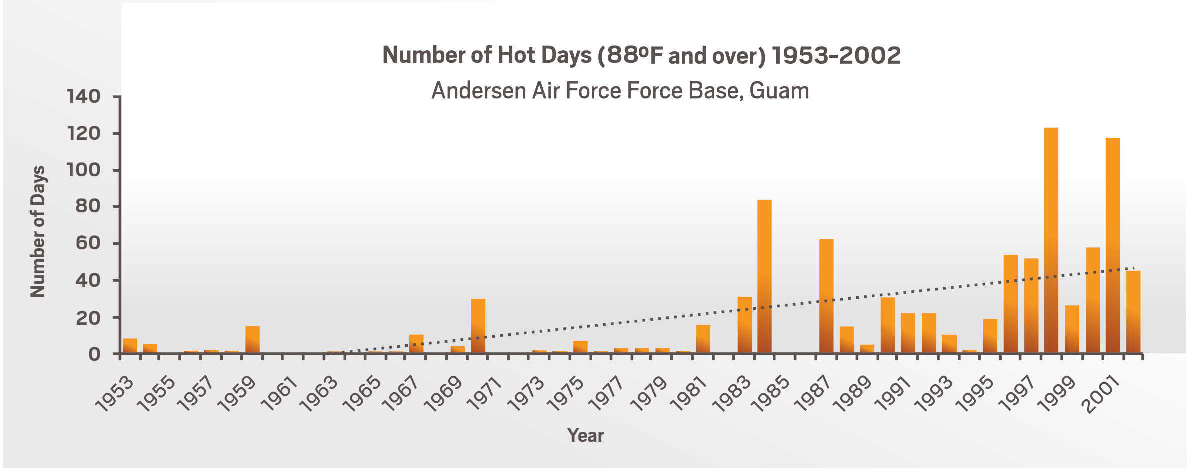


Figure 2. Annual number of days with maximum temperature 88ºF (31.1ºC) or hotter (at or above the 95th percentile of the data record) at Andersen Air Force Base in Guam from 1953 to 2002. The trendline (black, dotted line) shows there has been a long-term increase in the annual number of hot days. Original figure by Abby Frazier, using data from the NOAA GHCN-Daily database for 1953–2002 (NOAA 2020c; Menne et al. 2012).

Fig.3

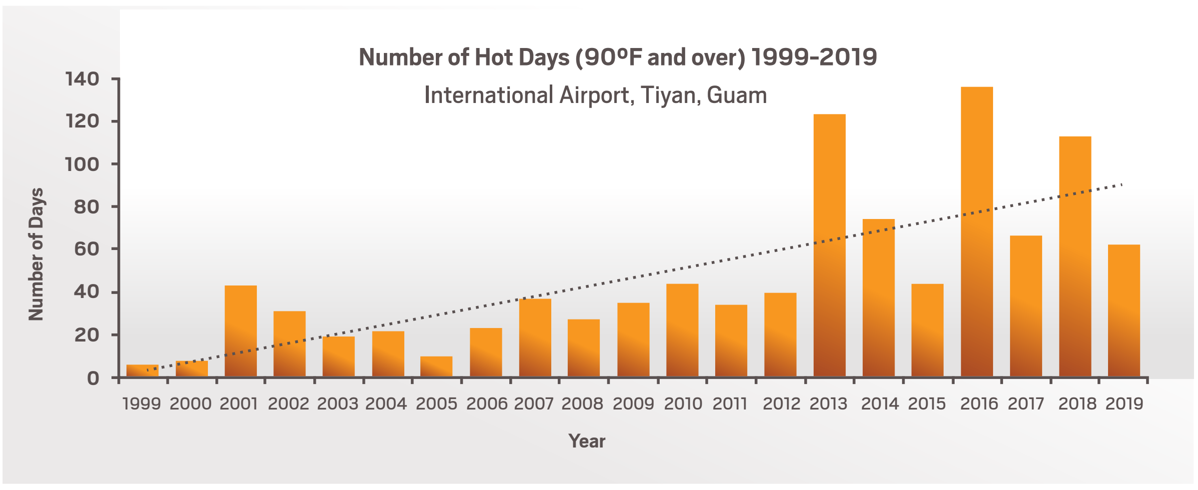


Figure 3. Annual number of days with maximum temperature 90ºF (32ºC) or hotter (at or above the 95th percentile of the data record) at the International Airport in Tiyan, Guam, from 1999 to 2019. The trendline (black, dotted line) shows there has been an increase in the annual number of hot days during this recent 21-year period. It should be noted that this station experienced equipment malfunctions from 2013 to 2019 that may have affected the maximum temperature readings. Original figure by Abby Frazier, using data from the NOAA GHCN-Daily database for 1999–2019 (NOAA 2020c; Menne et al. 2012).

Fig.4

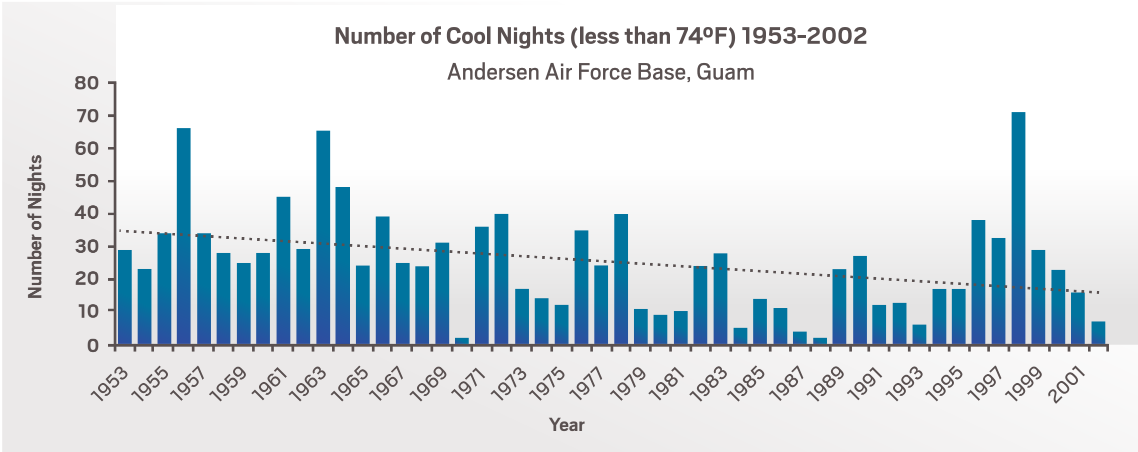


Figure 4. Annual number of nights with minimum temperature less than 74ºF (23.3ºC)—the 10th percentile of the data record—at Andersen Air Force Base in Guam from 1953 to 2002. The trendline (black, dotted line) shows a decrease on average in the frequency of cool nights during 1953–2002. Original figure by Abby Frazier, using data from the NOAA GHCN-Daily database (NOAA 2020c; Menne et al. 2012).

Fig.5

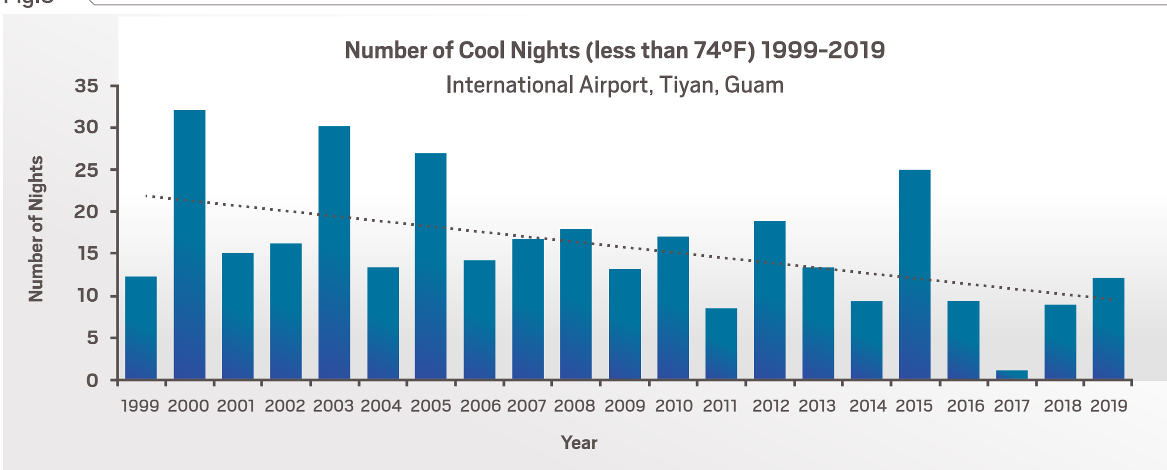


Figure 5. Annual number of nights with minimum temperature less than 74ºF (23.3ºC)—the 10th percentile of the data record—at the International Airport in Tiyan, Guam, from 1999 to 2019. The trendline (black, dotted line) shows a decrease in frequency of cool nights over the recent 21-year period. Original figure by Abby Frazier, using data from the NOAA GHCN-Daily database (NOAA 2020c; Menne et al. 2012).

Fig.6

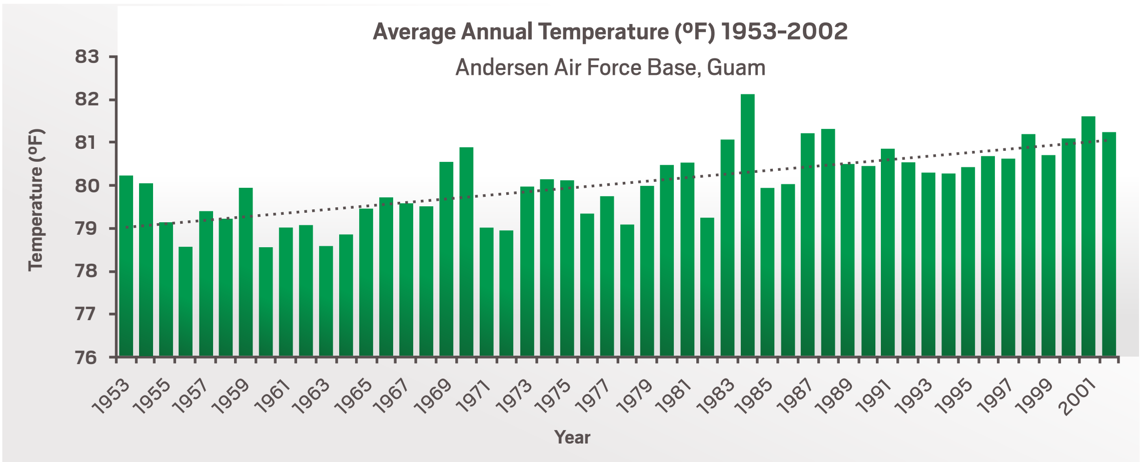


Figure 6. Average annual temperature at Andersen Air Force Base in Guam 1953–2002. The long-term linear trend indicated by the black, dotted line shows an increase over time. Original figure by Abby Frazier, using data from the NOAA GHCN-Daily database (NOAA 2020c; Menne et al. 2012).

