Pacific Islands Climate Change Monitor 2021

Australian Government
Bureau of Meteorology

Climate and Oceans Support Program in the Pacific

CSIRO

USGS
science for a changing world

NIWA
Taihoro Nukurangi

Pacific Islands Climate Adaptation Science Center

METEO FRANCE

WORLD METEOROLOGICAL ORGANIZATION

SPREP
Secretariat of the Pacific Regional Environment Programme

SPC
Secretariat of the Pacific Community

EAST-WEST CENTER

Pacific RISA
a NOAA RISA team

UPF
UNIVERSITÉ DE LA POLYNÉSIE FRANÇAISE

Report at a Glance

This report describes variability and change in Pacific Island climates, drawing on the latest meteorological and oceanographic data, information, and analyses. The report primarily focuses on observed changes across the Pacific Islands region in general and includes some country-specific information. It also includes some information about projections and the social, environmental, and economic impacts of rapid climate change. This information is intended to facilitate communication among, and inform decisions of, a broad spectrum of public and private sector stakeholders.

Historical observations and climate modeling paint a consistent picture of ongoing human-forced climate change interacting with underlying natural variability.

Where are we now?

Discernible trends are found in measures of atmospheric greenhouse gases, surface air temperatures, sea level, sea surface temperature, and ocean acidification. Most areas are experiencing increased, positive rates of change in all these parameters, while ocean chlorophyll concentration in surface waters is decreasing.

- Over the last 60 years, the concentration of carbon dioxide (CO_2) in the atmosphere measured at NOAA's Mauna Loa Observatory increased by more than 100 ppm (parts per million), to an annual average value over 414 ppm in 2020.
- The combined impact of the greenhouse gases carbon dioxide, methane (CH_4), nitrous oxide (N_2O), and halogenated compounds (mainly CFCs) in December 2020 is equivalent to a CO_2 concentration of 504 ppm.
- The Pacific Islands mean temperature over land has increased by 1.1°C (2°F) since 1951.
- Since the start of the satellite record in 1993, mean sea level has risen approximately 10–15 cm (4–6 in) in much of the western tropical Pacific and approximately 5–10 cm (2–4 in) in much of the central tropical Pacific.
- Rising mean sea levels have already resulted in (in some cases dramatic) increases in the frequency of minor flooding.
- Over the past few decades mean sea surface temperature across most of the Pacific has warmed by a few tenths of a degree per decade, with an overall warming of approximately 0.9°C (1.6°F) since 1982.
- From the 1980s to 2000s the duration of marine heat waves tended to be 5–16 days. This increased significantly in the 2010s over most of the Pacific to 8–20 days or longer.
- Over the period 1981 to 2018 subsurface oceanic heat content increased in most locations in the Western Warm Pool (WWP) region and in the northern and southern sub-tropics.
- Oceanic pH measurements since 1988 at Station ALOHA near Hawai'i show that the ocean became 12% more acidic over this time.
- Significant declines in phytoplankton size since 1998 are detectable across major portions of the Pacific Islands region.

Natural variability in rainfall, tropical cyclone (TC) properties and surface winds is high, and no statistically significant trends are apparent.

- Over the last 70 years, there has been little change in annual total rainfall and annual consecutive dry days at most of the Pacific Islands observation sites. Evidence for change in heavy rainfall across the Pacific Islands is mixed.
- No robust trends in the frequency or magnitude of TCs since the 1980s are evident.

The lack of high quality, long-term observational records, particularly with respect to in-situ stations, contributes to difficulties in discerning trends. To maintain and enhance our ability to assess environmental change, attention needs to be given to robust and sustained monitoring.

Front and Back Covers: Little islet in the Ant Atoll, Pohnpei, Micronesia © Adobe Stock/Michael Runkel/Danita Delimont

	Observations	Projections
ATMOSPHERE		
Greenhouse Gases		
Carbon Dioxide	Increasing	Increasing
Other Greenhouse Gases	Increasing	Increasing
Surface Temperature		
Mean Temperature	Increasing	Increasing
Hot Days	Increasing	Increasing
Cold Nights	Decreasing	Increasing
Rainfall		
Total Rainfall	Mixed	Mixed
Consecutive Dry Days	Mixed	Mixed
Heavy Rainfall	Mixed	Mixed
Tropical Cyclones and Surface Winds		
Total Tropical Cyclones	No Change	No Change
Severe Tropical Cyclones	Mixed	Mixed
Surface Wind Speed	Mixed	Mixed
OCEAN		
Sea level		
Mean Sea Level	Increasing	Increasing
Minor Flood Frequency	Increasing	Increasing
Temperature		
Mean Sea Surface Temperature	Increasing	Increasing
Marine Heat Waves	Increasing	Increasing
Subsurface Temperature	Increasing	Increasing
Biochemistry		
Ocean Acidification	Increasing	Increasing
Chlorophyll Concentration	Decreasing	Decreasing

PCCM Summary Graphic: *This table provides an overview of current and future environmental conditions in the Pacific Islands due to a changing climate. Indicators of change are given for three broad categories: greenhouse gases, the atmosphere more broadly, and the ocean. Increasing or decreasing trends of change observed and projected for each indicator are shown in the table with red and blue backgrounds, respectively. Mixed observations of change have a grey background.*

What does the future hold?

- Global surface temperature will continue to rise, and regional climate will continue to change until at least mid-century under any plausible emissions pathway the world follows.
- Warmer air temperatures with more heat extremes,
- Warmer sea surface temperatures with more marine heat waves.
- Increasing ocean acidification and decreasing oceanic oxygen.
- An increase in frequency and intensity of heavy precipitation events and riverine flooding.
- A greater proportion of TCs in the more intense categories.
- Continuously rising sea level rise that is significantly lower and slower under low emissions pathways, resulting in increased coastal flooding.
- Natural climate drivers and internal climate variability in the Pacific mean that there is a range of possibilities for any particular year, and short-term trends may go against the long-term (multi-decadal) projected trend due to climate change.
- Future net global greenhouse gas emissions will heavily influence what happens in the Pacific after mid-century.

There is a need for more analysis of climate models on the regional scale, as well as higher resolution models that will support downscaling.

Why should we care about climate change?

- Agriculture and Food Security—Increasing air temperature will have negative impacts on agroforestry and crops, and increase invasive species, pests, and diseases. Rising sea level will increase saltwater intrusion and thin freshwater lenses, impacting local food production and security.
- Disaster Risk Management—Tropical cyclones are projected to cause increased extreme rainfall, flooding, coastal erosion, wave inundation, freshwater contamination, and risks to human safety.
- Energy—Increasing air temperatures will lead to increasing energy demand. Increasing TC intensity and rising sea levels will result in increased impacts to electrical infrastructure.
- Health—Increases in air temperature, TC intensity, and rising sea levels, among other changes, will lead to increased incidence of heat-related illness, vector-borne disease, and threats to physical safety. This will contribute to increases in mental health-related illness.
- Water—Decreasing rainfall, projected for some areas, will reduce the quantity of freshwater resources. Increasing sea level will lead to increasing saltwater intrusion/thinning freshwater lenses and reduction in water quality. Increases in heavy rainfall leading to increased land-based pollution in ground and surface waters will all adversely affect water quality. Increasing severity of TCs and rising sea levels will adversely affect water and wastewater infrastructure.
- Fisheries and Aquaculture—Increasing surface and sea surface temperatures, increasing ocean acidification, and decreasing chlorophyll concentration will reduce commercial and subsistence catches due to shifting fisheries, reduction in fish size, and degradation of coral reefs.
- Tourism—Increasing TC intensity and rising sea levels will increase land-based pollution and beach erosion. The degradation of coral reef and open-ocean fishing habitats will adversely impact tourism and recreation-based activities.

Pacific Islands Climate Change Monitor: 2021

December 2022

Coordinating Authors:

John J. Marra, NOAA NESDIS NCEI; Geoff Gooley, CSIRO; Mari-Vaughn V. Johnson, USGS PI-CASC; Victoria W. Keener, ASU/EWC Pacific RISA; Michael Kruk, NOAA NESDIS NCEI; Simon McGree, COSPPac BoM; James T. Potemra, UH APDRC; Olivia Warrick, COSPPac

Chapter Authors:

Laura Brewington, ASU/EWC Pacific RISA; Savin Chand, CSIRO; Elise Chandler, COSPPac BoM; Howard Diamond, NOAA OAR ARL; Antonio Espejo, SPC; Nicolas Fauchereau, NIWA; Ayesha Genz, NOAA NESDIS NCEI; Zena Grecni, ASU/EWC Pacific RISA; Michael Grose, CSIRO; Vanessa Hernaman, CSIRO; Scott Heron, JCU; John J. Marra, NOAA NESDIS NCEI; Victoria W. Keener, ASU/EWC Pacific RISA; Michael Kruk, NOAA NESDIS NCEI; Simon McGree, COSPPac BoM; Elinor Lutu-McMoore, NOAA NWS WFO Pago Pago; James T. Potemra, UH APDRC; Grant Smith, COSPPac BoM; Leanne Webb, CSIRO; Olivia Warrick, COSPPac; Matthew J. Widlansky, UHSLC; Phoebe Woodworth-Jefcoats, NOAA NMFS PIFSC

Technical Contributors:

Arieta Baleisolomone, FMS; Keitapu Maamaatuaiahutapu, UPF; Philip Malsale, COSPPac SPREP; Tile Tofaeono, RoK PI-CLIPS SPREP; Laurent Victoire, Météo-France; Olivia Yu, Météo-France

How to cite this report:

Marra, J.J., Gooley, G., Johnson, M-V.V., Keener, V.W., Kruk, M.K., McGree, S., Potemra, J.T., and Warrick, O. [Eds.] (2022). Pacific Climate Change Monitor: 2021. The Pacific Islands-Regional Climate Centre (PI-RCC) Network Report to the Pacific Islands Climate Service (PICS) Panel and Pacific Meteorological Council (PMC). DOI: 10.5281/zenodo.6965143

Disclaimer:

This report is the result of a collaborative effort among a consortium of members of the WMO RA-V Pacific Islands Regional Climate Centre (PI-RCC) Network. The contents of this report are solely the opinions of the authors and do not constitute a statement of policy, decision, or position of member agencies, institutions, or organizations. The information contained in this report comprises general statements based on scientific research. Such information may be incomplete and is subject to change over time. Readers are advised to seek expert professional, scientific, and technical advice prior to its use in any specific situation and before taking any particular action. The authors are not liable to any person for any consequences, including but not limited to all losses, damages, costs, expenses and other compensation, arising directly or indirectly from use of information in this report in part or in whole.

For additional information contact John J. Marra (john.marra@noaa.gov) or James T. Potemra (jimp@hawaii.edu), or visit The WMO RA-V Pacific Regional Climate Centre (RCC) Network page at https://www.pacificmet.net/rcc”

Table of Contents

Figures

Figures

Tables

Pacific Climate Change Monitor: 2021

Suggested Citation:

Marra, J.J. and McGree, S. (2022). *The Pacific Islands*. In: Marra et al. (Eds.), Pacific Climate Change Monitor: 2021. The Pacific Islands-Regional Climate Centre (PI-RCC) Network Report to the Pacific Islands Climate Service (PICS) Panel and Pacific Meteorological Council (PMC). DOI: 10.5281/zenodo.6965143

Christmas Island and lagoon in Kiribati
© Adobe Stock/Lighting Strike Pro

The Pacific Islands

The Pacific Islands region is vast, comprising thousands of islands and spanning millions of square miles of ocean (Figure 1)[1]. The composition varies—from islands of volcanic rock, continental crust, coral (atolls), and limestone, to islands of mixed geologic origin. The "high" volcanic islands reach elevations of more than 4000 m (13,000 feet), while some of the "low" atolls peak at only a few meters (approximately 10 feet) above present sea level. Isolation and landscape diversity bring about some of the highest species' endemism (uniqueness to geographic location) in the world, with several islands surrounded by marine biodiversity hotspots.

The Pacific Islands region includes demographically, culturally, and economically varied communities, with as many as 1,500 languages spoken in the region[1]. In general, Pacific Island cultures recognize the value and relevance of their heritage and systems of traditional knowledge and customary law developed within their social, cultural, and natural contexts. There is an emphasis on long-term connection with lands and resources, and multigenerational attachment to place. The capacity to adapt to climate change in the region varies with the availability of socioeconomic and institutional resources[2]. Typically, high islands support larger populations and infrastructure, which in turn attracts industry and allows the growth of different types of institutions[2].