Fig.7

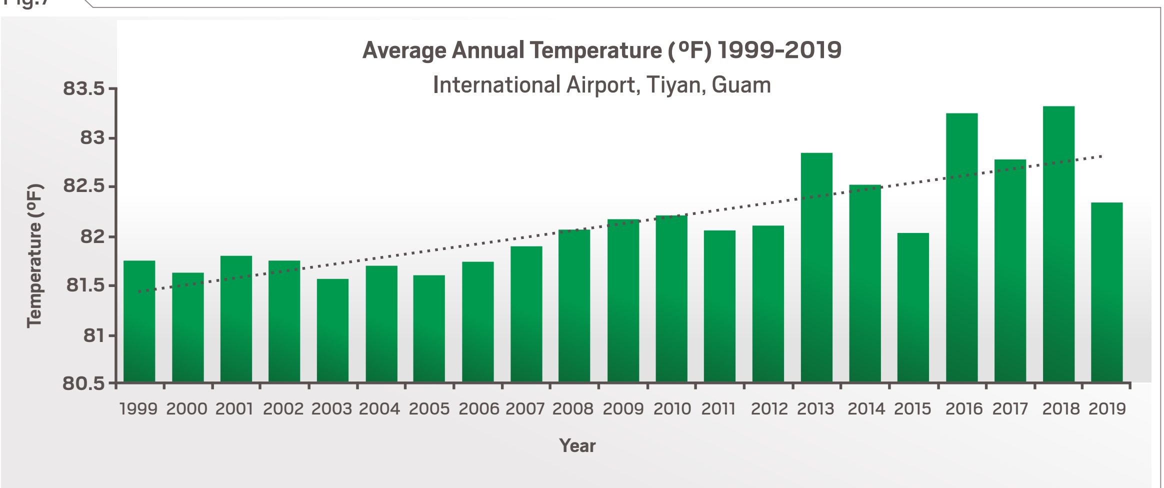


Figure 7. Average annual temperature at the International Airport in Tiyan, Guam, 1999–2019. The linear trend (black, dotted line) shows an increase over time. Original figure by Abby Frazier, using data from the NOAA GHCN-Daily database (NOAA 2020c; Menne et al. 2012).

Rainfall

Indicator	How has it changed?	Projected future change
Average rainfall	No change	↓
Rainy season average rainfall	No change	↓
Dry season 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 the Marianas region are strongly linked to monsoons of the Eastern Hemisphere and El Niño–Southern Oscillation (ENSO) events (Lander 1994; Polhemus 2017). As a result, Guam's rainfall is highly variable from year to year. At Andersen Air Force Base, the driest year recorded was 1998, during a strong El Niño, when rainfall was more than 35 inches (889 mm) below the normal total annual rainfall of approximately 90 inches (2286 mm) (Marra and Kruk 2017). The period 1969–1973 had the lowest total rainfall of any 5-year period and included the 1972–1973 El Niño event (Gingerich 2013). The wettest year was 1963 when the station recorded 59 inches (1499 mm) of above-normal rainfall. Rainfall is also highly seasonal, with approximately 30% of annual total rainfall delivered in the dry season (January through June) and 70% in the rainy season (July through December) (Lander and Guard 2003). Tropical cyclones passing near or over Guam bring extreme rainfall events and deliver an estimated 12% of total rainfall (Lander 1994; Johnson 2012; Polhemus 2017).

Average daily and annual rainfall are near the long-term normal values, with no statistically significant change from the 1950s to present (Marra and Kruk 2017). Under the high scenario average island-wide annual rainfall is projected to decrease about 7% overall by the end of the 21st century (2080–2099) relative to 1990–2009 (Gingerich et al. 2019a; Wang et al. 2016; Zhang et al. 2016). Rainfall in the rainy season (July to December) is expected to be reduced by 12% under the high scenario by 2080–2099, while dry season (January to June) rainfall is projected to increase by about 9% under the high scenario by 2080–2099. Overall, Guam is expected to become drier under a high emissions scenario (Gingerich et al. 2019a; Wang et al. 2016; Zhang et al. 2016). Under a lower warming scenario, projected future average annual rainfall shows no statistically significant change from present (Wang et al. 2016).

The frequency of **extreme rainfall** has changed little on average at Andersen Air Force Base since the 1950s (Marra and Kruk 2017; Fig. 8). A small increase in extreme rainfall days has been recorded at the International Airport in Tiyan over the past 20 years, though it is not significant (Fig. 9). Variability in the monsoon and other factors means rainfall is much greater in some years than others. In the future, the Marianas region is expected to experience more frequent and intense extreme rainfall events with global warming. Guam is projected to experience a higher number of extreme rainfall events annually (Zhang et al. 2016; IPCC 2013a). Increased heavy rainfall events will result in increased runoff and increased potential for flooding and erosion.

Fig.8

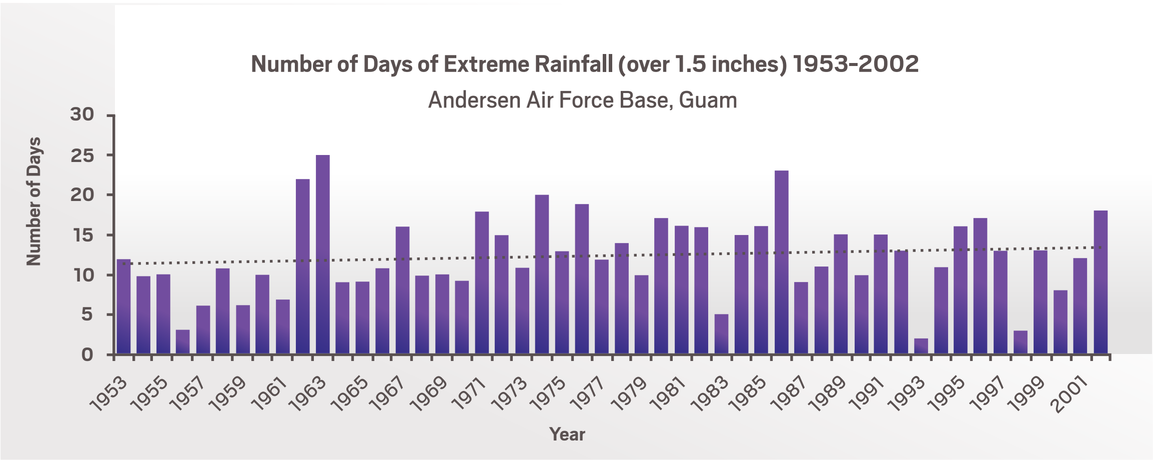


Figure 8. Annual number of extreme rainfall days, or days with daily rainfall totals exceeding the 95th percentile (approximately 1.5 inches) of the distribution at Andersen Air Force Base, Guam, from 1953 to 2002. The linear trend (black, dotted line) shows no trend over time. Original figure by Abby Frazier, using data from the NOAA GHCN-Daily database (NOAA 2020c; Menne et al. 2012).

Fig.9

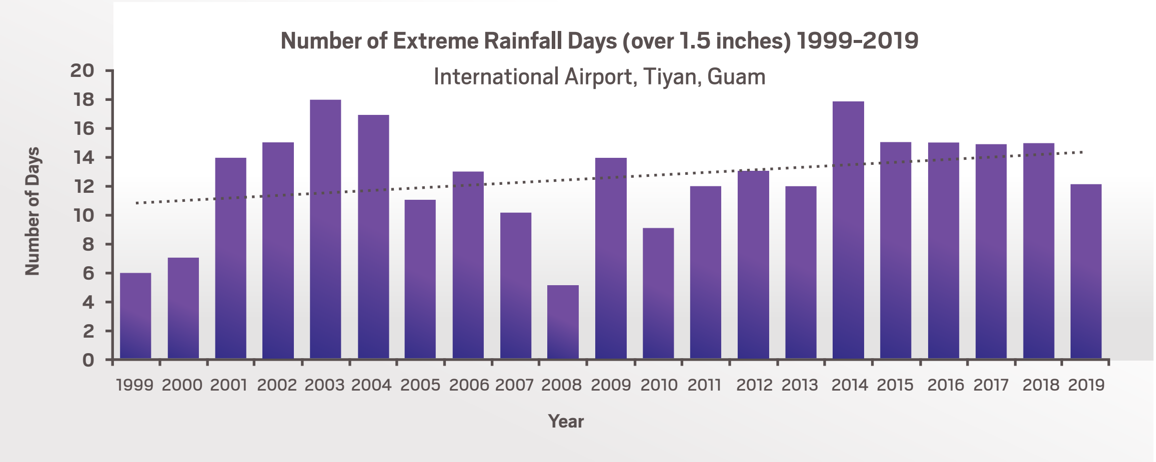


Figure 9. Annual number of extreme rainfall days, or days with daily rainfall totals exceeding the 95th percentile (approximately 1.5 inches) of the distribution at the International Airport in Tiyan, Guam, from 1999 to 2019. The linear trend (black, dotted line) shows no significant trend over time. Original figure by Abby Frazier, using data from the NOAA GHCN-Daily database (NOAA 2020c; Menne et al. 2012).

Indicator	How has it changed?	Projected future change
Frequency of drought	?	↑
Streamflow	?	↓

Drought conditions on Guam are conducive to wildfire ignitions and spread. Drought is also associated with water stress for crops and ecosystems (Frazier et al. 2019). Drought conditions will likely be more frequent in the future. Drought conditions (defined here as more than 20% below mean annual historic rainfall) are projected to occur in 4 out of 10 years on average in 2080–2099 under the high scenario. This is an increase in **drought frequency** from the historic rate of 1.6 years out of 10 years on average (Gingerich et al. 2019a; Zhang et al. 2016).

Any future changes in ENSO are likely to affect the frequency and intensity of drought (PEAC Center 2015). Recent studies show that the frequency of strong El Niño events has increased in the past 30 years as compared to previous centuries (Freund et al. 2019; Wang et al. 2019).

The annual number of days with no rainfall at Andersen Air Force Base shows a decreasing trend from 1953 to 2002 (Fig. 10). However, the recorded number of no-rainfall days at the International Airport has increased in the past 20 years (Fig. 11). It should be noted that neither trend is statistically significant. Many factors affect variations in the annual number of dry days, on scales from years to decades, including ENSO events and cyclical phenomena with extended phases such as the Pacific Decadal Oscillation (Polhemus 2017).

Fig.10

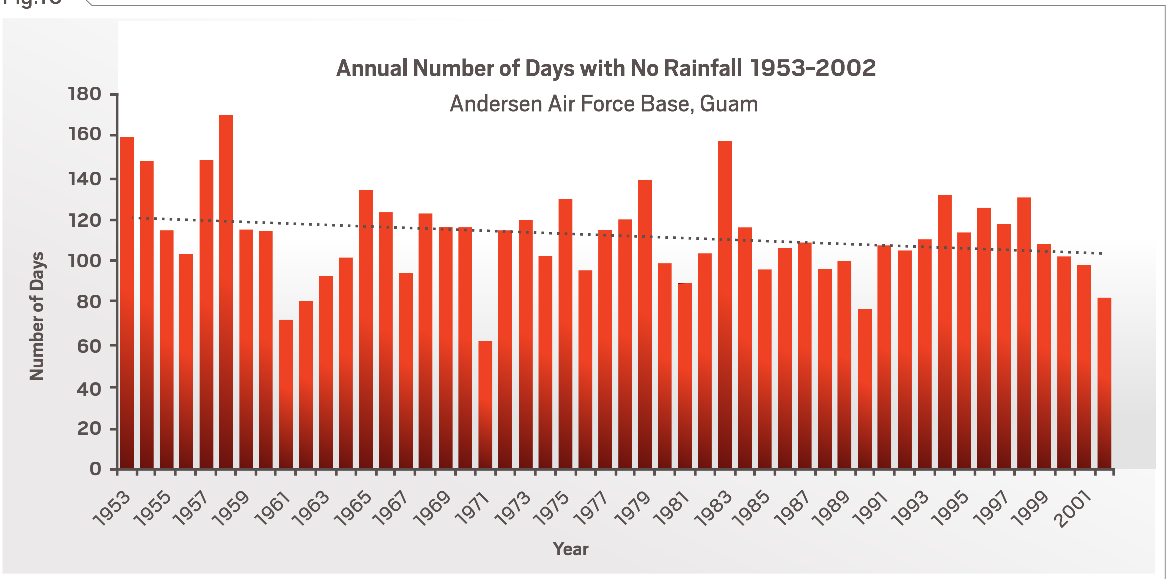


Figure 10. Annual number of days with no measurable rainfall at Andersen Air Force Base in Guam from 1953 to 2002. The black, dotted line shows no significant linear trend over time. Original figure by Abby Frazier, using data from the NOAA GHCN-Daily database (NOAA 2020c; Menne et al. 2012).

Fig.11

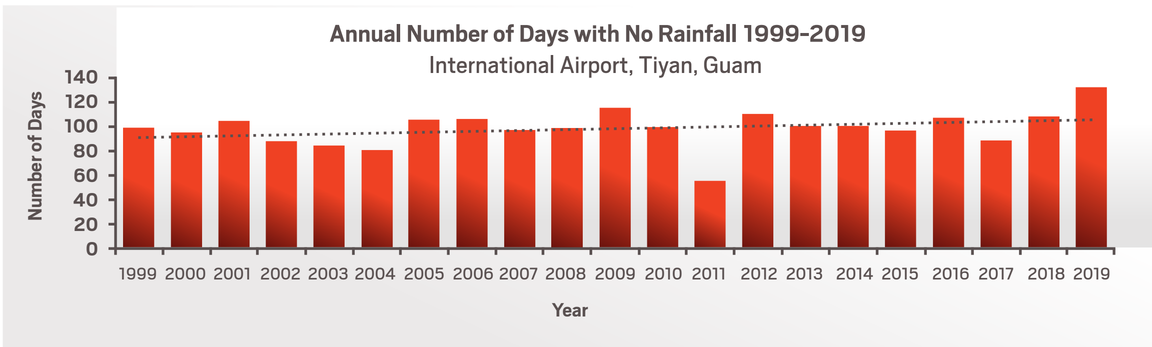


Figure 11. Annual number of days with no measurable rainfall at the International Airport in Tiyan, Guam, from 1999 to 2019. The linear trend (black, dotted line) shows no significant trend over time. Original figure by Abby Frazier, using data from the NOAA GHCN-Daily database (NOAA 2020c; Menne et al. 2012).

Streamflow records available for Guam are mostly short or discontinuous. Only two stream gauges on Guam have more than 35 years of record and are unaffected by artificial diversions (Keener et al. 2012; Rosa and Hay 2017). Average streamflow is projected to decrease by 12–36% in a future climate under the high scenario relative to historic streamflow (Gingerich et al. 2019a). Streamflow decreases are due to expected decreases in future rainfall and increases in temperature that cause increased evapotranspiration (Gingerich et al. 2019a).

Typhoons and storms

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

Typhoons, tropical storms, and tropical depressions (referred to collectively as tropical cyclones) can bring intense winds, torrential rainfall, high waves, and storm surges to islands near their path. The effects of a tropical cyclone strike or near miss can cause severe impacts to lives and property. Guam lies within one of the most active regions for tropical cyclones in the world. There is an increased risk of tropical cyclones striking Guam during an El Niño year (PEAC Center 2015). Guam is at a lower risk of experiencing tropical cyclones during La Niña years.

The number of named tropical storms and typhoons affecting Guam has remained fairly constant over the past 40 years (Marra and Kruk 2017; Knapp et al. 2010). Historically, Guam has expected 2 to 8 storms in any given year. In the northwestern Pacific basin, which encompasses Guam, the overall frequency of tropical cyclones decreased by 15% from 1980 to 2013 and storm tracks generally shifted northward. As a result, tropical cyclone exposure was lower during 1992-2013 compared to previous decades (Lin and Chan 2015; Kossin et al. 2016). Wind speeds in Guam are mostly low (under 20 knots) except in and near tropical cyclones and other storms.

There is scientific consensus that **tropical cyclone intensity** is likely to increase in a warmer climate for most regions, including around Guam (USGCRP 2017; IPCC 2013a; Marra and Kruk 2017; Knutson et al. 2015; Sobel et al. 2016; Zhang et al. 2016; Wang et al. 2016; Widlansky et al. 2019; Kossin et al. 2020). The change in tropical cyclone intensity is projected to affect stronger storms the most (resulting in increased maximum intensities), which would amplify the potential for severe damage (Widlansky et al. 2019).

Fewer tropical cyclones are projected to occur by the end of this century, both globally and around Guam (Kossin et al. 2016; Zhang et al. 2016; Wang et al. 2016; USGCRP 2017). The overall decrease in **tropical cyclone frequency** (occurrence) is expected because climate models suggest that the atmosphere will become more stable with continued greenhouse warming (USGCRP 2017; Widlansky et al. 2019). Compared to the historical yearly 2 to 8 tropical cyclones tracking near Guam, in the future, the occurence is likely to decrease to 1 to 6 storms per year (Widlansky et al. 2019). Thus, the likely overall outlook for Guam is for fewer but stronger storms in the future.

Sea level

Indicator	How has it changed?	Projected future change
Sea level	↑	↑
High water 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. The **sea level** around Guam is rising. Guam's tide gauge for measuring long-term sea level trends recorded an average rise of 0.13 inches (3.4 mm) per year since 1993 (NOAA 2020b). (An earthquake in 1993 caused vertical land motion and water-level change at the coast. The average rate of change reflects post-earthquake measurements).

Relatively small changes in average sea level, tropical cyclone occurrence, and monsoon wind activity can have large effects on **high water frequency** and coastal erosion. High water days (also called "tidal flooding") affect coastal areas when exceptionally high tides combine with high wave events. In Guam, the largest year-to-year variability in sea level is associated with El Niño and La Niña events (lower or higher than average by as much as 1 foot [0.3 m], respectively). Sea levels also vary with the Pacific Decadal Oscillation, annually due to the seasonal cycle of ocean temperature, and on shorter time spans due to abrupt changes in the winds and atmospheric pressure (for example, storm surges).

The number of high water days has increased from 2 days per year on average in the 1960s to 21 days per year today (for the decade 2005–2014) (Marra and Kruk 2017). In this case, a high water day is a day in which the water elevation at the tide gauge exceeded the value associated with a twice-a-year return interval (reference year is 2005). Although not as damaging as floods that occur during big storms, the impacts of minor high water can cumulatively cause problems such as increased erosion of buildings,

Fig.12

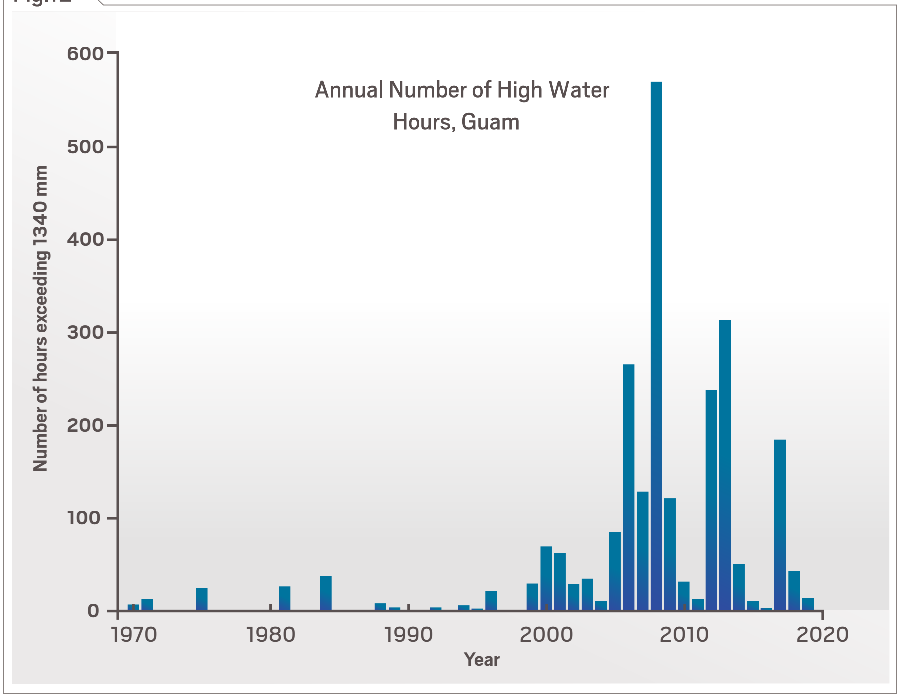


Figure 12. The number of high water hours per year at Guam's coast, 1970 to 2019. The high-water threshold (1340 mm, 4.4 feet) is defined as the Mean Higher High Water level plus 1/3 of the difference between that and the Mean Lower Low Water level at the tide gauge (that is, water levels above the daily average highest tide plus a factor of the typical tidal amplitude). High water hours per year are affected by seasonal factors (such as monsoon activity), cyclical phenomenon (such as ENSO and Pacific Decadal Oscillation), and sea level rise. Source: Figure courtesy of Matthew Widlansky, with data from the University of Hawai'i Sea Level Center Station Explorer (https://uhslc.soest.hawaii.edu/stations/?stn=053#datums).

roads, piers, and vegetation. Areas already affected by high water include, for example, Tumon, Agat, and Merizo. Conversely, with low sea level events, as are likely during El Niño, massive coral die-offs can occur due to air exposure (Raymundo et al. 2017).

Sea level rise will continue in Guam, and the rate is projected to accelerate in the future. Global Mean Sea Level is projected to rise 0.3–0.6 feet (0.1–0.2 m) by 2030. For 2050, the projected range of Global Mean Sea Level rise is 0.5–1.2 feet (0.2–0.4 m), and by 2100 the projected range is 1.0–4.3 feet (0.3–1.3 m) (USGCRP 2017). Emerging climate science suggests that Global Mean Sea Level rise of more than 8 feet by 2100 is possible, though the probability of this extreme outcome cannot be assessed (USGCRP 2017; Sweet et al. 2017). There is very high confidence in the lower bounds of these projections. Global sea levels are expected to continue to rise after 2100 (USGCRP 2017; Sweet et al. 2017).