The Pacific Islands are exposed to climate changes that affect every aspect of life[2,3,4]. Ocean and island ecosystems are changing with warming air and ocean temperatures, an increase in the proportion of more intense TCs, rising sea levels, and increasing ocean acidification. Fresh water supplies for natural systems, as well as communities and businesses, are at risk. Food security is threatened through impacts on both agriculture and fisheries. Communities on low-lying

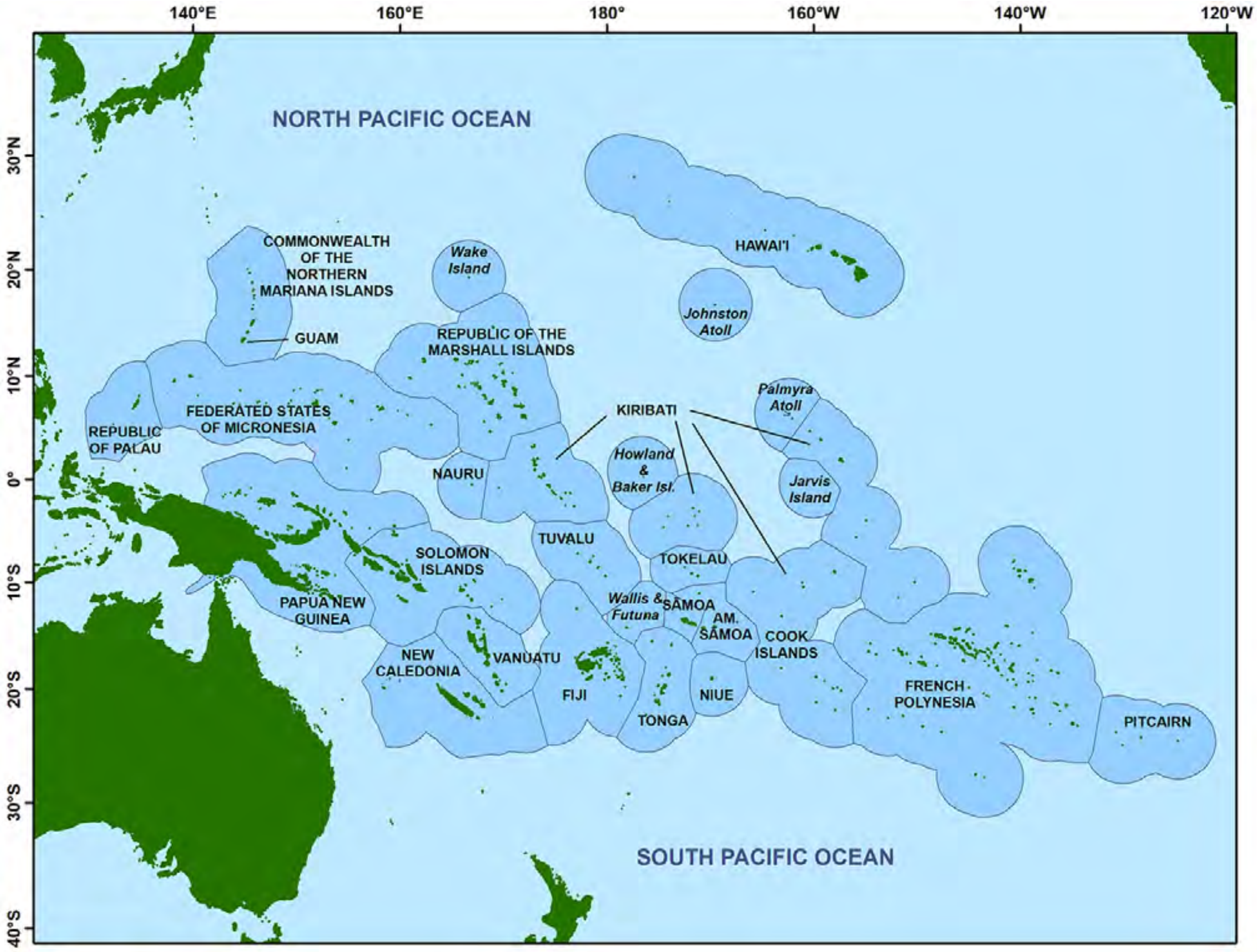


Figure 1. The Pacific Islands. Shading indicates each island's Exclusive Economic Zone (EEZ). *Map courtesy of Laura Brewington.*

atolls are particularly at risk, and the built environment on all islands is at risk from coastal flooding and erosion. Loss of habitat and other changes to ecosystems threaten the regions' biodiversity.

About this Report

Purpose

This report draws on the latest meteorological and oceanographic data and information to describe historical change in Pacific Island climate.

There is significant demand at regional, national and local community levels within the Pacific Islands for science-based climate data and information to inform decision-making, including high-quality monitoring, analysis, and communication of observed and future climate change. At the 15th Pacific Islands Forum in Funafuti, Tuvalu in 2019, leaders called on "the international community to immediately increase support and assistance for Pacific-led science-based initiatives intended to improve our understanding of risk and vulnerability, as well as build capacity for evidence-based decision-making and project development". Members of the 4th Pacific Meteorological Council (PMC), in Honiara in 2017, welcomed the renewed focus on climate change science, especially underpinning meteorology and climate services.

This report was produced by the WMO RA V Pacific Regional Climate Center (RCC) Network https://www.pacificmet.net/rcc, specifically members of the Nodes on Climate Monitoring and Climate Change Projections. The WMO RA V Pacific RCC Network is a virtual center of excellence for supporting national meteorological services with up-to-date regional long-range climate forecasts, climate monitoring products, climate change projections, climate data services, and information on regional training activities. The RCC Network was endorsed by PMC-4 and is currently in a demonstration phase. The node on Climate Monitoring is co-led by NOAA and the University of Hawai'i, while the node on Climate Change Projections is led by Commonwealth Scientific and Industrial Research Organisation (CSIRO). Consortium members include the Australian Bureau of Meteorology (BOM), Secretariat of the Pacific Regional Environment Programme (SPREP), and The Pacific Community (SPC). Author invitations were extended to the Pacific Meteorological Council (PMC) member countries.

The regional indicators described here are intended to provide:

- meaningful regionally and locally relevant information about the status and trends of key physical, biological, and chemical variables in light of a rapidly changing climate; and
- information in a form that is accessible and useful to a wide variety of stakeholders in the public and private sectors, as well as the education and scientific communities. This will assist communication and inform decisions on management, research, and education.

Background

We examine temperature, rainfall, and sea level, as well as biological and chemical observations that are indicative of current, past, and possible future states of the climate system (Table 1) [1-5]. Sources for information about climate variables are typically measurements obtained from *in situ* stations, satellites, or climate models. These observing systems and climate models provide information that can be used to characterize long term trends in mean and extreme states on regional to local scales. The Pacific Islands region is the scale of focus in this report, both with respect to geography and physical processes. In some cases, information is presented at a subregional scale. In general, the subregions represent loosely defined geographic areas in the Pacific Basin with quasi-unique combinations of atmospheric and/or oceanic conditions. While not necessarily reflective of change at the local or national scale, they provide a rational basis for a more granular characterization of observed and projected change throughout the region. This report also includes some country-specific information.

Attention is given to three broad categories of indicators: greenhouse gases, the atmosphere, and the ocean, each in separate sections of this document. Each section contains the following elements:

- **Highlights**—summarizing and emphasizing important information in the section;
- **Background**—briefly noting why a given indicator is important to assessing environmental conditions and impacts under a changing climate; and
- **Indicators**—what a given indicator shows using multiple measures, reflecting different data sources and/or different ways to characterize the data.

Atmosphere	
Greenhouse Gases	The concentration of carbon dioxide (CO2) in the atmosphere is a benchmark indicator of environmental conditions. Changes in CO2 and other greenhouse gases drive changes that cascade throughout the environment.
Surface Temperature	Changes in surface temperature, such as more frequent and intense extreme heat events, can lead to human health issues and agricultural damage. Warming temperatures, both during the day and at night, also lead to an increase in energy usage needed to maintain indoor comfort.
Rainfall	Changes in rainfall can have a wide-ranging impact on humans and ecosystems; for example, affecting fresh drinking water supply, the quantity of moisture available for agriculture, or streamflow necessary to maintain aquatic habitat. Heavy or extreme rainfall events can increase crop damage, soil erosion, and riverine flooding. Runoff from excessive precipitation can also carry harmful pollutants into nearby water bodies, endangering aquatic species as well as human health.
Tropical Cyclones and Surface Winds	TC impacts can be devastating, especially for small islands across the Pacific. Changes in TC frequency and intensity can dramatically impact human life and property. Changes in wind speed can increase evaporation, thus resulting in greater water demand for agriculture.
Ocean	
Sea Level	Changes in mean sea level are indicative of overall warming of the ocean and melting of ice on land. Rising sea levels increase the potential for coastal flooding and erosion. This can have significant economic, social, and environmental costs.
Temperature	Sea surface temperature (SST) is one of the most important measures of long-term global climate change. SST is used to monitor modes of climate variability that affect patterns of wind and rain as well as ocean circulation. SST is also an indicator of the state of marine ecosystems (e.g., coral health). Marine heat waves are occurrences of elevated SST that last for several days to months. Subsurface temperature provides an estimate of oceanic heat content stored in the upper ocean.
Biochemistry	Measures of changing ocean chemistry include changes in the acidity of the ocean and changes in phytoplankton abundance. Increased acidity (pH) in the ocean (resulting from of the absorption of CO2) affects marine organisms' ability to build calcium carbonate shells or skeletons. Changes in chlorophyll-a concentration in the surface ocean (measured by satellites as ocean color) are used as a proxy for changes in phytoplankton abundance and biological production at the base of the ocean food chain. Decreasing phytoplankton abundance has the potential to negatively impact ocean and coastal fisheries.

TABLE 1. INDICATORS OF CLIMATE CHANGE IN THE PACIFIC ISLANDS

The individual indicator sections are followed by sections on:

- **Future Climate**—what changes in the indicator are expected over time; and
- **Observed and Expected Impacts**—what are the socio-economic and bio-cultural impacts attributable to observed and expected indicator change over time. Information on impacts is considered in the context of sectors.

Sources of information and methods are outlined in the Appendix: Traceable Accounts.

The authors note with concern the gradual decline in data quality and frequency of observations over the last two to three decades. Pacific regional averages are increasingly biased towards U.S., French, Australian, and New Zealand territory or affiliated country observation sites where *in situ* records are more complete. Surface temperature observations that are more than 80% complete and long enough for climate change monitoring are now largely limited to one or two observation sites in each country. To maintain and enhance our ability to assess environmental change, attention needs to be given to robust and sustained monitoring. We also note the need for more analysis of climate models on the regional scale, as well as higher resolution models that will support downscaling required to make information actionable at the national to local level.

Atmosphere

Suggested Citation:
McGree, S., Kruk, M., Marra, J.J., Chandler, E., Diamond, H., Lutu-McMoore, E. (2022). *Atmosphere*. In: Marra et al. (Eds.), Pacific Climate Change Monitor: 2021. The Pacific Islands-Regional Climate Centre (PI-RCC) Network Report to the Pacific Islands Climate Service (PICS) Panel and Pacific Meteorological Council (PMC). DOI: 10.5281/zenodo.6965143

Storm clouds at sunset © Adobe Stock/czamfir

Greenhouse Gases

Highlights

- Over the last 60 years, the concentration of carbon dioxide (CO_2) in the atmosphere measured at NOAA's Mauna Loa Observatory has increased by more than 100 parts per million (ppm), to an annual average value over 414 ppm in 2020.
- The annual average rate of increase in CO_2 since the 1960s at Mauna Loa is +1.6 ppm per year. Over the last decade, the annual mean rate of growth of CO_2 was almost +2.5 ppm.
- The annual average rate of increase in CO_2 at the BOM and CSIRO's CO_2 monitoring station at Cape Grim in Tasmania since 1979 is +1.85 ppm per year. The growth rate increased to +2.4 ppm per year during the last decade.
- The combined impact of the greenhouse gases carbon dioxide, methane, nitrous oxide, and halogenated compounds in December 2020 is equivalent to a CO_2 concentration of 504 ppm.

Background

Rising concentrations of CO_2 and other greenhouse gases (e.g., methane-CH_4, nitrous oxide-N_2O, halogenated compounds-mainly fluorinated gases) contribute to increased global warming. They drive changes that cascade throughout the climate system and are reflected in other climate change indicators considered here. Once they enter the atmosphere, greenhouse gases can persist for tens to thousands of years[1]. The rise in the concentration of CO_2 and other greenhouse gases can be attributed primarily to human activity, with emissions increasing primarily in response to the burning of fossil fuels and changes in land use[1,2].

In the Pacific Islands, climate is strongly influenced by natural phenomena such as El Niño and La Niña, and the Pacific Decadal Oscillation/Interdecadal Pacific Oscillation[3,4]. This results in significant year-to-year and decade-to-decade variability. The presence of this natural climate variability can make it difficult to discern long-term changes in climate due to increasing greenhouse gases.

Indicator: Atmospheric Concentration of Carbon Dioxide (CO_2)

NOAA's Mauna Loa Observatory in Hawaiʻi and BOM/CSIRO's monitoring station at Cape Grim in Tasmania are two out of the three Premier Global Baseline Stations in the WMO-Global Atmosphere (GAW) Global Network (Figure 2). The annual mean concentration of CO2, at Mauna Loa in 1959, the onset year of observations, was 315.97 ppm (Figure 3)[5]. It passed 350 ppm in 1988 and 400 ppm in 2015. The annual mean concentration of CO_2 at Mauna Loa in 2020 was 414.24 ppm. That corresponds to an increase of almost 100 ppm over the last 60 years or more than +1.6 ppm per year. The rate over the last 25 years, since the early 1990s, is higher (about +2.0 ppm per year). Over the last decade, the annual mean rate of growth of CO_2 was even higher (almost +2.5 ppm per year). The monthly high during the period of record ending in December 2020 was 417.31 ppm, a record value reached in May of that year.