For Guam and tropical Pacific Islands, which are far away from the decreasing gravitational attraction of melting land ice, sea level rise is expected to be higher than the global average (USGCRP 2017: 12.5.4; Sweet et al. 2017; Kopp et al. 2014). For example, if Global Mean Sea Level rises 1 foot (or 0.3 m—the low end of the rise likely by 2100), Guam is expected to see 1.2 feet (0.38 m) of sea level rise. With 3.3 feet (1.0 m) of

Global Mean Sea Level rise relative to historical levels (considered likely by 2100 under a high scenario), Guam is expected to see 3.9 feet (1.2 m) of rise by 2100. It is possible that sea level rise may exceed these levels (Sweet et al. 2017). Sea level rise will cause coastal flooding to become more frequent and severe, which could be exacerbated by sea level variability associated with more extreme El Niño and La Niña events (Widlansky et al. 2015). Under a scenario of 3 feet of sea level rise, 58% of Guam's infrastructure (including electricity, water, wastewater, roads and bridges, and buildings) is exposed to impacts. This increases to 74% of infrastructure with 5 feet of sea level rise, with the southern villages most affected under both scenarios (King et al. 2019).

Ocean changes

Indicator	How has it changed?	Projected future change
Sea surface temperature	↑	↑
Frequency and intensity of heat stress on coral	↑	↑
Ocean acidification	↑	↑

Human activities have resulted in changes in the chemical composition, temperature, and circulation of oceans, which have ramifications for marine ecosystems. Changes in **sea surface temperature**—the temperature of water at the ocean's surface—can dramatically alter marine ecosystems. Sea surface temperature has increased globally since 1880. Average sea surface temperatures around Guam in recent years (2010–2015) were higher than the long-term average (1982–2011) (Marra and Kruk 2017).

The **frequency of heat stress** responsible for coral reef bleaching is increasing in Guam. The number of days per year that at least some corals were exposed to heat stress, as categorized by the NOAA Coral Reef Watch, has risen from 9 days per year (in 1982–1991) to 32 days per year (in 2007–2016) on average, a 252% increase (Marra and Kruk 2017). The **intensity of heat stress** has also increased. The Degree Heating Week metric shows how much heat stress has accumulated in an area over the past 12 weeks. In 5 of the last 10 years, Guam was exposed to at least Alert Level 1 conditions (Degree Heating Week value ≥4°C–weeks, when ecologically significant bleaching is likely). Heat stress in 2017 was the most intense since satellite measurements began.

High sea surface temperatures produced severe, widespread bleaching of Guam's reefs in 2013, 2014, 2016, and 2017 (NOAA Coral Reef Watch 2018; Raymundo et al. 2019). More than one third of Guam's shallow corals died during this multi-year bleaching event (37% along the western coast and 34% at seaward sites around the island; Raymundo et al. 2019).

Unless coral species adapt to ocean warming, all coral reef areas in Guam are projected to begin to experience annual severe bleaching before 2045, and some areas are expected to experience annual severe bleaching beginning in about 2035 (Fig. 3) (van Hooidonk et al. 2016). However, a study at Asan Bay suggests that natural circulation of cooler water from lower depths to shallow coral reef areas is likely to somewhat reduce thermal stress from projected increases in water temperatures (Storlazzi et al. 2013). Semidiurnal temperature fluctuations are expected to cause small (less than 10 years) to no delays in the onset of annual severe coral bleaching in reefs across Guam (Storlazzi et al. 2020).

As extra carbon dioxide in the atmosphere reacts with sea water, the ocean becomes slightly more acidic. Data collected over 30 years at Station ALOHA north of Oʻahu, Hawaiʻi, are considered the best available documentation of ocean acidity for the western and central Pacific and show that **ocean acidification** has been slowly increasing (roughly by 9%) since records began in 1988 (Marra and Kruk 2017). Ocean chemistry will continue to change, and under a high warming scenario, all coral reefs are projected to exist in conditions that will impede their ability to grow by the end of the century (Australian BOM and CSIRO 2014).

Projected Onset of Annual Severe Coral Reef Bleaching

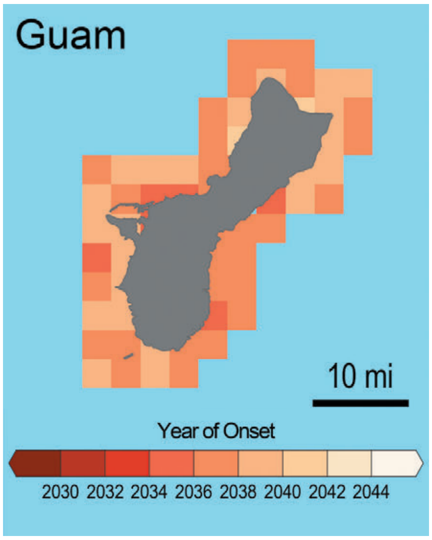


Figure 13. Projected year of onset of annual severe bleaching caused by ocean warming for corals in the waters of Guam. Under projected warming, coral reefs will experience annual bleaching beginning in about 2035 in the Mariana Archipelago. Source: Adapted from Keener et al. 2018, using data from van Hooidonk et al. 2016.

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, KM 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 (Fatoric and Seekamp 2017).

Two such approaches, that 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, as in critical infrastructure vulnerability assessment.

In some cases, comprehensive risk management helps 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 minimize the impacts from sea level rise, and the sea level rise turns out to be higher than expected, the infrastructure could actually contribute to flooding if storm water and sewer systems are unable to handle the rising 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 Guam's Families, Households, and Vulnerable Populations?

Climate change is anticipated to disrupt many aspects of life. More intense extreme weather events, declining water quantity and quality, increasing wildfire, poor air quality, 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, food production, and global economics are projected to cause large shifts in prices and commodity availability, potentially leading to price shocks and food insecurity (USGCRP 2018, Ch. 16, KM 1 and 3).

Although climate change is expected to affect all people in Guam, 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, older adults, low-income communities, and those experiencing discrimination, are harmed more by extreme weather and climate events, in part because they are often excluded in planning processes (USGCRP 2018, Ch. 14, KM 2; Ch. 15, KM 1–3; Ch. 28, Introduction).

The following are examples of how vulnerable populations are expected to be affected in Guam:

- Hot days are increasing, and children have a higher rate of heat stroke and heat-related illness than adults (USGCRP 2016; EPA 2016).
- Rising food prices and energy bills (from cooling) will have a disproportionate impact on low-income families and households.
- Older adults and persons with disabilities are more vulnerable to extreme events, such as storms, that cause power outages or require evacuation. Emergency response plans specifically accommodating these groups can lessen the risks (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, fishermen, 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 flood-prone areas, are more likely to experience higher risks to health and safety (USGCRP 2016).

A Social Vulnerability Index assessed social vulnerability in each of the municipalities on Guam, using Centers for Disease Control and Prevention (CDC) methodology (King et al. 2019). The Social Vulneraiblity Index ranked Guam's municipalities based on variables from the Guam census indicating: socioeconomic status; household composition and disability; minority status and language; and housing and transportation. The three most vulnerable villages were found to be Agat, Mongmong-To-to-Maite (MTM) and Hagåtña, and the three villages found to be least vulnerable were Piti, Santa Rita, and Asan-Maina (King et al. 2019). This index, however, does not include climate-related factors and is intended to be used in conjunction with information about exposure and sensitivity to climate risks.

Certain populations may also be affected more than others by actions to address the causes and impacts of climate change, if not implemented in ways that consider existing inequalities (USGCRP 2018, Ch. 11, KM 4 and Ch. 28, KM 4). For example, policies that tax fossil fuels could avoid harm to low-income communities through tax rebates or other payments that alleviate the cost burden. Plans that consider these vulnerable communities and improve access to healthcare and services can help address social inequalities.

Global action to significantly cut greenhouse gas emissions can reduce climate-related risks and increase opportunities for these populations 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 scenario (RCP8.5) (USGCRP 2016).

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

The Pacific Islands Regional Climate Assessment suggests the following considerations for managers working in key sectors based on an up-to-date review of published literature on climate science, climate-related risks in the Pacific Islands, and risk management approaches.

If you are a water resources or utilities manager...

- ***Expect hotter conditions to increase water demand and decrease available surface fresh water.*** Southern Guam depends on surface water supplied from rivers and the Fena Valley Reservoir. Streamflow in southern Guam and Fena Reservoir water volume decrease below usable levels in long, severe droughts. Rising temperatures will increase evapotranspiration (about 14% higher and up to 29% higher in some locations), affecting both the amount of fresh water available and the human population's demand for water (Gingerich et al. 2019a; Zhang et al. 2016; Wang et al. 2016).

- ***Monitor salinity levels in aquifers, and plan for reduced recharge.*** The increased rate of water evaporation from soils, plants, wetlands, reservoirs, and streams means less water will likely be available to replenish the groundwater aquifers of Guam. Northern Guam is dependent on the Northern Guam Lens Aquifer for water for household use and drinking. As on other small oceanic islands, the freshwater aquifers (called the freshwater lens) are underlain by saltwater (Fig. 14). Mean annual recharge for the Northern Guam Lens Aquifer is projected to decrease by about 19% by late this century under a high warming scenario (Gingerich et al. 2019a). The combined effects of higher demand and the need to increase pumping, more frequent drought, and sea level rise could bring salt water closer to wells that supply drinking water. In the past, drought has significantly decreased the recharge rate of the Northen Guam Lens Aquifer. In the Yigo-Tumon Basin, for example, recovery of the lens thickness from drought has taken up to 5 years (Gingerich 2013). Many of northern Guam's wells already show increasing saltwater contamination (McDonald and Jensen 2003). Water conservation, particularly during dry spells, may be necessary more often in the future.

- ***Consider proactive strategies to mitigate the impacts of drought, sea level rise, stronger storms, and increasing population.*** Making changes in pumping depth or withdrawal rates for areas of the aquifer that may experience salinity problems could reduce the vulnerability of groundwater resources. Guam's population more than doubled from 1970 to 2010, and the aquifers of Guam are now pumped at higher rates. Thus, aquifers are likely now more vulnerable to drought-linked depletion than in the past. During droughts, depleted surface water sources (in southern Guam) can increase dependence on well water. Increasing knowledge and awareness among community members about how water systems may be impacted by climate change and variability could increase

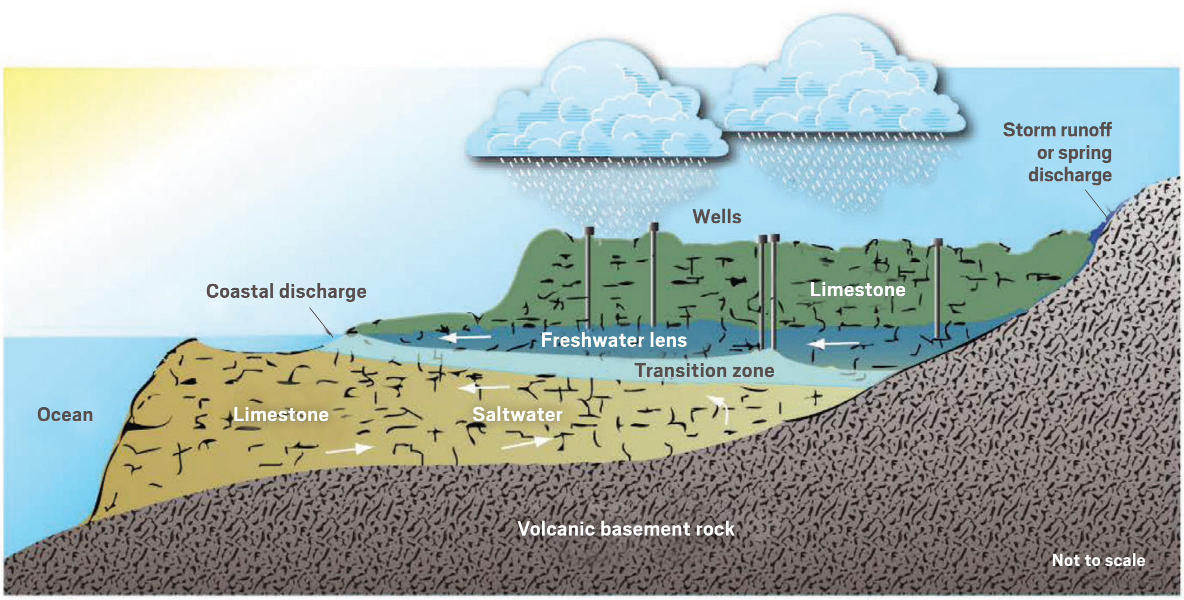


Figure 14. Schematic cross-section of the Northern Guam Lens Aquifer. Source: Adapted from Gingerich and Jenson 2010.