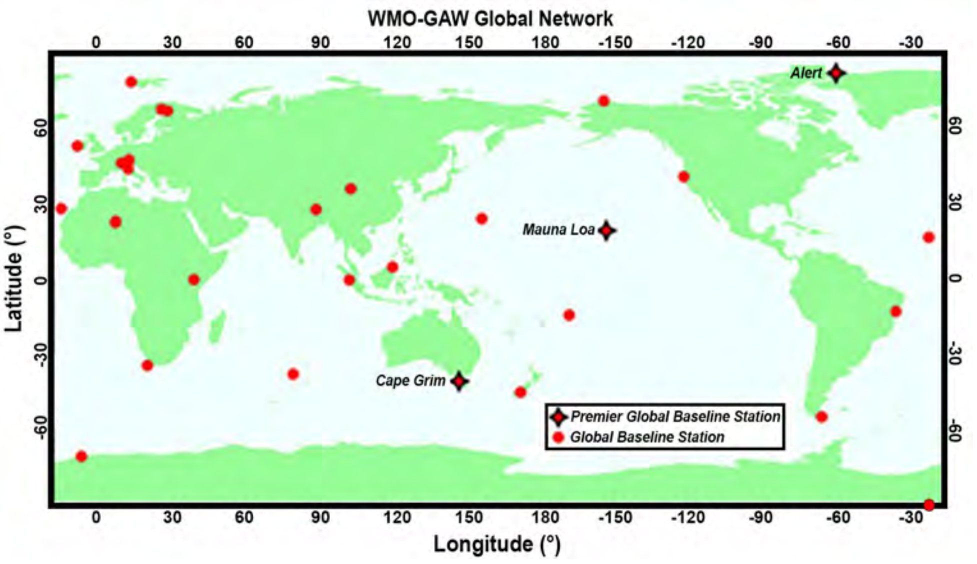


Figure 2. WMO-Global Atmosphere (GAW) Global Network. The Cape Grim Baseline Air Pollution Station monitors Southern Hemispheric air. In the Northern Hemisphere, the Mauna Loa Observatory in Hawaiʻi has continuously monitored and collected data related to atmospheric change since the 1950s. Source https://capegrim.csiro.au/

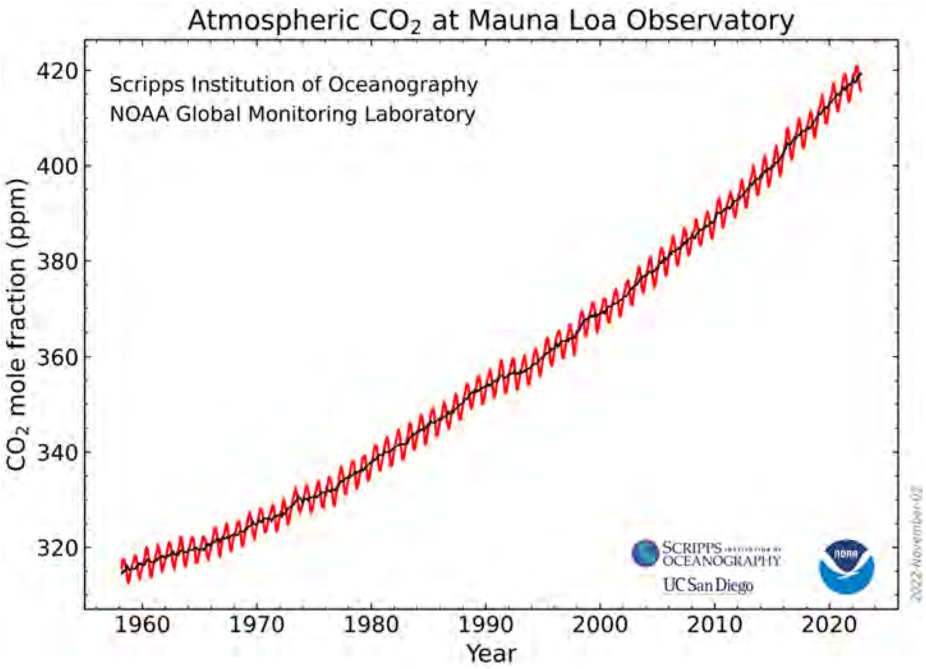


Figure 3. Monthly Mean Concentration of Atmospheric CO_2 at Mauna Loa since 1959. The red line represents the monthly mean values, centered on the middle of each month. The black line represents the same, after correction for the average seasonal cycle. The annual oscillations at Mauna Loa are due to the seasonal imbalance between the photosynthesis and respiration of plants on land. From NOAA ESRL Global Monitoring Division. https://www.esrl.noaa.gov/gmd/ccgg/trends/

In 1976, at the onset year of observations, concentration of CO_2 at Cape Grim was 328.86 ppm (Figure 4)[6]. It passed 350 ppm in 1989 and 400 ppm in 2016. The annual mean concentration of CO_2 at Cape Grim in 2020 was 404.21 ppm. That corresponds to an annual mean rate of growth of CO_2 of 1.85 ppm per year over the past 41 years (1979–2020). This increase in CO_2 concentrations is accelerating—while it averaged about 1.6 ppm per year in the 1980s and 1.5 ppm per year in the 1990s, the growth rate increased to 2.4 ppm per year during the last decade (Figure 5).

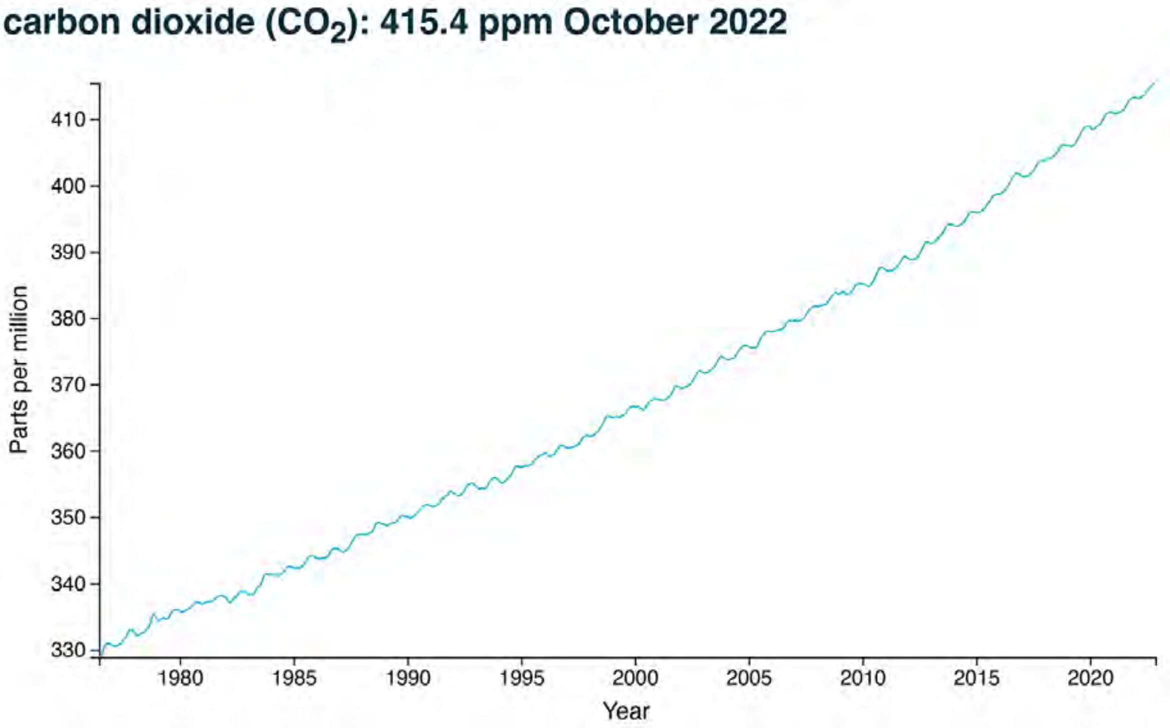


Figure 4. Monthly mean baseline concentration of CO_2 measured at the Cape Grim Baseline Air Pollution Station, Tasmania. https://www.csiro.au/en/research/natural-environment/atmosphere/latest-greenhouse-gas-data (accessed 10/12/21)

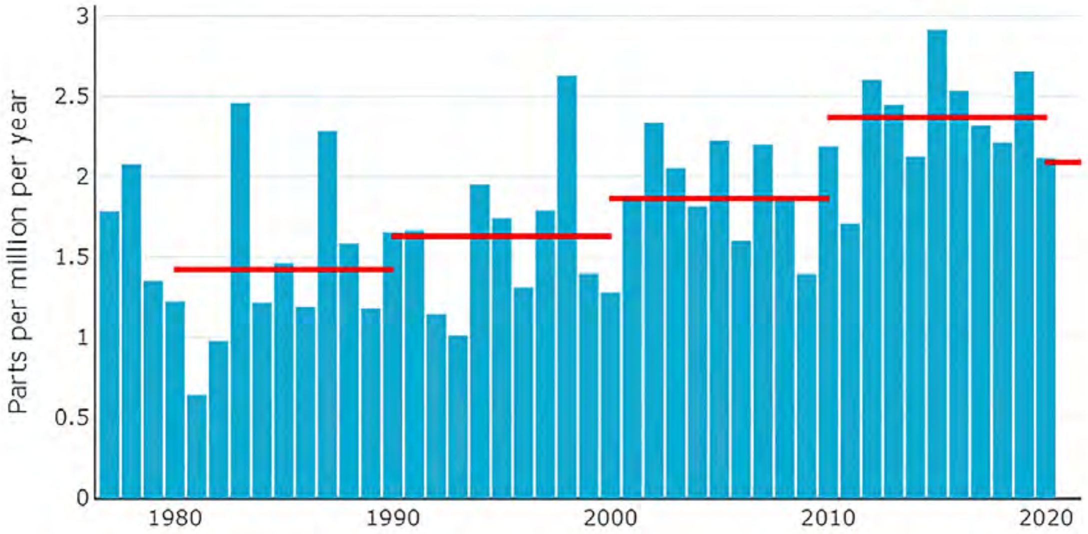


Figure 5. Annual (blue bars) and decadal (red horizontal lines) growth rates of CO2 in the atmosphere at Cape Grim. https://www.csiro.au/en/research/natural-environment/atmosphere/latest-greenhouse-gas-data (accessed 10/12/21)

Indicator: Other Greenhouse Gasses

The Annual Greenhouse Gas Index (AGGI) is a simple measure of the abundance of greenhouse gases in the atmosphere, it is indexed to 1 for the year 1990 (the baseline year for the Kyoto Protocol) (Figure 6.). The observationally based index is proportional to the change in the direct warming influence since the onset of the industrial revolution. The AGGI was designed to enhance the connection between scientists and society by providing a normalized standard that can be easily understood and followed. In 2020, for example, the AGGI was 1.47[7], which represents a 47% increase in total direct radiative forcing from human-derived emissions of these gases since 1990. Expressed as a greenhouse gases volume equivalent, in 2020 the atmosphere contained 504 ppm. Carbon dioxide alone accounts for more than 82% (414 ppm) of this value; the rest comes from other greenhouse gases. It took approximately 240 years for the AGGI to go from 0.0 to 1.0 (i.e., to reach the 1990 100% value).

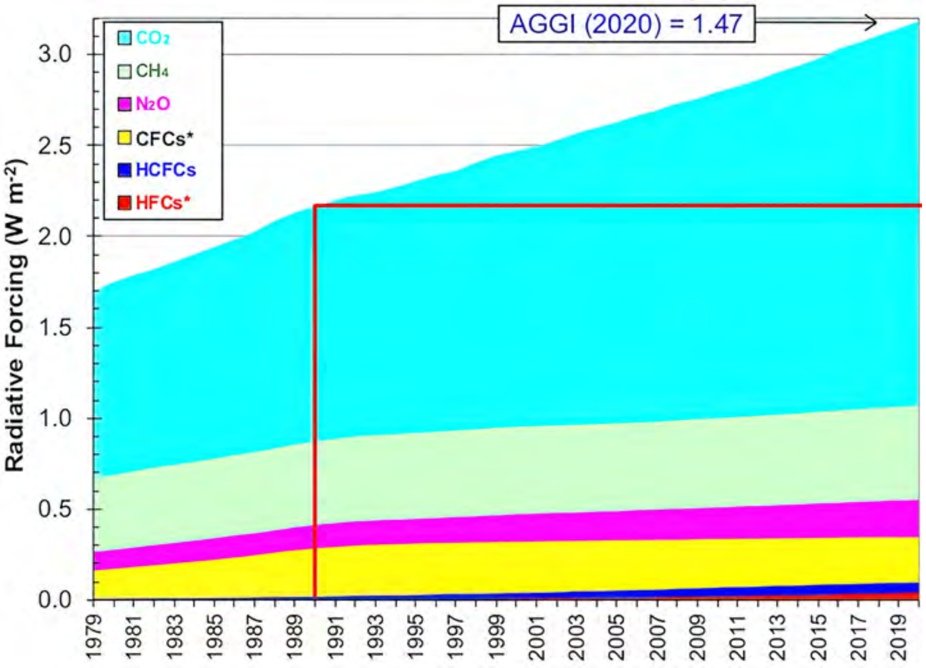


Figure 6. Radiative forcing, relative to 1750, of all the long-lived greenhouse gases and a set of 15 minor long-lived halogenated gases. NOAA's AGGI, which is indexed to 1 for the year 1990, is shown on the right axis. The AGGI is defined as the ratio of the total direct radiative forcing due to long-lived greenhouse gases for any year for which adequate global measurements exist to that which was present in 1990, which was chosen because it is the baseline year for the Kyoto Protocol. https://www.esrl.noaa.gov/gmd/aggi/aggi.html

Surface Temperature

Highlights

- The Pacific Islands mean temperature over land increased by 1.1°C (2°F) since 1951.
- Seven of the warmest eight years on record have occurred since 2007. Every year since 1983 has been above the 1961–1990 average.
- The average magnitude of change in hot days at the indicator stations was 3.1%/decade with most within the range of 0.7–5.5%/decade.
- The average magnitude of change in cold nights at the indicator stations was -1.2%/decade with most within the range of -1.9 to -0.6%/decade.
- On a regional scale, the increase in hot days is much stronger than the decrease in cold nights.