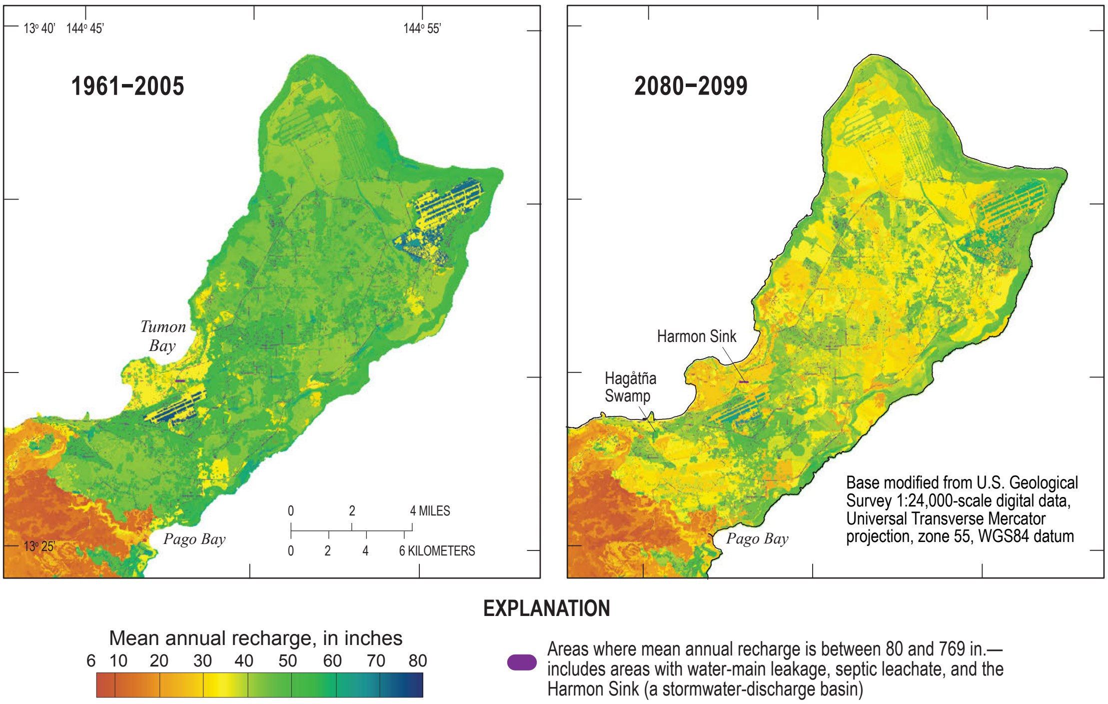


Figure 15. The distribution of average annual groundwater recharge (in inches) estimated for the Northern Guam Lens Aquifer for historic (1961—2005, left) and future (2080—2099, right) climate conditions. Source: Gingerich et al. 2019c.

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. 2019b).

- ***Energy consumption is projected to 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. Increased hot days will generally increase the need for water and the loss through evaporation. More energy will also be required to cool homes on hot days. Meanwhile, a growing tourism industry and resident population would further increase demand for water and electricity. Guam is looking to grow its tourism industry, and the US military anticipates adding at least 4,000 Marines over the next 10 years. Thus, a greater amount of energy is expected to be required to pump and distribute water in the future (Gingerich et al. 2019b).

- ***Monitor El Niño–Southern Oscillation and its effects on rainfall.*** The El Niño–Southern Oscillation (ENSO) strongly influences rainfall amounts, which vary greatly from year to year in Guam. El Niño events typically bring more tropical cyclones and extreme rainfall followed by a period of dry weather to Guam (Fig. 16). A strong El Niño can cause severe drought. Evidence shows an increased frequency of strong El Niño events with climate change (Freund et al. 2019; Wang et al. 2019; Cai et al. 2014). Seasonal forecasts can help water managers to prepare for potential water shortages during drought years.

Fig.16

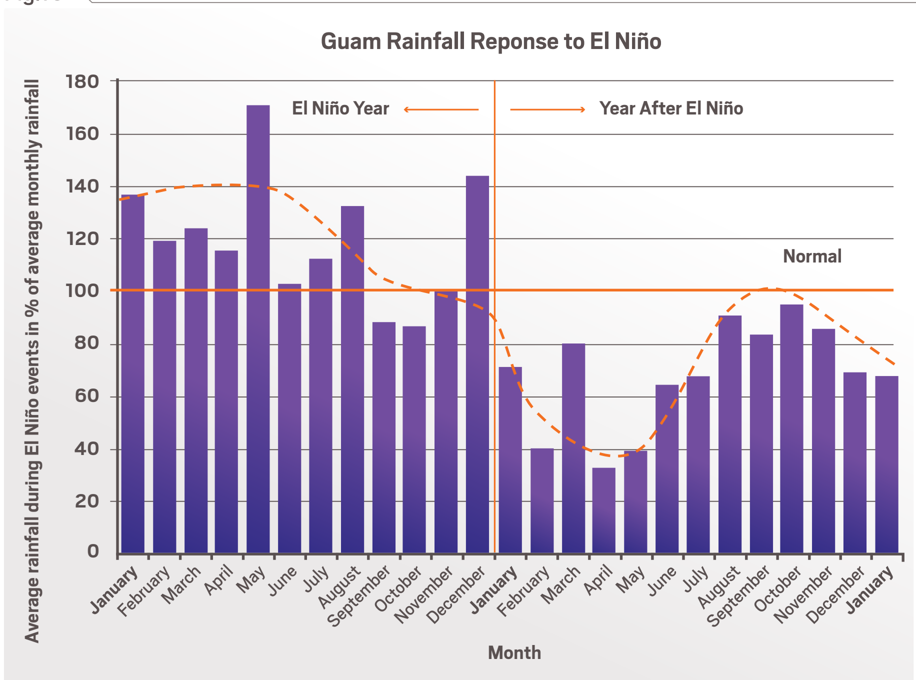


Figure 16. Average rainfall in Guam during El Niño events shown as the percent of average monthly rainfall. Source: Pacific ENSO Applications Climate Center 2018.

If you work in public health and safety...

- ***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, KM3).

- ***Prepare for more frequent extreme heat events that are expected to increase heat-related illness and death.*** Even small increases in average air temperature can increase extreme heat, which is associated with heat-related illness and death. 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). On Guam, the leading causes of death are non-communicable diseases (NCDs), including heart disease, cancer, stroke, and diabetes (Ichiho et al. 2013). Temperature extremes can worsen chronic conditions. Prolonged exposure to hot temperatures has been observed to increase hospitalizations for cardiovascular, kidney, and respiratory disorders (Sarofim et al. 2016). Extreme heat is linked to an increased risk of cardiovascular and respiratory deaths in the elderly (Åström et al. 2011). Rising temperatures can also affect the management of NCDs including diabetes, since hot weather makes it uncomfortable and even unsafe to practice proper exercise. To assess the risks of rising air temperatures and other climatic changes on local health, the US Center for Disease Control and Prevention developed the “Building Resilience Against Climate Effects” (BRACE) framework (CDC 2019),

Firefighters battle a large wildfire near LeoPalace Resort in 2018. Beyond the direct threat to safety, fires produce fine particles and smoke that have health consequences, especially for those with respiratory conditions. Photo courtesy of Guam Department of Agriculture, Forestry Division.

which could be used to inform local climate and health strategies (Marinucci et al. 2014).

- ***Plan for increased wildfire, already frequent and extensive in Guam.*** About 3% of Guam's land area burns annually (Trauernicht 2019). This percentage is high, greater than that in Palau, Hawai'i, and the western United States (Trauernicht 2019). The potential for wildfire greatly increases under dry conditions, and the incidence of fire and the extent (acres burned) tends to be higher in the year following an El Niño event (Minton 2006). Drought events can significantly increase the area burned by wildfire even on very wet islands like Guam (Trauernicht 2019). Wildfire has consequences for health beyond the direct threat to safety around fire. Fine particles produced by fires make them a respiratory health hazard (Fann et al. 2016). In the spring of 2019, Guam experienced a post-El Niño drought and rampant grass fires that caused heavy smoke, threatening residents with respiratory issues (*Guam Pacific Daily News*, April 21, 2019).

- ***Expect water supply impacts and more frequent floods.*** The monsoon and heavy rains have periodically caused flooding in parts of Guam. In August 2018, several heavy downpours caused flash flooding that closed roads, downed power lines and trees, and stranded hikers who were caught off guard by the sudden flooding (leading to one death) (Staff, *The Guam Daily Post,* 2018). Similar floods are expected to become more frequent, and flooding will intensify in a warmer future climate. In addition to direct health risks, heavy rainfall and flooding are linked to increased levels of pathogens in drinking water and can increase waterborne disease, such as diarrheal illness (Bell et al. 2016; Brunkard et al. 2011).

- ***Expect stronger tropical cyclones.*** Although they may occur less frequently in the future, the tropical cyclones that do affect Guam are expected to bring stronger winds 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 the protection from storms. Injuries, fatalities, and mental health impacts are associated with strong storms, especially in vulnerable coastal populations. Health risks increase after a storm when infrastructure and housing are damaged, and electricity, sanitation, safe food and water supplies, communication, and transportation are disrupted. Super Typhoon Pongsona in 2002 was one of the strongest and costliest storms to strike the island. It caused nearly

200 injuries and destroyed 1,300 houses; yet, deaths were kept to a minimum due to strong building standards and experience with repeated typhoons.

- ***Prepare for disaster response and recovery from stronger storms.*** 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). To protect infrastructure, engineers and government policymakers can account for the risk of future changes in extreme weather when planning and designing infrastructure (including buildings, communication and energy facilities, and distribution, transportation, and water and wastewater systems) and when rebuilding after disasters (Olsen 2015). Many local governments and communities exposed to strong storms have developed pre-disaster recovery plans (APA 2014; FEMA 2017). Pre-planning for disaster recovery can help communities seize opportunities and funds to improve resilience to future disasters during recovery and rebuilding phases (FEMA 2017).