Background

Surface temperature is an important indicator of climate change and variability. Higher temperatures generally mean more frequent and intense heat events are likely to happen. This can lead to human health issues, affect agricultural production, and cause other changes to plants and animals. Warming temperatures, during the day and night, also lead to an increase in energy usage required to maintain indoor comfort. When combined with clear skies and only a light breeze, warming temperatures can exacerbate coral bleaching and result in even warmer sea surface temperatures.

Interpretation of historical temperature records across the Pacific Islands is difficult. Changes in station location, physical changes at the sites, and even instrumentation changes have had large impacts on the observational record[1,2,3].

Indicator: Regional and Local Mean Surface Temperature

The Pacific Island climate has warmed with mean temperature over land, increasing by 1.1°C since 1951 (Figure 7). At a regional scale, mean temperature increased over both halves of the 70-year period (1951–1985, 0.5°C [0.9°F] and 1986–2020, 0.6°C [1.1°F]) and in all seasons. Daytime maximum and overnight minimum temperatures increases were similar. On a regional scale, 2020 was the warmest year on record, 0.9°C (1.6°F) above the 1961–1990 average of 24.9°C (76.8°F). Seven of the warmest eight years on record occurred from 2007. Every year since 1983 has been above the 1961–1990 average.

Figure 7 shows a period of smaller increasing trend from about 2001–2015, followed by the continuation of rapid warming experienced from the early 1970s to

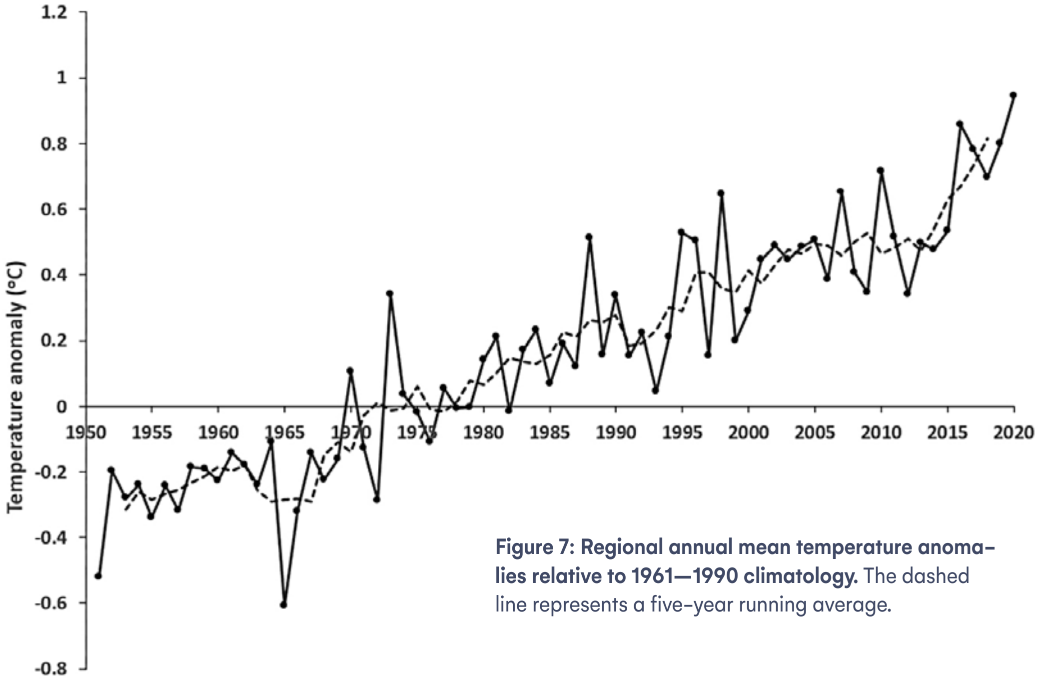


Figure 7: Regional annual mean temperature anomalies relative to 1961—1990 climatology. The dashed line represents a five-year running average.

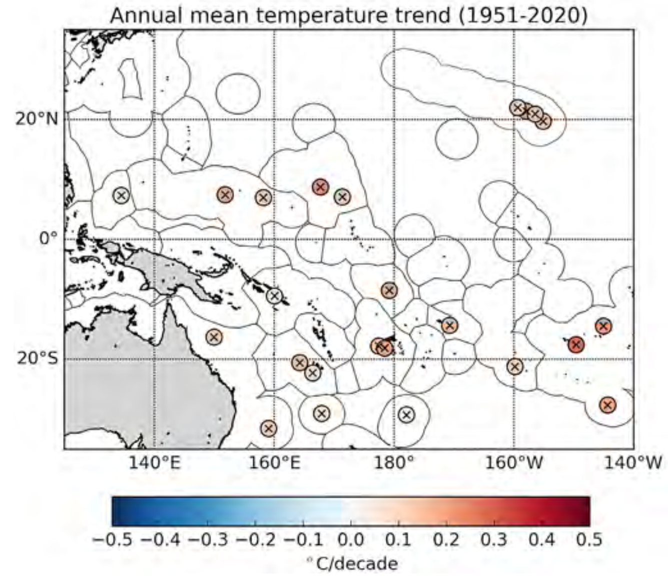


Figure 8: Change in annual mean temperature from 1951—2020 as observed in *in-situ* station data from locations across the tropical/subtropical Pacific. Trends are presented in the form of a circle over the station location. The color of the circle is proportional to the magnitude of the trend: the deeper the shading, the greater the observed warming. For air temperature, the positive change is denoted by red shading and negative change with blue shading. In practice, all trends are positive, therefore, all circles are shaded red. Circles with an 'x' are significant at the 95% level.

late 1990s. The slowdown is linked to a negative phase of the naturally occurring Interdecadal Pacific Oscillation[4]. The warming trend occurs against a background of year-to-year climate variability, mostly associated with El Niño and La Niña in the tropical Pacific. The warming trend can modify the impact of these natural drivers on Pacific Island climate[2,5].

Figure 8 shows increases in annual mean temperature at all the indicator stations, in both hemispheres. Trend magnitudes for the period 1951–2020 range from 0.05°C (0.09°F)/decade at Raoul Island in the subtropics of the South Pacific to 0.28°C (0.5°F)/decade at Tahiti-Faaa in French Polynesia. The average trend value is about 0.16 °C (0.29°F)/decade. Overall, warming in the northern hemisphere (0.17°C/decade) is marginally stronger than that in the southern hemisphere (0.16°C/decade). All site specific annual mean temperature trends are statistically significant at the 95% level.

The regional annual mean temperature warming trend over land, presented above, is likely to be higher than the annual mean temperature trend over land and ocean for the area presented in Figure 8. Limited long-term station data are available for the central tropical Pacific (central and eastern Kiribati, northern Tuvalu, northern Cook Islands, Tokelau and the Pitcairn Islands), which has experienced little change or negative ocean surface temperature trends (similar mean temperature trends likely) in recent decades (see Figure 19). The absence of observations from the central Pacific does not negate regional statistically significant mean temperature warming over the last 70 years. Alternative sources of data are available, however, these global datasets contain little Pacific Island data for many countries. Where data are available, the quality and completeness of the records is limited[1,2,3]. Previous studies showed regional means from global gridded datasets (e.g., HadCRUT4) to be as much as 0.2–0.3 °C (0.4–0.5°F) warmer than regional means calculated from locally sourced station records for the 1940s to mid-1960s. There is better agreement between the two datasets in recent decades[1].

Indicator: Amount of Hot Days

According to the Intergovernmental Panel on Climate Change (IPCC) AR6 WG1 report, it is *virtually certain* that the number of warm days and nights has increased and the number of cold days and nights has decreased on the global scale since 1950[6]. Both the coldest and hottest extremes display increasing temperatures. It is also *very likely* that these changes also occurred in regions neighboring the Pacific, namely, Australasia, Asia, and North America.

The shift to a warmer climate in the Pacific is accompanied by more extreme daily heat events. These extreme temperature events are also increasing in frequency. Figure 9 shows that the annual number of hot days has increased at most of the indicator stations. A hot day is defined as a day when the highest temperature is within the highest 10% of observations (for the respective location) between 1961 and 1990.

The regional average change in hot days was 3.1%/decade. At the station level, about 70% of the trend magnitudes were within the 0.7–5.5%/decade range.

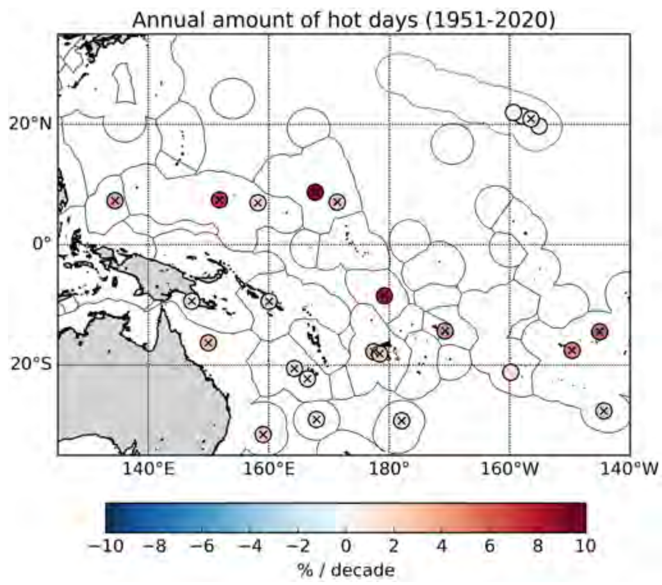


Figure 9: Trend in the annual amount of hot days over 1951—2020. Circles with 'x' represent trends statistically significant at the 95% level.

For Kwajalein in the Marshall Islands, the increase in hot days is highly significant with an average of 73% of days defined as "hot" during 2011–2020, compared to 3% of days during 1951–1960.

Indicator: Amount of Cold Nights

The shift to a warmer climate in the Pacific is also accompanied by fewer cold nights. Figure 10 shows the annual amount of cold nights has decreased at most of the indicator stations. A cold night is defined as when the lowest recorded temperature (in a 24-hour period) is within the lowest 10% of observations (for the respective location) between 1961 and 1990.

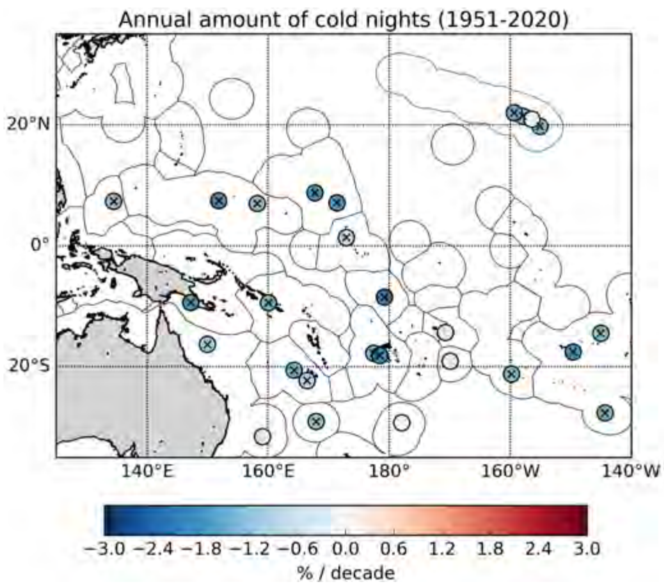
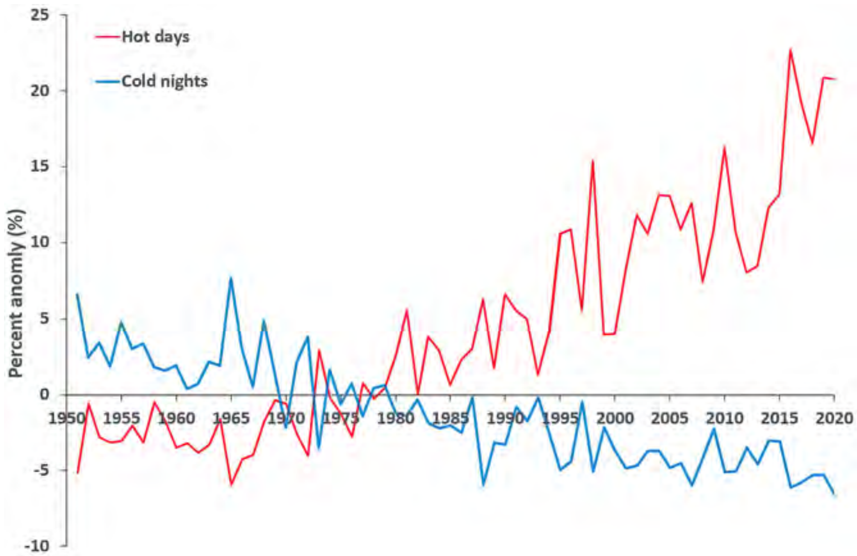


Figure 10: Trend in the annual amount of cold nights over 1951—2020. Circles with 'x' represent trends statistically significant at the 95% level.

The regional average change in cool nights was -1.2%/decade. At the station level, about 70% of the trend magnitudes were within the -1.9 to -0.6%/decade range. For Funafuti in Tuvalu, the decline in cool nights is highly significant with an average of 3% of nights defined as "cold" over 2011–2020, compared to 14% of nights over 1951–1960.

Hot days were about three times as common in the 2010s as they were in the 1950s (Figure 11). A record amount (percentage) of hot days occurred in 2016 (32.3%), which is 22.7% greater than the 1961–1990 average (9.5%). Cold nights were about 60% less frequent in the 2010s, compared to the 1950s.

Figure 11: Regional amount of hot days (TX90p) and cold nights (TN10p) anomalies relative to the WW1961—1990 climatology.



Rainfall

Highlights

- Over the last 70 years, there has been little change in annual total rainfall at most of the Pacific Islands observation sites. However, drying trends are observed in Hawai‘i and at three locations in the South Pacific subtropics.
- Over the last 70 years, there has been little change in annual consecutive dry days at most of the Pacific Islands observation sites. Consistent with the annual total rainfall drying trends, there is a trend towards longer periods of low rainfall in Hawai‘i and the South Pacific subtropics.
- There is mixed evidence for change in heavy rainfall across the Pacific Islands. In the Southwest South Pacific Convergence Zone (SPCZ) region, annual heavy rainfall has increased.

Background

Precipitation has wide-ranging impacts on humans and ecosystems, including: providing fresh drinking water to low-lying atolls; replenishing freshwater lenses; and water supply necessary for agriculture. Changes in precipitation frequency or quantity could disrupt these and other natural processes. Heavy or extreme rainfall events can increase or enhance impacts to crop damage, soil erosion, and floods. Runoff from excessive precipitation also carries harmful pollutants into nearby water bodies, endangering aquatic species and humans who depend on those resources for sustenance and their way of life.

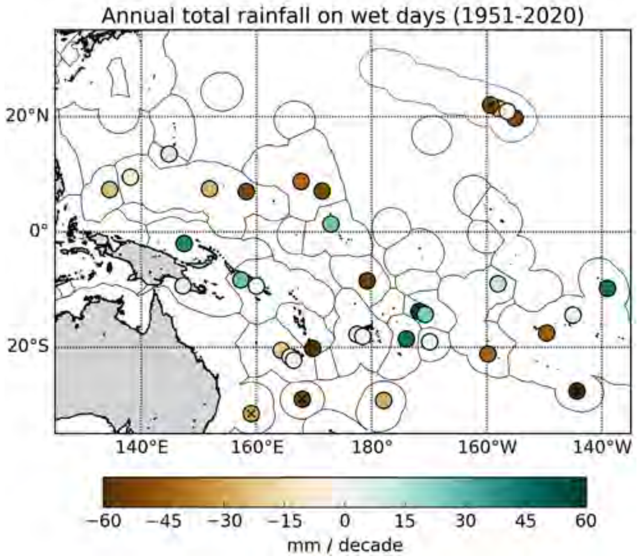


Figure 12: Trends in annual total rainfall on wet days over 1951—2020. Circles with ‘x’ represent trends statistically significant at the 95% level.

Indicator: Total Wet-Day Rainfall

Over the last 70 years, there has been little change in annual total rainfall on days where rainfall was greater or equal to 1 mm (0.04 inches) at most of the Pacific Islands observation sites (Figure 12). One of the four sites recording drying trends (station markers with ‘x’) is in Hawai‘i with the remainder in the South Pacific subtropics. The drying trend observed on the Hawaiian Island of Kaua‘i is strongest from December to February. This is consistent with numerous studies that found that Hawai‘i has become drier in recent years[7,8,9]. In the South Pacific subtropics, the strongest drying trends are over September–November in the eastern South Pacific and July–August in the west. The latter is consistent with drying in recent decades across southern Australia over April–October[10,11].

TABLE 2. SUBREGION MEAN RAINFALL INDICATOR TRENDS. Trend values in boldface are statistically significant at the 95% level. The 95% confidence intervals are shown in parentheses. The trend values are based on a subset of Pacific Island observation stations. Station selection influences the subregional trend values (and trend confidence).

	Annual total rainfall on wet days	Annual consecutive dry days	Annual heavy rainfall
Hawaiian Islands	–36.1 (–75.0, 0.2)	0.7 (–0.5, 1.7)	–2.3 (–7.1, 1.9)
Northwest Pacific	–28.4 (–71.7, 13.9)	–0.1 (–0.4, 0.1)	–0.4 (–3.9, 2.4)
Central Tropical Pacific	16.8 (–74.3, 105.9)	0.4 (–1.3, 0.5)	3.0 (–0.1, 6.3)
Southwest SPCZ	4.1 (–39.7, 60.0)	0.5 (–0.3, 1.2)	**3.1** (0.7, 5.5)
Northeast SPCZ	30.0 (–31.0, 87.3)	–0.3 (–0.8, 0.1)	3.1 (–1.1, 7.2)
Southeast French Polynesia	**–85.9** (–146.1, –16.2)	–0.3 (–1.0, 0.3)	–3.7 (–8.8, 1.4)
South Pacific Subtropics	**–40.7** (–67.0, –11.6)	0.2 (–0.2, 0.6)	–1.6 (–5.3, 1.0)

In Table 2 the Pacific Islands are divided into subregions with similar year-to-year variability. Negative total rainfall trends are observed in the South Pacific subtropics and in the Southeast French Polynesia region (Society and Tubai Islands). The Hawaiian trend is marginally statistically significant. Elsewhere, there has been little change in annual total rainfall on wet days.

The drying trend in the southern hemisphere is associated with higher mean sea level pressure and a shift in large-scale weather patterns, with more atmospheric high pressure systems and fewer atmospheric low pressure systems[10,12]. This increase in mean sea level pressure across southern latitudes is a known response to global warming[6,13].

Closer to the equator, Pacific Island rainfall is highly variable from year-to-year and strongly influenced by phenomena such as El Niño and La Niña[14,15]. Climate drivers such as the Pacific Decadal Oscillation/Interdecadal Pacific Oscillation also influence Pacific rainfall resulting in significant decade-to-decade variability[16,17]. The high variability and apparent drying trends align with the conventional placement of both the Intertropical Convergence Zone (ITCZ) and SPCZ, indicating that these subregions may be experiencing even higher variability compared to the rest of the Pacific, consistent with anticipated changes in circulation patterns.

Indicator: Consecutive Dry Days

The consecutive dry days indicator used here measures change in longest sequence of days in a year where rainfall is less than 1 mm (0.04 inches). High positive (negative) values correspond to a change to longer (shorter) periods of low rainfall in recent years. Table 2 and Figure 13 show little change in annual consecutive dry days at most locations over the last 70 years. In the Hawaiian region and South Pacific subtropics, there is a trend towards longer periods of low rainfall, which is consistent with the annual total rainfall drying trends for the same locations.

Indicator: Heavy Rainfall

The annual heavy rainfall indicator (Figure 14) is defined as the year-to-year trend in the highest annual 1-day rainfall total. There is mixed evidence for change in heavy rainfall across the Pacific Islands (also see Table 2). In the Southwest SPCZ region (stations from Southern PNG southeast to southern Tonga) annual heavy rainfall has increased. This is likely to be associated with a number of large rainfall events at the selected indicator stations in recent years and not a feature of the subregion as a whole. On seasonal timescales, the proportion of statistically significant trends is 10% or less and trend pattern is mixed (both positive and negative).

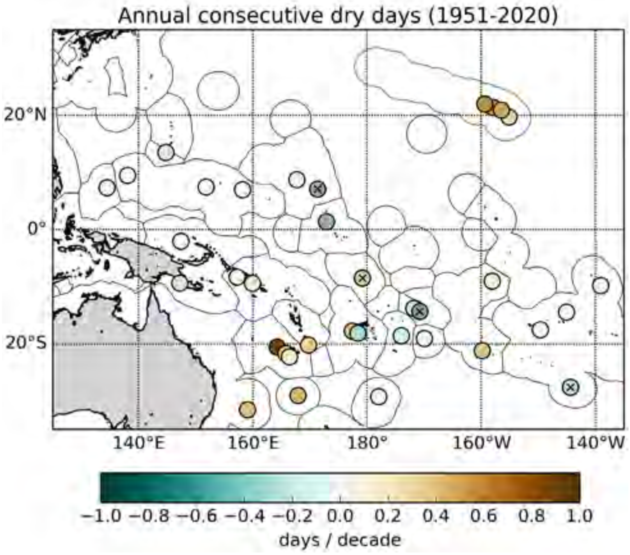


Figure 13: Trend in annual consecutive dry days over 1951—2020. Circles with 'x' represent trends statistically significant at the 95% level.

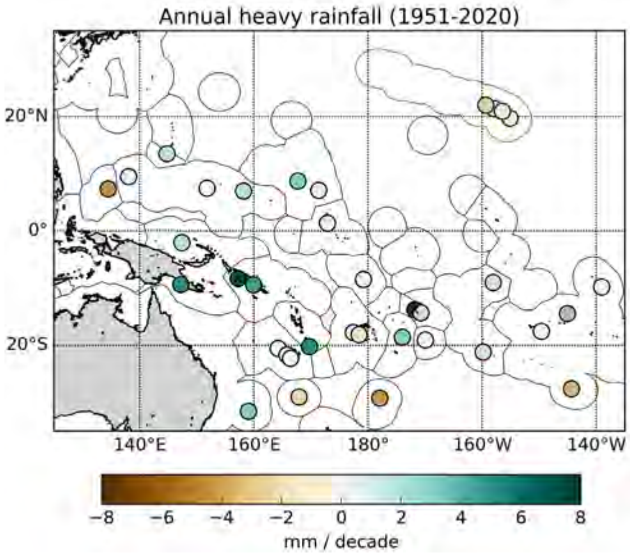


Figure 14: Trend in annual heavy rainfall over 1951—2020. Circles with 'x' represent trends statistically significant at the 95% level.

Tropical Cyclones and Surface Winds

Highlights

- In all three subregions—Western North Pacific, Central North Pacific, and Western South Pacific—there is no notable up or down trend in the frequency or magnitude of storms and cyclones since the 1980's, with nearly an equal number of above- and below-normal season activity.
- In the Central North Pacific, frequency counts since 1980 of surface winds greater than or equal to 34 knots show no statistically significant trends.
- In the Western South Pacific, the extratropical subregion shows a statistically significant rise in the frequency of 34 knot wind events since 1980.

Background

Changes in the intensity, frequency, and location of TCs is an important consideration with respect to climate variability and change. The impact to human life and property from a landfalling TC can be devastating, especially for small islands across the Pacific. Changes in wind speed can increase evaporation, resulting in greater water demand for agriculture[1].

The Pacific Ocean basin covers a large geographic area, near 40°N–40°S, 120°E–120°W, and as such, is broken down into three subregions: Western North Pacific (0°–40°N, 120°E–180°), Central North Pacific (0°–40°N, 180°–120°W), and Western South Pacific (0°–40°S, 120°E–120W°) for TC monitoring and recording keeping according to the International Best Track Archive for Climate Stewardship (IBTrACS)[2,3]. These subregions map closely to the Regional Specialized Meteorological Centre (RMSC)-Tropical Cyclones areas of responsibility.

Indicator: Total Number of TCs by Basin

Western North Pacific (Figure 15a): Since 1980, trends in the number of named storms and typhoons have remained constant, with nearly an equal number of above- and below-normal season activity. The quietest season was during 2010 with only 15 named storms. However, nine out of the last ten years have seen relatively shorter-lived TCs, despite the TC count being near normal. This is also reflected in a broad area of decreasing activity between 20°–40°N latitude (and an increase near the Philippines).

Central North Pacific (Figure 15b): Since 1980, trends in the number of named storms and hurricanes have remained constant, with nearly an equal number of above- and below-normal season activity. The last three seasons (2017/2018, 2018/2019, 2019/2020) witnessed TC numbers close to the long-term averages compared to the period 2010–2015, which had TC seasons with TC numbers below average. The most active year was 1992 with 28 named storms. For the period 1991–2020, the IBTrACS dataset indicates a reduction in the number of TCs near 120°W, west of Mexico, but with a slight increase in occurrences over the Baja Peninsula.

Western South Pacific (Figure 15c): The busiest year on record since 1998 was 2016 with 12 TCs. Like the other subregions, long-term trends do not exhibit noticeable trends in the frequency or magnitude of storms or cyclones across the region. The past five years, however, witnessed a drop in TC frequency around Vanuatu and the Cook Islands, but an increase around the northern island of New Zealand.

Indicator: Number of Severe Tropical Cyclones by Subregion

Western North Pacific (Figure 15a): Since 1980, trends in the number of major typhoons remain constant, with nearly an equal number of above- and below-normal season activity. The long-term trend in severe tropical cyclones in this subregion is flat across the period, despite the 2015 season that had the highest number of severe tropical cyclones during the last 30 years.