- ***Prepare for more food insecurity in Guam's households.*** Disruption of food supply and production systems is a key risk in the health sector. Currently most food consumed in Guam is imported and local food production has been in decline (Bucayu-Laurent and Hollyer 2016). This trend leaves Guam vulnerable, since it is highly likely that climate change will drive up the prices of imported foods, threatening food security.

- ***Monitor emerging research on climate and vector-borne diseases.*** Dengue and other mosquito-borne pathogens have increased as global health threats in recent years (Beard et al. 2016). Globally, future warming and precipitation changes will likely increase the suitable habitat for pathogens and vectors, thereby increasing the risk of outbreaks 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 vector-borne disease (Beard et al. 2016; Radke et al. 2009; Reiter et al. 2003).

If you are a coastal infrastructure decision-maker...

- ***Prepare for more frequent coastal flooding and increased erosion to affect infrastructure.*** Both sea level rise and more frequent and intense heavy rainfall events will produce erosion and flooding in coastal and urban areas in Guam. Communities and critical infrastructure are located in low-lying coastal areas. Buried utilities in these areas may be subject to sub-surface inundation. This could increase corrosion of utilities, increase inflow and infiltration of wastewater lines, and contaminate drinking water lines (Habel et al. 2017). A climate change vulnerability assessment for Guam revealed the potential impacts of three different sea level rise scenarios on key infrastructure (water, wastewater, roads, power, and buildings) for each municipality (King et al. 2019). The greatest percentage of infrastructure impacted under the sea level rise scenarios was in southern villages. The only villages with zero percent impact in all infrastructure categories under all three scenarios were Agana Heights, Barrigada, and Mangilao (King et al. 2019).

- ***Coastal erosion, accelerated by sea level rise, is expected to lead to beach loss along***

hardened shorelines and erosion of coastal property. When strong winds from the west or typhoons produce wave energy that hits Guam's west coast and sandy beaches, the result can be damaging erosion (loss of land due to waves, currents, tides, and wind-driven water, and made worse by sea level rise) in areas such as Agat. Seawalls and other structures that are intended to protect the land and property from erosion have often had the unintended consequences of causing beach loss fronting the structures and increasing erosion on unprotected neighboring property. Coral reefs currently offer protection from flooding valued at approximately $17 million annually (in 2010 USD) along Guam's coastline (Storlazzi et al. 2019). Prioritizing reef and mangrove ecosystem protection has a range of benefits that include climate adaptation and protection from coastal hazards (Ferrario et al. 2014).

- ***Expect less frequent but more intense typhoons and storm surge.*** Combined with continued acceleration in global average sea level rise, storm surge associated with tropical cyclones has the potential to destroy built and natural infrastructure on the coast and severely disrupt communities.
- ***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.

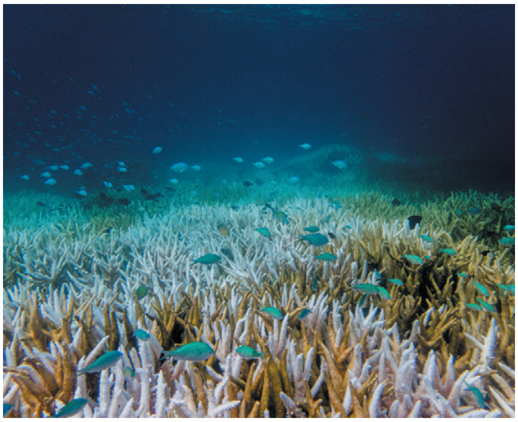
If you manage ecosystems and biodiversity...

- ***Prepare for elevated wildfire risk and soil loss, which threaten Guam's forests, savanna, badlands, other land-based ecosystems, and reefs.*** Human-caused fire burns about 3% of Guam's area on average annually. In 2018 alone, more than 6,000 acres or nearly 5% of the island's land area burned (Trauernicht 2019). Following a wildfire, erosion from burned lands increases dramatically. Large storm events contribute to soil loss. Burned areas are also prone to the spread and establishment of invasive grasses such as Australian Beard Grass (*Bothriochloa bladhii*) and mission grass (*Pennisetum polystachion*), that heightens the fire risk (Minton 2006). Sediment runoff affects habitat in streams and contaminates nearshore waters, with the potential to impact reefs. As dry periods increase, fire risk rises, so these stresses on Guam's terrestrial and marine ecosystems are expected to increase in the future.
- ***Monitor and prepare for changes in temperature, rainfall, and tropical cyclones that promote the spread of invasive species and reduce the ability of terrestrial habitats to support protected species.*** On land, deforestation and non-native invasive plants and animals (most significantly the brown tree snake) have caused a rapid decline in Guam's native species and ecosystems. Guam is now home to only a few native bird species, one endangered bat species, and several threatened reptile species found nowhere in the world outside of the Mariana Islands (Pacific Islands Fish and Wildlife Office 2014). Unprecedented changes in air temperatures, along with intensifying drought, rainfall, and erosion, bring additional challenges for native species conservation (Keener et al. 2018; Goulding et al. 2015; Raxworthy et al. 2008).

Burned land near Masso after a wildfire in 2019. Soil erodes more easily from newly burned land, affecting land-based ecosystems, streams, and nearshore waters. Photo courtesy of Brent Tibbatts.

- ***Promote measures that protect and enhance biodiversity and ecosystem services as a critical way to support communities in adapting to climate change.*** Natural resources underpin the sustenance and resiliency of Pacific Island communities. For example, mangrove forests provide storm protection and are productive estuaries for food species (Victor et al. 2004). Land development and expansion of US military facilities historically have resulted in loss of some mangrove forests, wetlands, and estuaries. The area suitable for mangroves may shrink as sea level rises and their landward migration is constrained by multiple factors (Gilman et al. 2008; Gilman et al. 2006). 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).

- ***Expect declining ocean ecosystem health. Watershed conservation measures can protect refugia for coral populations.*** The waters of Guam and the Mariana Islands contain some of the most biodiverse marine ecosystems in the world (Paulay 2003). Ocean warming and ocean acidification will combine with other stressors, such as fluctuating sea levels, overfishing, and pollution, to threaten nearshore and open-ocean marine ecosystems and the livelihoods they support. The total economic value of coral reefs in Guam (including all goods and services that reefs provide, the value to tourism, and the cultural and social value) has been estimated at $158 million per year (in 2019 USD) (van Beukering et al. 2007) and the value to tourism was more recently estimated higher, at $343 million (in 2019 USD), or 6% of GDP (Spalding et al. 2017). The heating of Guam's waters is already causing coral mortality. Approximately a third of Guam's shallow corals died during 2013–2017 as a result of bleaching from unusually warm ocean temperatures (record-breaking at times) combined with extreme low tides that left some reefs exposed. In most locations around Guam, annual severe bleaching is projected to begin before 2040 (van Hooidonk et al. 2016). Reef characteristics and ocean features appear to help corals withstand sea surface warming in certain locations (Maynard et al. 2017; Storlazzi et al. 2013), however nearshore reefs are threatened by pollution and soil erosion. Managing coral reefs and adjacent watersheds as an integrated unit is a strategy that can reduce sediment and other pollution and help to protect reefs (Richmond et al. 2007).



Bleached coral, 2017.
Photo courtesy of David Burdick / University of Guam Marine Laboratory.

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

- ***Coastal historical and cultural sites will likely be affected by erosion, storm surge, and coastal inundation from sea level rise.*** Although it is not known how climate change will specifically affect individual archeological and cultural sites in Guam, coastal areas are likely to be affected by erosion, storm surge, and coastal inundation from sea level rise. For example, multiple cemeteries in Agat and the villages of Agaña, Umatac, and Inarajan are threatened by future sea level rise and increasing coastal erosion. Agat Invasion Beach, a historical site where American military forces landed in the 1944 Battle of Guam, already experiences coastal erosion and is considered vulnerable to the impacts of sea level rise (Gonzalez 2015). Numerous other historical sites, including, for example, portions of War in the Pacific National Historical Park, Spanish Bridge, and Merizo Bell Tower, are situated in low-lying coastal areas, which are very likely to experience increased erosion in the future.

- ***Climate change exacerbates challenges to the continued availabilty of cultural foods and culturally significant plants and animals.*** Changes in environmental conditions such as warming oceans, reduced streamflow, saltwater intrusion, and long periods of drought, threaten the ongoing cultivation and availabity of traditional foods such as fish and other seafood, edible seaweed, and coconut (Keener et al. 2018). Certain medicinal plants may also be threatened if their optimal growing ranges decline.

If you are involved in recreation or tourism...

- ***Expect coral reefs and marine ecosystems to be more sensitive to background stressors and support fewer tourism opportunities.*** Visitors and residents of Guam enjoy significant recreational benefits from coral reefs, particularly fishing, snorkeling, diving, and protection for swimmable waters (van Beukering et al. 2007). Coral reefs play a central role in the tourism industry. It is estimated that 29% of tourism sector revenues rely on healthy marine ecosystems (van Beukering et al. 2007). Changes in Guam's marine environment, including increased runoff, pollution, and sedimentation, are already apparent to Guam's residents. A warming climate adds to and worsens these existing issues. Over the next few decades, more frequent and severe coral bleaching events and ocean acidification will combine with other stressors to threaten coral reefs. By 2040 or earlier, coral bleaching is projected to occur annually in Guam's waters, potentially resulting in widespread coral mortality (van Hooidonk et al. 2016). There could be negative impacts on Guam's tourism brand as coral reefs decline.
- ***Conditions at beaches and shoreline areas will continue to decline.*** Coastal erosion and beach loss are already issues in Guam, and certain erosion-control structures (such as seawalls) have the unintended consequence of beach loss when installed on chronically eroding sandy shorelines. Sea level rise will increase erosion rates and worsen impacts to beaches and shoreline properties. Additionally, high bacterial pollution already periodically causes visitors and residents to avoid beaches and shores. Water quality is expected to be impaired more severely and frequently in the future as storm drainage systems and on-site sewage disposal systems are compromised by intense rainfall and sea level rise (Chargualaf 2018).
- ***More intense flash floods may create dangerous conditions for hiking and other recreational activities.*** Already a concern in Guam, the risk to the safety of people recreating outdoors from sudden, unexpected floods will increase in a warmer world.

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

- ***Expect economic disruptions and increased costs from necessary disaster prevention, clean-up, recovery, and operation of essential services during disasters.*** Climate changes—both gradual and abrupt—disrupt the flow of goods and services that form the backbone of economies (Houser et al. 2015). They also stress or damage natural ecosystems, such as coral reefs, that supply goods and services. Ecosystem-based adaptation remains underutilized as a cost-effective approach for reducing climate risk (Goldstein et al. 2019).
- ***Anticipate rising import prices and climate-related issues worldwide to affect local businesses.*** Climate change is expected to increasingly affect trade and economy internationally beyond Guam and the United States, including import and export prices (Smith et al. 2018). 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).

- ***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 catastrophies (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 Territorial Government could consider similar mechanisms for protecting Guam's significant ecological resources.

If you are involved in food systems...