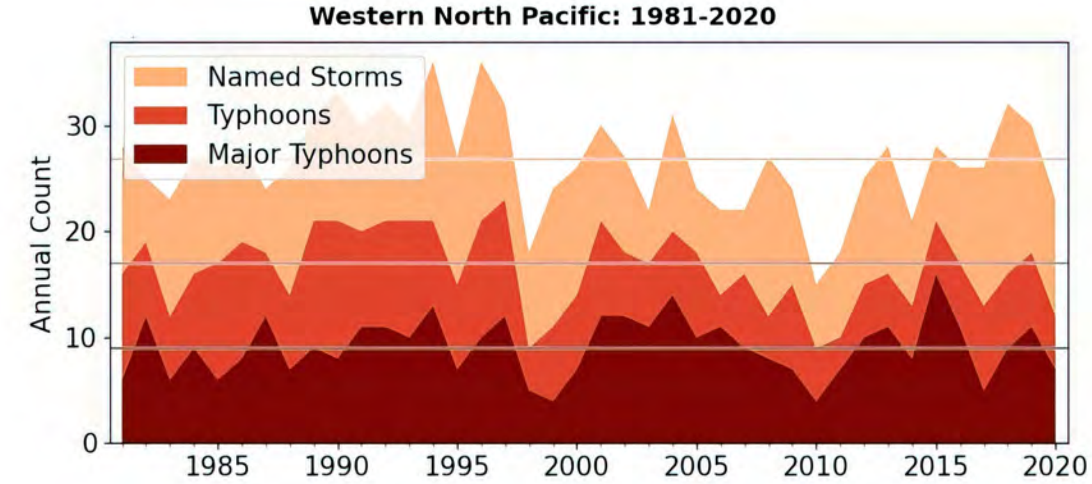
Central North Pacific (Figure 15b): Since 1970, trends in the number of major hurricanes have remained constant, with nearly an equal number of above- and below-normal season activity. The most recent period 2019–2021 has seen fewer severe tropical cyclones than the period 2015–2018.

Western South Pacific (Figure 15c): Like the other subregions, long-term trends do not suggest a notable up or down trend in the frequency or magnitude of major cyclones across the region. The recent period between 2010–2020 does indicate fewer major cyclones than 1995–2005 but the frequency counts are so low to begin with that these slight changes are not statistically significant.

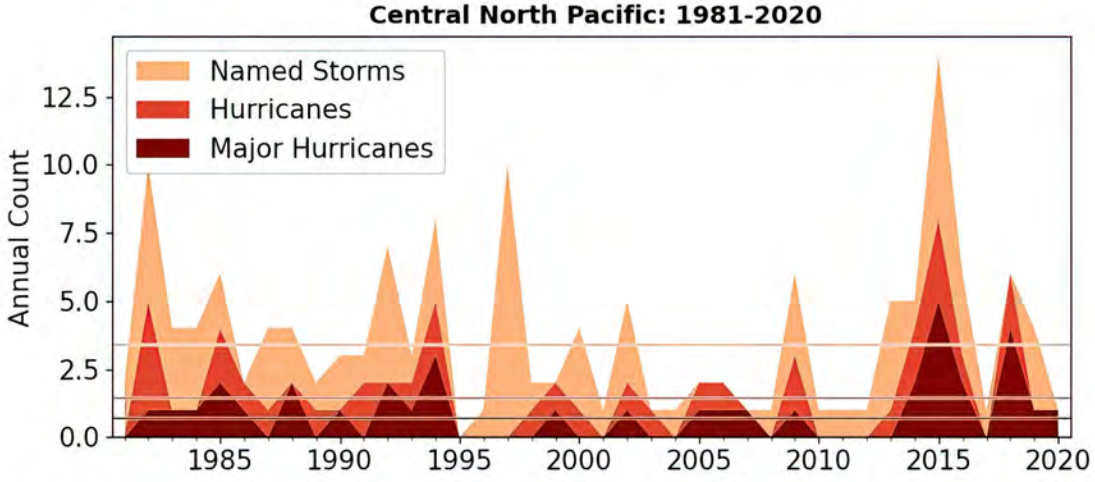
Indicator: Surface Wind Speed

In the Western North Pacific, frequency counts of surface winds[4] greater than or equal to 34 knots (TC wind speed threshold following the U.S. Saffir-Simpson Hurricane Wind Scale; see methods) show a lot of

(15a)



(15b)



(15c)

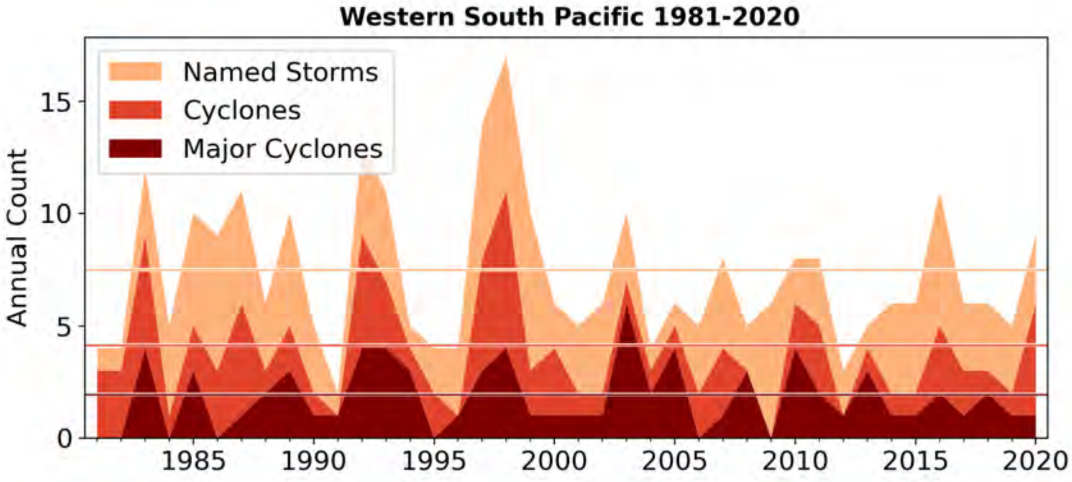


Figure 15. Tropical cyclone (TC) activity 1981—2020. Storm counts for: a) Western North Pacific; b) Central North Pacific; c) Western South Pacific. Major cyclones with winds greater than or equal to 110 kt and major hurricanes with winds greater than or equal to 96 kt (110 mph). The horizontal lines represent trends in Named Storms, Cyclones and Major Cyclones.

year-to-year variability with an unusually low number of events in 2019 in the 0–20°N latitude (tropical) subregion. Meanwhile for the 20-40°N (extratropical) subregion of the Northwest Pacific, a near steady state of frequency of these events since 1980 have occurred with no discernable upward or downward trends.

In the Central North Pacific, frequency counts of surface winds greater than or equal to 34 knots appears to have increased in the 0-20°N latitude (tropical) subregion since 1980, but especially since 2010 (Figure 16). Since 1980, the 20–40°N (extratropical) subregion region of the Central Pacific appears to exhibit a downward trend in the frequency of these 34 knot wind events. However, neither of these trends is statistically significant.

In the Western South Pacific, the trend in the 0–20°S latitude (tropical) subregion is not statistically significant. However, the 20–40°S (extratropical) subregion shows a statistically significant positive trend in the frequency of 34 knot wind events. This rise is consistent with global climate model projections showing the expansion of the Hadley Cell[5] outside of its current equatorial commonplace. The expansion of the Hadley Cell into the mid-latitude regions suggests these areas are increasingly likely to see drier and windier weather[6].

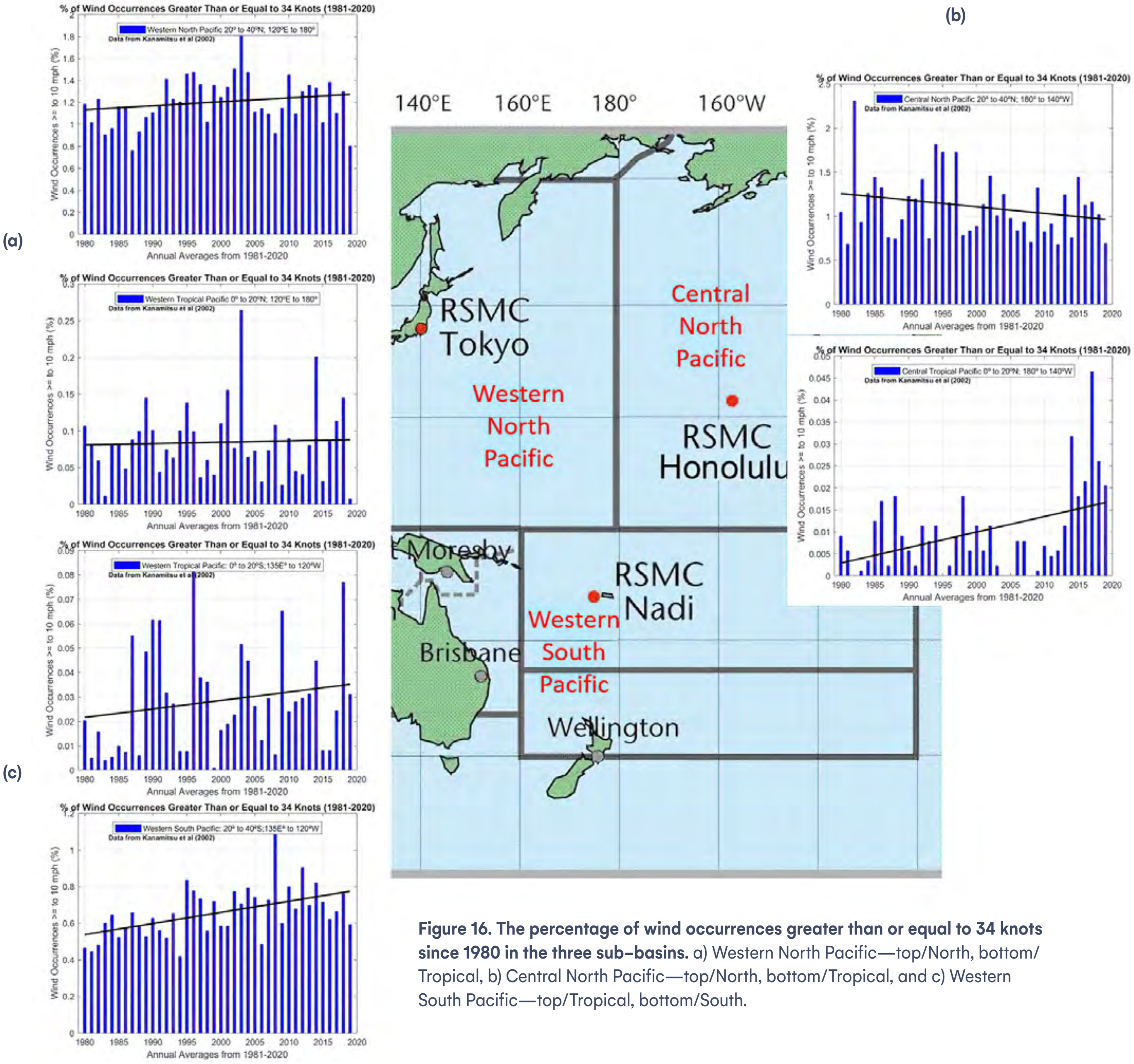


Figure 16. The percentage of wind occurrences greater than or equal to 34 knots since 1980 in the three sub-basins. a) Western North Pacific—top/North, bottom/Tropical, b) Central North Pacific—top/North, bottom/Tropical, and c) Western South Pacific—top/Tropical, bottom/South.

Underwater sunlight © Adobe Stock/Lighting Strike Pro

Ocean

Suggested Citation:

Marra, J.J., Potemra, J.T., Espejo, A., Fauchereau, N., Genz, A., Hernaman, V., Heron, S., Smith, G., Webb, L., Widlansky, M.J., Woodworth-Jefcoats, P. (2022). *Ocean*. In: Marra et al. (Eds.), Pacific Climate Change Monitor: 2021. The Pacific Islands-Regional Climate Centre (PI-RCC) Network Report to the Pacific Islands Climate Service (PICS) Panel and Pacific Meteorological Council (PMC). DOI: 10.5281/zenodo.6965143

Sea Level

Highlights

- Sea level has risen across the Pacific Islands region. In much of the western tropical Pacific sea level has risen approximately 10–15 cm (4–6 in), close to or nearly twice the global rate measured since 1993. In the central tropical Pacific sea level has risen approximately 5–10 cm (2–4 in).
- For the most part, local rates of change obtained from tide gauges are in agreement with those derived from satellites. However, owing to vertical land motion and other factors, there are locations such as Pago Pago, American Samoa where the local change of 31 ± 7 cm. (12 in ± 3 in) since 1993 as measured in the tide gauge is well above the amount derived from satellite observations.
- Natural patterns of variability play an important role in regional and local variation in sea level. These seasonal, interannual, and multidecadal changes in sea level sometimes exceed 30 cm (12 in) above or below normal, which is a much larger amplitude than the observed long-term trend.
- Rising mean sea levels have resulted in dramatic increases in the frequency of minor flooding since 1980. Notable increases include: Guam from 2 to 22 times a year (a 1000% increase); Penrhyn, Cook Islands from 5 to 43 times a year (a 760% increase); Majuro, Republic of the Marshall Islands from 2 to 20 times a year (a 900% increase); Papeete, French Polynesia from 5 to 34 times a year (a 548% increase); and Pago Pago, American Samoa from 0 to 102 times a year.

Background

Sea level rise is a crucial issue for many coastal regions in the Pacific due to the associated increase in damaging inundation, flooding, erosion and receding sandy coasts[1,2]. Impacts of higher sea levels also occur through saltwater intrusion and flood inundation of aquifers and other domestic water supplies, as well as salinization and flood damage to agriculture[3,4].

Since the start of continuous satellite measurements of global sea level in 1993, the global mean sea level (GMSL) has risen at an average rate of 3.3 mm (0.13 in) per year[5]. A new record high GMSL was set in 2020 of 9.1 cm (3.6 in) above 1993 levels[6]. This rise in GMSL is primarily attributable to greenhouse warming, which influences sea level in two ways. Heating of the ocean causes the water to become more buoyant and expand. Additionally, melting glaciers and ice sheets transfer water mass from the land to the ocean. Changes in storage of water on land (e.g., in lakes and reservoirs) also affect the global sea level, especially on year-to-year time scales, but have a much smaller contribution to the long-term trend.

Sea level trends measured in many parts of the Pacific Islands region differ *relative* to the *absolute* GMSL rate, often by as much as five times depending on the location and year. Several factors contribute to this spatial and temporal variability. There are contrasting regional fingerprints in sea level rise (SLR) caused by global warming[5,7,8]. Trends driven by global warming are accompanied by naturally-occurring regional SLR variations due to, e.g., the El Niño-Southern Oscillation (ENSO) on interannual time scales[9-14], and the Interdecadal Pacific Oscillation (IPO)/Pacific Decadal Oscillation (PDO) on decadal to multi-decadal time scales[12,15,16]. The natural variations can amplify or dampen the underlying trends arising from global warming. Natural climate variability is associated with large sea level fluctuations in the tropical western and Pacific, with below-normal sea levels during El Niño events and above-normal sea levels during La Niña. In Guam, for example, ENSO-related variations in sea level are on the order of ± 30 cm (12 in) and the anomalies typically last for several months. Hawai‘i, in the central North Pacific, experiences less sea level variability on interannual and decadal time scales. There are also factors other than climate variability that have a strong effect on coastal sea levels in the tropical Pacific. Vertical land motion (e.g., associated with some earthquakes) is large for several Pacific Islands[17,18], such as the Samoan Archipelago where it accounts for substantial differences in sea level trends measured by tide gauges and satellites, because the tide gauge instruments record water levels relative to the land[19].

Indicator: Regional and Local Sea Level

The mean sea level has risen since 1993 in nearly all regions and island locations of the Pacific Basin, although the amount varies widely (Figure 17). Generally, the SLR observed by satellites and tide gauges is largest in the tropical western Pacific (approximately 10–15 cm

[4–6 in]), especially within 15°N/S of the equator. In most of the tropical central Pacific, substantially less SLR has occurred (approximately 5–10 cm [2–3 in]), which is closer to the GMSL rise.

Tide gauge measured SLR is consistent with the satellite-measured local trends for most of the tropical Pacific Islands (Figure 17). There are some notable exceptions, which are mostly explained by processes affecting the local sea level measured relative to land (e.g., subsidence manifests as sea level rise recorded by tide gauges). Locations where trends observed in tide gauges (means and ± standard deviations above GMSL) show marked differences from trends derived from satellites are: Kawaihae, Hawaiʻi (24 ± 5 cm: 9 ± 2 in); Apia, Samoa (28 ± 7 cm: 11 ± 3 in); Pago Pago, American Samoa (31 ± 7 cm: 12 ± 3 in); Nukuʻalofa, Tonga (19 ± 5 cm: 8 ± 2 in); Suva, Fiji (19 cm ± 5 cm: 7 ± 2 in); and Funafuti, Tuvalu (13 ± 7 cm: 5 ± 3 in).

Indicator: Minor Flood Frequency

Local sea level variability and trends account for substantial changes in the minor flood frequency [20,21]. Minor floods sometimes occur when exceptionally high tides combine with large waves and/or other oceanic and atmospheric phenomena that raise the coastal water level [22,23,24]. Though their impacts are less than major floods, which occur during severe storms, the cumulative impacts associated with minor flooding can be considerable[25].

The total number of minor flood days per year for a select set of tide gauges in the western and central tropical Pacific is shown in Figure 18. Here, a *minor flood day* is defined as a day in which the sea level at a given tide gauge exceeds the elevation reached twice a year on average (i.e., the 0.5 year return interval derived from extreme value analysis). Increases in minor flood frequency are apparent (*white to red scale*), which is consistent with the regional trends in mean sea level. During the decade 2010–2019 relative to the decade 1980–1989, minor flood frequency increased at all but three out of 31 locations across the Pacific. The three exceptions are: Easter Island, Chile; Christmas Island, Kiribati; and Saipan, Commonwealth of the Mariana Islands. Some of the increases have been extraordinary. For example, minor flood counts increased in Guam from 2 to 22 times a year (a 1000% increase); in Penrhyn, Cook Islands from 5 to 43 times a year (a 760% increase); in Majuro, Republic of the Marshall Islands from 2 to 20 times a year (a 900% increase); in Papeete, French Polynesia from 5 to 34 times a year (a 548% increase); and in Pago Pago, American Samoa from 0 to 102 times a year. Average annual minor flood frequency counts over these same time periods (the 1980's versus the 2010's) for all stations combined increased from 93 to 709 (a 654% increase). Interannual variability of minor flood occurrence is also discernable in Figure 18. La Niña events (e.g., occurring during 1988–1989, 1998–2001, 2005–2006, 2007–2008, 2010–2012, and 2016–2018) are associated with high counts of minor flood days in Guam and Yap, Federated States of Micronesia. In contrast, El Niño (especially the strongest events that began in 1997 and 2015) is rarely associated with high counts of minor flood days, at least in the northwestern tropical Pacific around these two places.

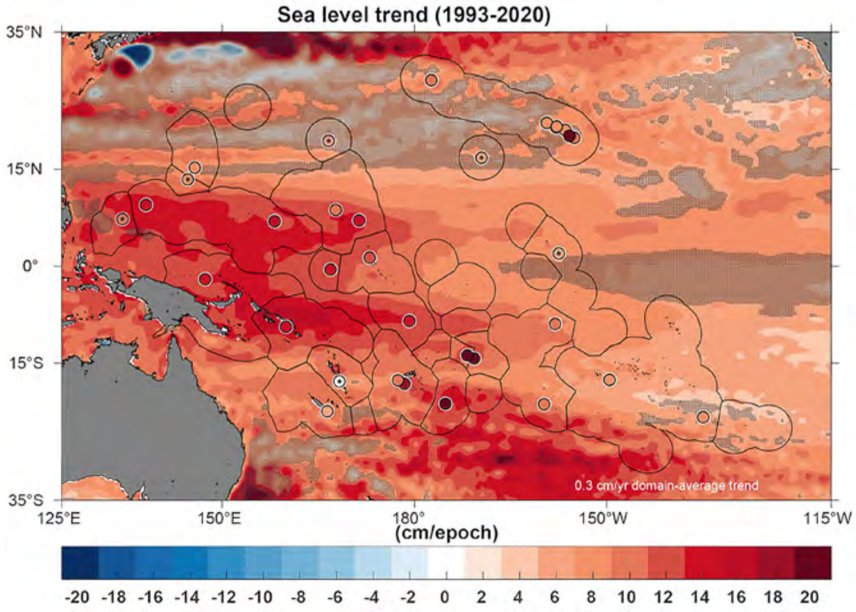


Figure 17. Regional Sea Level Trends from Satellite Altimetry and Tide Gauges. The maps shows sea level trends from satellite altimetry (colored contours) and from tide gauges (circles) since the beginning of the satellite record (1993—2020). Hatching and circles with dots, altimetry and tide gauges, respectively, indicate trends less than interannual variability as determined by the standard deviation of sea level monthly anomalies.

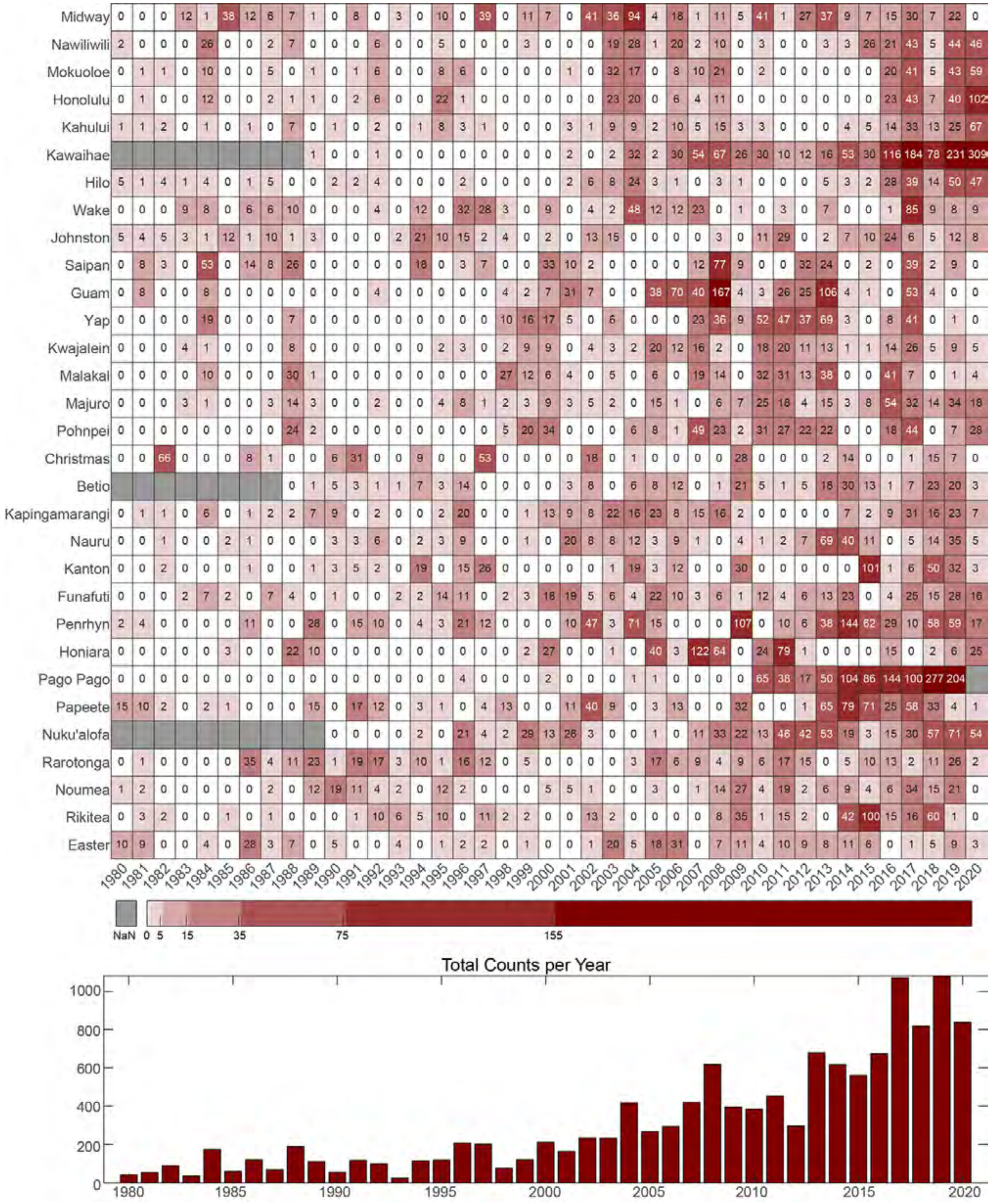


Figure 18. Minor flood frequency from selected tide gauges in the tropical Pacific. The top plot shows the total number of minor flood days per year for 1980—2020. Stations are organized by latitude (north at the top). At the bottom of the figure is a plot showing annual total of minor flood counts for all stations combined.

Ocean Temperature

Highlights

- For the most part, mean sea surface temperature in the Pacific has warmed over the past few decades by a few tenths of a degree per decade, with an overall warming of approximately 0.9°C (1.6°F) since 1982.
- From the 1980s to 2000s the average duration of marine heat waves is consistent, with much of the Pacific region within the 5- to 16-day range. However, there is a significant increase in event duration in the 2010s, with most of the Pacific in the 8 to 20+ day range.
- Trends in subsurface heat content over period 1981 to 2018 are largely positive in the Western Warm Pool region and northern and southern subtropics.
- The highest positive trends in subsurface heat content were found in western PNG, Solomon Islands, Nauru, and Tokelau. Slightly negative trends were found in the eastern Pacific just north and south of the equator.

Background

Changes in ocean temperature are one of the most important measures of long-term global climate change. Ocean temperature is an indicator of the state of marine ecosystems, as surface and subsurface variations surface can influence species distribution, growth, and lifespan, alter their migration and breeding patterns, and threaten sensitive ecosystems such as coral reefs[1].

Indicator: Mean Sea Surface Temperature

Sea surface temperature (SST) is probably one of the most well-known and widely observed climate indicators[2]. SST is used to monitor human-forced climate change and modes of natural climate variability that affect patterns of wind and rain as well as ocean circulation, such as the ENSO and the IPO/PDO[3,4]. The Physical Sciences Division at NOAA produces an SST product based on optimum interpolation (OI) analysis. The product, NOAA OISSTv2[5,6,7], is produced weekly on a 1-degree grid. Monthly averages are presented in this report. The temporal coverage of the monthly data used is from January 1982 through December 2021.