- ***Extreme weather threatens food security.*** Transportation disruptions along the supply chain limit food mobility and prevent it from reaching the destination. The majority of food for Guam is imported and passes into the territory through the Port of Guam. High winds and storm surge associated with increasingly intense typhoons can damage port facilities or otherwise interfere with food shipping and distribution. Loss of electricity from storms or other extreme weather leads to food spoilage. Price volatility and international food shortages strain household finances and limit nutrition and cultural foods (USGCRP 2018, Ch. 11, KM3). Populations who already experience food insecurity are likely to be affected the most.

- ***Expect climate change to worsen impacts on agriculture and agroforest production.*** The value of locally grown agricultural goods accounts for $2.8 million annually (in 2007 USD), or just 0.06% of Guam's GDP (USDA 2007). Subsistence crop production was once a dominant occupation and source of food in Guam prior to World War II. The transition to a cash-based economy shifted the workforce away from farming and to a reliance on imported food (Marutani et al. 1997). Introduction of pests and diseases, the appropriation of agricultural lands by the US military and government, warfare-related pollution, and residential and commercial development have all contributed to a decline in agriculture on Guam (Marutani et al. 1997; USDA 2007). Climate change will likely hasten the decline in production 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). More intense major storms pose a threat to agroforestry crops.

- ***Monitor research and development of farming methods that improve food security.*** Resilience to climate change is expected to require changes in farming and agroforestry methods and cultivars (Bell and Taylor 2015). Traditional farming methods have demonstrated the ability to enhance resilience to external shocks and bolster food security (McGregor et al. 2009).

- ***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; however, warming temperatures can increase the incidence and spread of disease, as higher nighttime temperature does for taro leaf blight.

- ***Monitor seasonal forecasts and the El Niño–Southern Oscillation to assist agricultural planning***. The El Niño–Southern Oscillation (El Niño, La Niña, and neutral phases) dramatically affects the timing, intensity, and amounts of rainfall and other factors affecting crops including winds, cloudiness, and air temperatures. Seasonal forecasts are used to enhance risk management and help to avoid financial losses in agriculture (Everingham et al. 2012; Carberry et al. 2000).

- ***Expect reduced available catch for subsistence fishing.*** Rapidly changing conditions in oceans are expected to cause coral reef fish to decline 20% by 2050 in tropical Pacific Island countries and territories including Guam (Bell et al. 2013; Asch et al. 2018). Rapidly changing conditions also affect open ocean fisheries, and declines in maximum potential catch of more than 50% are projected under a business-as-usual scenario by 2100 for most of the islands in the central and western Pacific including Guam (Bell et al. 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 impacts to student health and learning (Goodman et al. 2018; Sarofim et al. 2016). School building designs that reflect local environmental conditions—including projected increases in air temperature—can benefit students' health and learning outcomes.

- ***Prepare for stronger typhoons and greater wave inundation, and consider adaptation options for schools and educational facilities.*** Typhoons and extreme weather affect students through displacement and mental health impacts, and can worsen the challenges for students experiencing poverty. Typhoons may cause schools to temporarily close for repairs or rebuilding, or to be used as shelters. Continually updating building and energy codes is known to improve community safety and resilience (FEMA 2017). Locating and designing buildings to withstand extreme weather can avoid costs and protect students (FEMA 2017).

Needs for Research and Information

Evidence-based information, scientific studies, and data on extreme weather and climate change can inform adaptation and preparedness. This assessment identified the following needs for research and information, which if met could support responses to extreme weather and climate change:

- ***Assessments of community vulnerability*** – Risks posed by extreme weather and climate change vary by the vulnerability of the people experiencing impacts (King et al. 2019). Particularly needed are assessments of risks that account for the social, economic, and locational factors that drive vulnerability of people in Guam to climate extremes and changes (Spooner et al. 2017). Such studies can improve understanding of who is at greatest risk. For example, since poor households and communities face barriers when preparing for and recovering from climate-related threats, research into the ability of poverty-reduction actions to protect communities may be useful to decision-makers.

- ***Research on "climate proofing" critical infrastructure*** – Governments and resource managers commonly use various forms of vulnerability assessment as a foundational tool to tailor solutions and policies to address the specific ways critical infrastructure is threatened. Assessing climate vulnerability involves technical analysis of changing hazards; often evaluates exposure, sensitivity, and adaptive capacity; and ranks 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 and support problem solving. Methods of completed assessments and guidance are available (see for example: Canadian Engineering Qualifications Board 2014; Olsen 2015; USGCRP 2018, Ch. 28).

- ***Quality controls and expanded coverage in climate data*** – Stations collecting climate data (air temperature, rainfall, windspeeds, etc.) have changed location and some station records are not continuous. For example, recent data (since 2002) is omitted from the temperature and rainfall records for Andersen Air Force Base in the Global Historical Climatological Network-Daily database. Records of 30 years or more at the same location are needed for tracking climate trends and changes, and to improve and validate future projections. An assessment of the quality of the data at each station, especially temperature data, would provide a foundation for determining which records are best suited to climate studies. The existing climate data are also difficult to access online in formats suitable for non-specialists. A central data portal or "climate explorer" tool for Guam could increase data access and use. Developing localized predictive modeling for agriculture and other applications would require more data collection stations, especially in agricultural areas.

- ***Information about how native plants are affected by climate change*** – Research focused on the response of populations and communities of rare and native/endemic species to disturbance, and research into the interactions of climate change with other threats, including invasive species and fire, can help conservation managers. Such research could answer questions such as: What are the consequences for ecosystems of less frequent but stronger typhoons?

- ***Updates to typhoon vulnerability studies for Guam*** – Reasonable estimates of the strength of a worst-case-scenario typhoon were developed for historical climate (Guard et al. 1999), and updated estimates under warming scenarios are needed to assist emergency preparedness and community design. Additionally, cost estimates based on the intensity category of the storm and inflation have applications for insurance and finance industries and organizations providing disaster relief.

- ***Research supporting food security*** – Decision-making and local food security can be improved through building evidence for which crop varieties (for example, taro and yam varieties) and farming practices are better adapted to future conditions.

- ***Development and trials for stormwater management*** – Engineered and nature-based solutions that account for combined sources of flooding, including inland flooding (a current issue) and coastal/tidal flooding (a future issue) will take time to develop and test before implemented at a larger scale.

- ***Development of coastal erosion and wave run-up models for Guam*** – Localized coastal erosion and sea level projections and mapping, including wave run-up model development, can provide decision-makers and communities with better information from which to plan for sea level rise.

- ***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 policymakers and community planners—can inform climate adaptation planning at multiple scales (for example, see the 2017 *Hawaiʻi Sea Level Rise Vulnerability and Adaptation Report*—https://climate-adaptation.hawaii.gov/wp-content/uploads/2017/12/SLR-Report_Dec2017.pdf). Sea level rise exposure mapping is required first, before estimates of economic loss in the public and private sectors can be mapped.

- ***Exchange of adaptation experiences with other Pacific Islands*** – Literature that conveys experiences and lessons learned from targeted efforts to address climate-related vulnerabilities can assist decision-makers in understanding the benefits and risks of such measures. For example, there is interest in understanding how rainwater harvesting systems in Saipan have worked as an adaptation to drought.

Guam Sources of Climate Data and Projections

NOAA Coral Reef Watch:
https://coralreefwatch.noaa.gov/satellite/index.php

NOAA Sea Level Rise Viewer:
https://coast.noaa.gov/digitalcoast/tools/slr.html

NOAA Digital Coast Sea Level Change Curve Calculator:
https://coast.noaa.gov/digitalcoast/tools/curve.html

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

PacIOOS Six-Day High Sea Level Forecast for Guam:
http://www.pacioos.hawaii.edu/shoreline/highsea-apra/

Relative Sea Level Trend at Apra Harbor, Guam (NOAA):
https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?stnid=1630000#tab50yr

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

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

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 the 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.

▶ **Traceable Accounts**

Indicator	How has it changed?	Source	Data Range	Projected future change	Source
Hot days	↑	Global Historical Climatological Network – Daily (GHCN-Daily), Andersen Air Force Base (GQC00914025) and Weather Forecast Office-Guam at the International Airport (GQW00041415)	1953–2002 (AAFB); 1999–2019 (WFO-Guam)	↑	Zhang et al. 2016 (CMIP5); IPCC 2013a
Cool nights	↓	GHCN-Daily, Andersen Air Force Base and WFO-Guam	1953–2002 (AAFB); 1999–2019 (WFO-Guam)	↓	Zhang et al. 2016 (CMIP5); IPCC 2013a
Average air temperature	↑	GHCN-Daily, Andersen Air Force Base and WFO-Guam	1953–2002 (AAFB); 1999–2019 (WFO-Guam)	↑	Zhang et al. 2016 (CMIP5); IPCC 2013a; IPCC 2013b
Average rainfall	No change	GHCN-Daily, Andersen Air Force Base and WFO-Guam	1953–2016	↓	Zhang et al. 2016 (CMIP5)
Rainy season average rainfall	No change	GHCN-Daily, Andersen Air Force Base and WFO-Guam	1953–2016	↓	Zhang et al. 2016 (CMIP5)
Dry season average rainfall	No change	GHCN-Daily, Andersen Air Force Base and WFO-Guam	1953–2016	↑	Zhang et al. 2016 (CMIP5)
Extreme rainfall days	No change	GHCN-Daily, Andersen Air Force Base	1953–2016	↑	Zhang et al. 2016 (CMIP5); IPCC 2013a
Frequency of drought	?	No analysis available; No statistically significant change in annual number of days without rainfall (GHCN-Daily, Andersen Air Force Base, 1953–2002, and WFO-Guam, 1999–2019; Marra and Kruk 2017)	1953–2016	↑	Zhang et al. 2016 (CMIP5)
Streamflow	?	No analysis available		↓	Gingerich et al. 2019a
Tropical cyclone intensity	No change	Kruk et al. 2015 (using GHCN-Daily)—Analysis of annual 1-day extreme rainfall amounts showed a near-zero trend for Guam; Knapp et al. 2010		↑	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
Tropical cyclone frequency	No change	Marra and Kruk 2017; Knapp et al. 2010	1980–2013	↓	Kossin et al. 2016; Zhang et al. 2016; Wang et al. 2016; USGCRP 2017; Widlansky et al. 2019
Sea level	↑	NOAA 2020b	1993–2020	↑	Sweet et al. 2017; USGCRP 2017; IPCC 2013a
High water frequency	↑	NOAA 2020b; UH Sea Level Center	1993–2020	↑	Marra et al. 2015
Sea surface temperature	↑	NOAA NCEI ERSSTv5—Huang et al. 2017	1854–2020	↑	Bopp et al. 2013; USGCRP 2017
Frequency and intensity of heat stress on coral	↑	NOAA Coral Reef Watch 2018 (Liu et al. 2014)—Daily Global 5km Satellite Coral Bleaching Heat Stress Monitoring	1985–2020	↑	van Hooidonk et al. 2016
Ocean acidification	↑	Marra and Kruk 2017, Data collected at Station ALOHA	1988–2020	↑	USGCRP 2017; Australian CSIRO and BOM 2014

Temperature – Daily air temperature at Andersen Air Force Base is cataloged by NOAA for 1953–2002 (NOAA 2020c). While other records from the Weather Forecast Office (WFO) and the NOAA Weather Service Meteorological Observatory (WSMO) do exist, Andersen Air Force Base has the longest continuous record in Guam. Starting in 1998, it should be noted that the NOAA daily air temperature data for the Andersen Air Force Base were rounded to the nearest whole degree Celsius, a change which could impact trend analyses. Daily air temperature data recorded by the WSMO at Finegayan (from 1957 until mid-1990s) and the WFO at the Antonio B. Won Pat International Airport in Tiyan (mid-1990s–present) are available from the NOAA GHCN-Daily database as a single station (GQW00041415, NOAA 2020c). A major location change took place in 1995 when the station was moved to the Airport location and NOAA created the WFO-Guam (Mark Lander, per. comms., July 29, 2020). NOAA metadata indicates additional location discontinuities in 1996–1998. Thus, only WFO-Airport data from NOAA GHCN-Daily for 1999–2019 are plotted here. In the last 7 years of this period (2013-2019), Automated Surface Observing System (ASOS) equipment malfunctions affected the daytime maximum air temperature readings at the Tiyan Airport, impacting the data quality (Mark Lander and Chip Guard, per. comms., July–August 2020).

Annual mean temperatures show a warming trend during the period of record. Hot days are days that maximum temperature is at or exceeds the 95th percentile of the distribution—88°F (31.1°C) at Andersen Air Force Base and 90°F (32°C) at the International Airport. Cool nights are days for which minimum temperatures were colder than the 10th percentile of the distribution—roughly 74°F (23.3°C)—at both Andersen Air Force Base and the International Airport.

Further temperature increases in the US-Affiliated Pacific Islands region are considered *extremely likely*. In 2016, researchers at the International Pacific Research Center at the University of Hawaiʻi used general circulation model (GCM) simulations taken from the international Coupled Model Intercomparison Project Phase 5 (CMIP5) to project fine-resolution future climate changes over Guam and American Sāmoa by the late 21st century (2080-2099) with both a high emissions scenario (RCP8.5)—that assumes a business-as-usual future development path with no major policy changes to reduce greehouse gas emissions—and a low emissions scenario (RCP4.5)—that is based on reducing greenhouse gas emissions (about 85% lower emissions than the high scenario by the end of the 21st century).

Rainfall – There are very few locations on Guam where rainfall has been measured consistently over several decades. The Andersen Air Force Base weather station has the longest continuous record and is considered sufficient for computing monthly and annual averages. Therefore, we are reporting long-term trends from Andersen Air Force Base, 1953-2002. Since the GHCN-Daily Andersen Air Force Base rainfall record ends in 2002, more recent (1999–2019) data from WFO-Airport are plotted as well. (See "Temperature" section, on previous page, for station history.)

Gingerich et al. 2019a applied a variety of modeling techniques to project future rainfall on Guam. Methods consisted of (1) applying consistent criteria to select a subset of five well-performing GCMs from the CMIP5, (2) examining the statistics of simulated future typhoons over Guam, and (3) providing detailed climate projections for Guam through dynamical downscaling of an average of the selected well-performing global GCMs to higher-resolution regional climate models (results released in Zhang et al. 2016). The variables estimated by the regional climate model for 2080–99 are for the RCP8.5 emissions scenario, a business-as-usual scenario referred to here as the "high scenario."

A source of uncertainty in future rainfall projections arises from the differing results between the global and downscaled model results. Projections of future climate using the downscaled regional climate model show an overall decrease in rainfall amounts (Zhang et al. 2016), whereas the CMIP5 GCM results indicate a wetter climate for the region including Guam by the end of the century under the high scenario (RCP8.5) (IPCC 2013a, see Figure SMP.8; IPCC 2013b). The downscaled climate model results that show drier conditions account for local orographic conditions for Guam (Gingerich et al. 2019a). Further study is needed to understand why the downscaled projections disagree even at locations far from the fine-scale topographic influences of Guam.

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.

Drought – The frequency of drought (defined here as more than 20% below mean annual historic rainfall) was projected to occur more frequently under the high scenario (RCP8.5). This projection comes from a University of Hawaiʻi run of GCM simulations taken from the CMIP5 models to project fine-resolution future climate changes over Guam and American Sāmoa by the late 21st century (2080-2099), as compared to historical conditions (1990-2009) (Zhang et al. 2016). The future projected duration and severity of droughts (mild, moderate, severe, and extreme drought events) was not assessed. During extended periods of drought, wells throughout the Northern Guam Lens Aquifer become more saline and less usable water is available. Additionally, streamflow and Fena Reservoir water volume decreases below usable levels in long, severe droughts. El Niño–Southern Oscillation (ENSO) will likely continue to play a large role in future droughts. While there is no consensus on how ENSO may change in the future, there is evidence that climate change has resulted in an increase in strong El Niño events (Freund et al. 2019; Wang et al. 2019; Cai et al. 2014).

Typhoons and Storms – The future is less certain for tropical cyclone frequency than other elements. The environmental conditions to produce a cyclone, for example, the state of ENSO and the intensity and phase of the Madden-Julien Oscillation, are at timescales much shorter than global climate model simulations (Diamond and Renwick 2015). There is a *medium* level of confidence that globally tropical cyclone frequency will decrease (USGCRP 2017). A likely overall decrease this century in the number of tropical storms and typhoons affecting Guam is projected (20%–30% decrease; multi-model average; Widlansky et al. 2019). 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). Recently, a 39-year homogenized data record showed statistically significant increases in tropical cyclone intensity globally, raising confidence in the future projection of increasing tropical cyclone strength (Kossin et al. 2020). Since tropical cyclone damage potential increases exponentially with tropical cyclone intensity (that is, strong cyclones cause much more damage than weak cyclones), increasing intensity of strong storms is expected to cause more damage overall, even if the total number of tropical cyclones declines (Guard and Lander 1999; Nordhaus 2006).

Sea Level Rise – The recent sea level data for Guam indicate a positive trend. However, the long-term trend is uncertain owing to the short length of the record and the high interannual and multidecadal variability in measured sea level. The relative sea level trend at Apra Harbor, Guam is 0.13 inch (3.4 mm) per year with a 95% confidence interval +/- 0.15 inch (3.77 mm) per year based on monthly mean sea level data from 1993 to 2019. This is equivalent to a change of 1.12 feet in 100 years (NOAA 2020b). The Apra Harbor record is short due to a major earthquake in 1993 that caused vertical land motion, and thus the measured trend reported here only reflects post-earthquake measurements. In Guam, ENSO-driven variation in sea level can exceed 12 inches (30 cm) (Marra et al. 2015). These patterns of variability make it difficult to discern a reliable long-term trend in local sea level in records of less than 50 years. Tide gauge records have been recently cross-validated with satellite altimetry, showing that tide gauges and satellite data correlate well.

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*)."

Table 1 (next page) shows the probability of exceeding each of 6 scenarios for global mean sea level (Fig. 17) in 2100 under three of the RCPs. However, new evidence regarding the Antarctic Ice Sheet would support much higher

Fig.17

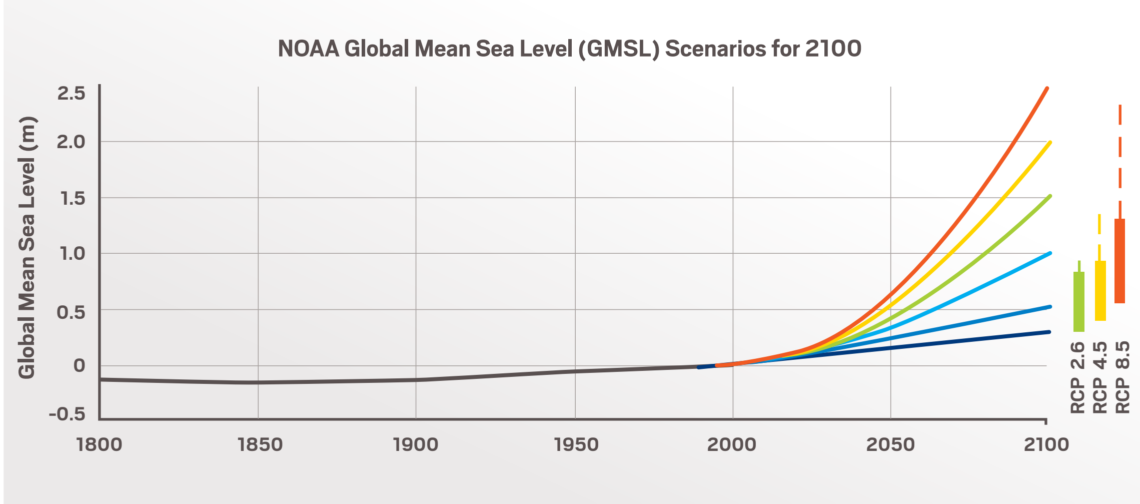


Figure 17. Six representative Global Mean Sea Level (GMSL) rise scenarios for 2100 (6 colored lines) relative to historical geological, tide gauge and satellite altimeter GMSL reconstructions from 1800-2015. The colored boxes show central 90% conditional probability ranges of RCP-based GMSL projections from recent studies. Dashed lines extending from the boxes show the median contribution from Antarctic melt from recent studies. Source: Sweet et al. 2017.

GMSL rise Scenario	RCP 2.6	RCP 4.5	RCP 8.5
Low (0.3 m)	94%	98%	100%
Intermediate-Low (0.5 m)	49%	73%	96%
Intermediate (1.0 m)	2%	3%	17%
Intermediate-High (1.5 m)	0.4%	0.5%	1.3%
High (2.0 m)	0.1%	0.1%	0.3%
Extreme (2.5 m)	0.05%	0.05%	0.1%

Table 1. Probability of exceeding Global Mean Sea Level scenarios in 2100. Source: Sweet et al. 2017, based on Kopp et al. 2014.

probabilities of exceeding the Intermediate-High, High, and Extreme scenarios in 2100 (Sweet et al. 2017).

In Guam and other islands in the tropical Western Pacific, sea level rise is projected to be greater than GMSL due to static-equilibrium effects because the region is far from all sources of melting land ice (Sweet et al. 2017; USGCRP 2017: 12.5.4; Kopp et al. 2014). For local relative sea level change scenarios, see the *USGCRP Sea Level Change Viewer: An Interactive Guide to Global and Regional Sea Level Rise Scenarios for the United States*: https://js-169-194.jet-stream-cloud.org/terriamap/. These scenarios account for vertical land motion in Guam (Sweet et al. 2017).

Ocean Changes – The third global bleaching event caused more reefs in the Pacific to be exposed to heat stress than any time before. In Guam, bleaching began in 2013 with 85% of Guam's coral types affected, and reefs bleached again in 2014, 2016 (during an El Niño event), and 2017. 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). Internal tides could delay the onset of bleaching fewer than 10 years at certain locations, depending on future warming scenarios (Storlazzi et al. 2020). NOAA's Pacific Reef Assessment and Monitoring Program studied coral heat stress at 17 sites in the Northern Mariana Islands and Guam and found coral bleaching heat stress at all depths from surface down to 38 meters and thus no meaningful refuge from heat stress for corals at depths (Venegas et al. 2019).

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Notes

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The flying proa is a unique and fast sailing canoe that enabled ancient Chamoru settlers to migrate to the Mariana Islands and move between islands in the archipelago and in the broader Pacific. It appears on Guam's seal, flag, and quarter.

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