The observed SST trend at each 1-degree grid point, in °C per decade, is shown in Figure 19. Almost all Pacific

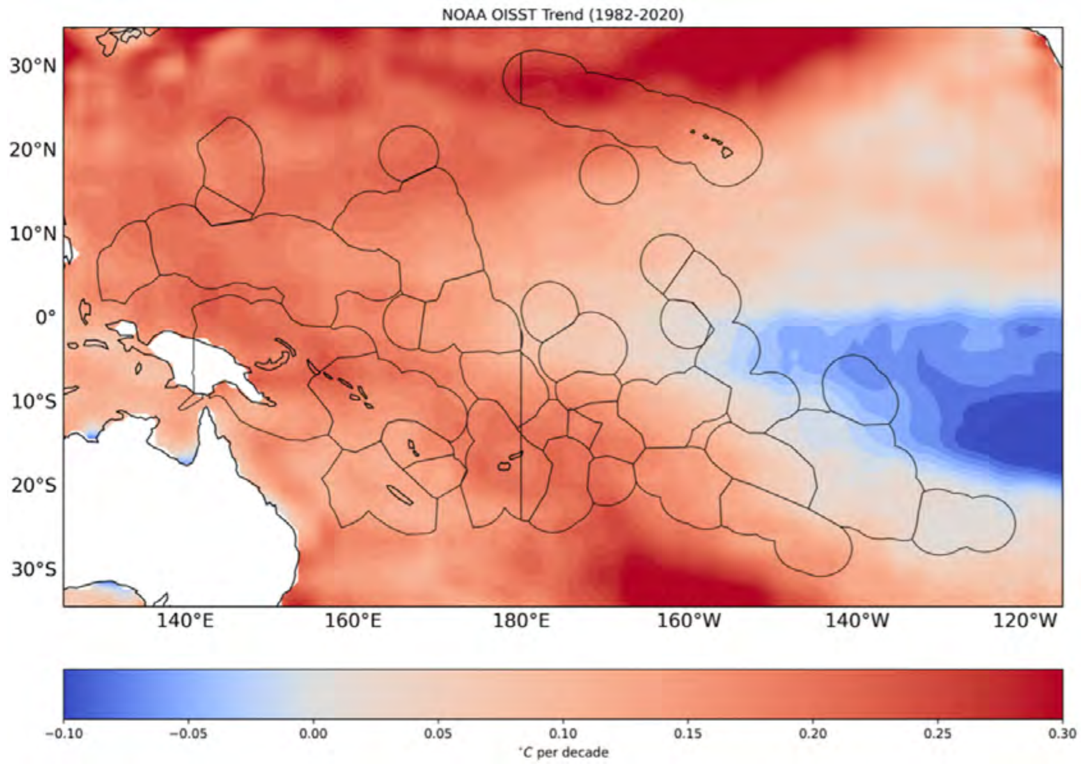


Figure 19. Sea Surface Temperature Trends. The map shows SST trends (°C per decade) over the period 1982—2020 from the NOAA ISSTv2 satellite and *in situ* analysis.

Island countries have experienced SST warming during this period. Hawai'i, Niue and Tonga have all experienced at least 0.2°C (0.4°F) per decade SST warming, while most other countries have experience warming between 0.1 and 0.2°C (0.2 to 0.4°F) per decade. The southeastern region around the Marquesas is a notable exception. There, temperatures show cooling trends over the period 1982–2021, which may be related to changes to the large-scale winds[8].

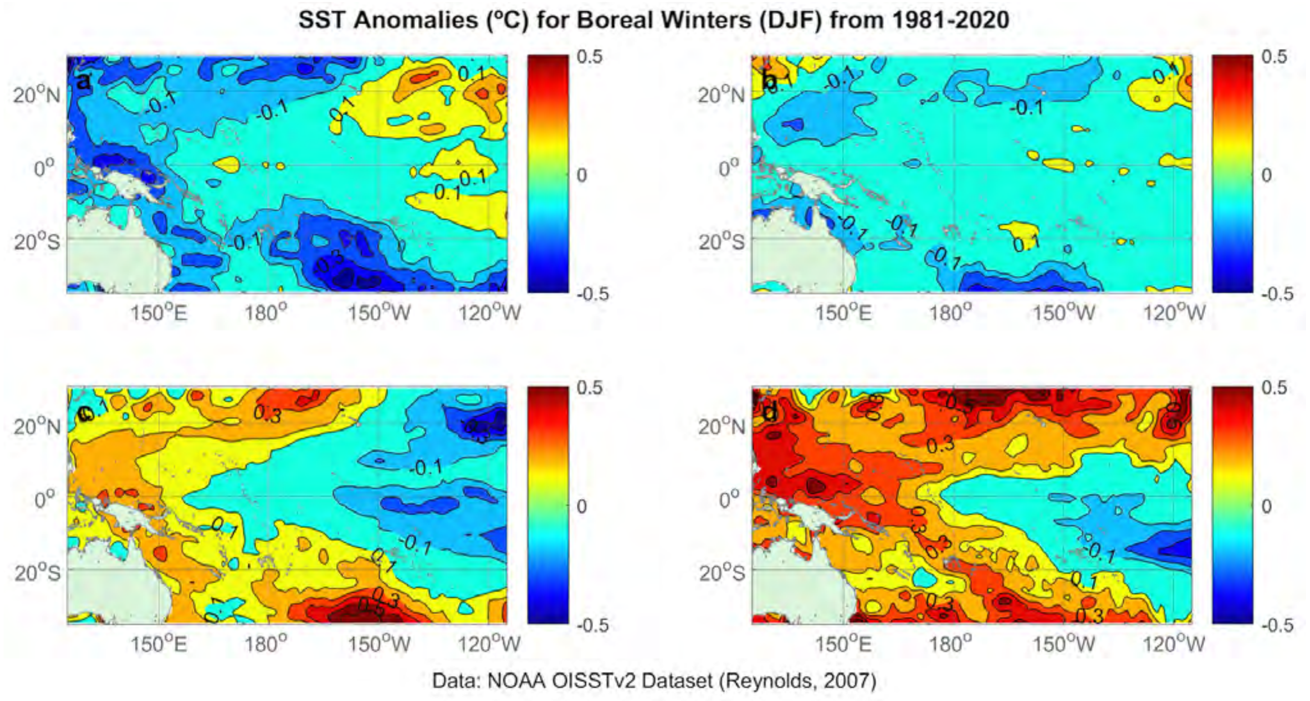
The SST trends throughout the observation period vary from decade to decade, primarily due to increased ENSO activity during some decades compared to others. For example, the 1990's saw four El Niño events with two very strong ones (1991/92 and 1997/98). The decade ended with a big La Niña event. The SST trends in this decade would likely show cooling due to this shift from warm to cold (see Figure 20).

This is reflected in the average SST anomalies (departures from 1981 to 2020 seasonal means) computed over the boreal winter months (December, January, February [DJF]) for each decade. Figure 20 shows the mean DJF SST anomalies for each decade, with the 1990's being mostly neutral (balance of warm and cold events during the decade), and the 2010's showing more 'La Niña'-like conditions.

Indicator: Marine Heat Waves

Marine heat waves are episodes of much higher than normal ocean temperatures that persist from between five days to many months. The SST threshold that signifies a marine heat wave is the 90th percentile, which is the highest 10% of SSTs experienced on a given day, determined by looking at many years of data[9]. When the 90th percentile temperature is exceeded for five or more consecutive days, the event is referred to as a marine heat wave. Marine heat wave intensity is characterized by four categories—Moderate, Strong, Severe, and Extreme[10]. Marine heat waves can occur year-round. The western tropical Pacific is a global hotspot for increase in marine heat waves.

Marine heat waves can have ecological impacts, ranging from coral bleaching, lagoon health, seagrass and mangrove die-off, fisheries and aquaculture, impacting economies and livelihoods in the Pacific. Impacts depend on the severity, duration, extent and timing of marine heat wave. As an example of a short duration high impact event, in February of 2016 Fiji experienced a marine heat wave that only lasted about two weeks. However, due to its rapid onset and high severity it caused significant fish die off in lagoons due to reduced dissolved oxygen in the water resulting from the ex-


SST Anomalies (°C) for Boreal Winters (DJF) from 1981-2020

Data: NOAA OISSTv2 Dataset (Reynolds, 2007)

Figure 20. Seasonal Sea Surface Temperature Anomalies. The maps show mean boreal winter (DJF) SST anomalies for four different decades (1980's upper left, 1990's upper right, 2000's lower left and 2010's lower right). Data are NOAA OISSTv2 satellite and *in situ* analysis.

treme temperatures. Conversely in some instances, impacts only arise from marine heat waves if they persist over many months. An example from 2015 occurred in the waters around Kiritimati Island in the Kiribati Line Islands when a long-duration event was driven in part by the El Niño event occurred that year. The result was significant coral bleaching and mortality, as the event did not subside in time for the corals to recover.

Daily SST data from satellite and *in situ* observations are available from 1st September 1981, providing the opportunity to assess the history of marine heat waves in the Pacific over 40 years. Marine heat wave summaries showing frequency of events, maximum severity, and average duration in each decade since 1981 are shown in Figure 21.

The number of marine heat waves remained fairly constant in the tropical regions in the 1980s and 1990s, with around 10–15 events per decade in the western Pacific and up to 30 events per decade in the east. Compared to the 1980s, the northwest Pacific had an increase in the frequency of events in the 1990s to about 30. In the 2000s, numbers decreased within the central and eastern tropical Pacific, and increased in the eastern Pacific and subtropics up to approximately 40 events. The 2010s had the highest number of events, reaching above 50 in the Western Warm Pool, a band spanning from PNG to the central Pacific, and off the coast of Mexico.

The maximum marine heat wave severity near the equator occurred in the 1980s and 1990s, reaching the Extreme category. Most of the remainder of the Pacific reached the Strong category, with pockets of Severe in the tropics, and Moderate in the subtropics. The central and western equatorial Pacific showed a decrease in maximum severity in the 2000s, reaching only Moderate, with mostly Strong severity in the remainder of the region. The maximum marine heat wave severity increased during the 2010s just north of the equator and in the southern subtropical region.

The average duration of marine heat waves is consistent for the three decades from the 1980s to 2000s, with much of the Pacific region within the 5- to 16-day range. However, there is a noticeable increase in event duration in the 2010s, with most of the Pacific in the 8 to 20+ day range.

Indicator: Subsurface Temperature

Ocean temperature integrated over a given depth range provides an estimate of oceanic heat content. This is an important parameter as the ocean sequesters much of the increased atmospheric heat from anthropogenic

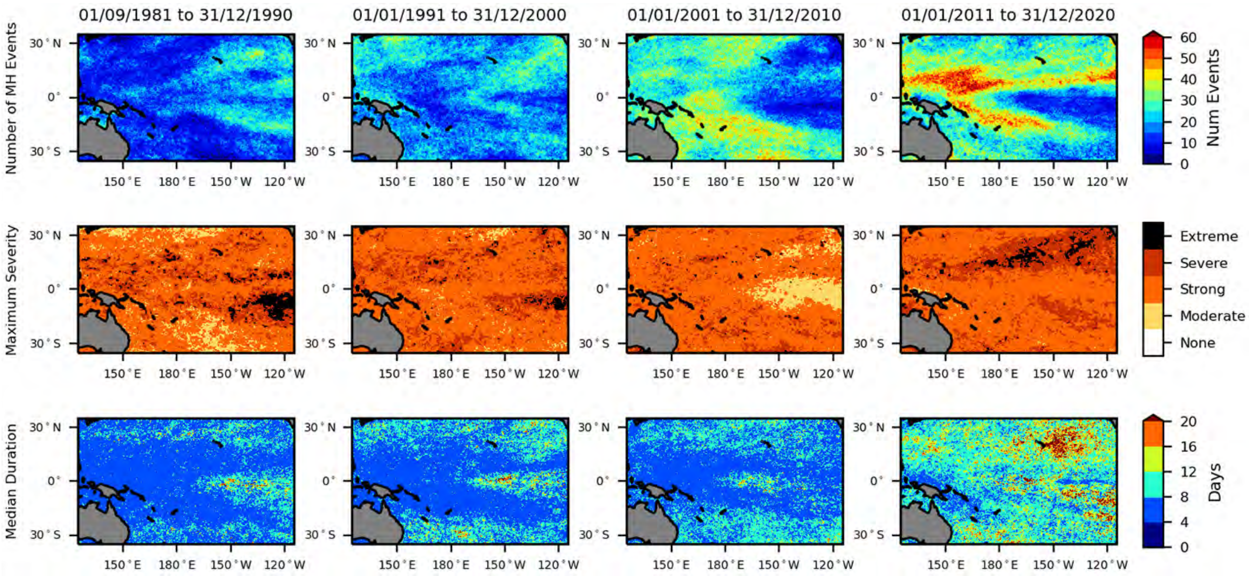


Figure 21. Marine Heat Wave Summaries. Daily NOAA OISSTv2.1 SST data[6] for 1981—2020 were used to calculate number of marine heat wave (MH) events (top row), maximum severity[9] (middle row) and median duration (bottom row). The climatology period was set from 1981—2010 for calculation of the 90th percentile threshold. Summaries are split into decadal periods from left to right: 1980s, 1990s, 2000s, 2010s.

processes. Ocean temperature is integrated over the upper 300 m of the ocean and then a linear fit is applied to the result from 1981–2018. The result (Figure 22) gives an indication of the trends in oceanic heat content (H300) during this period. Trends over this period are expected to be affected by both human-forced global warming and natural climate variability.

Trends in heat content over the 38-year period are largely positive in the Western Warm Pool region and in the northern and southern subtropics, indicating the ocean is absorbing and retaining more heat in these regions. Highest trends are found in western PNG, Solomon Islands, Nauru, and Tokelau. Slightly negative trends are found in the eastern Pacific just north and south of the equator.

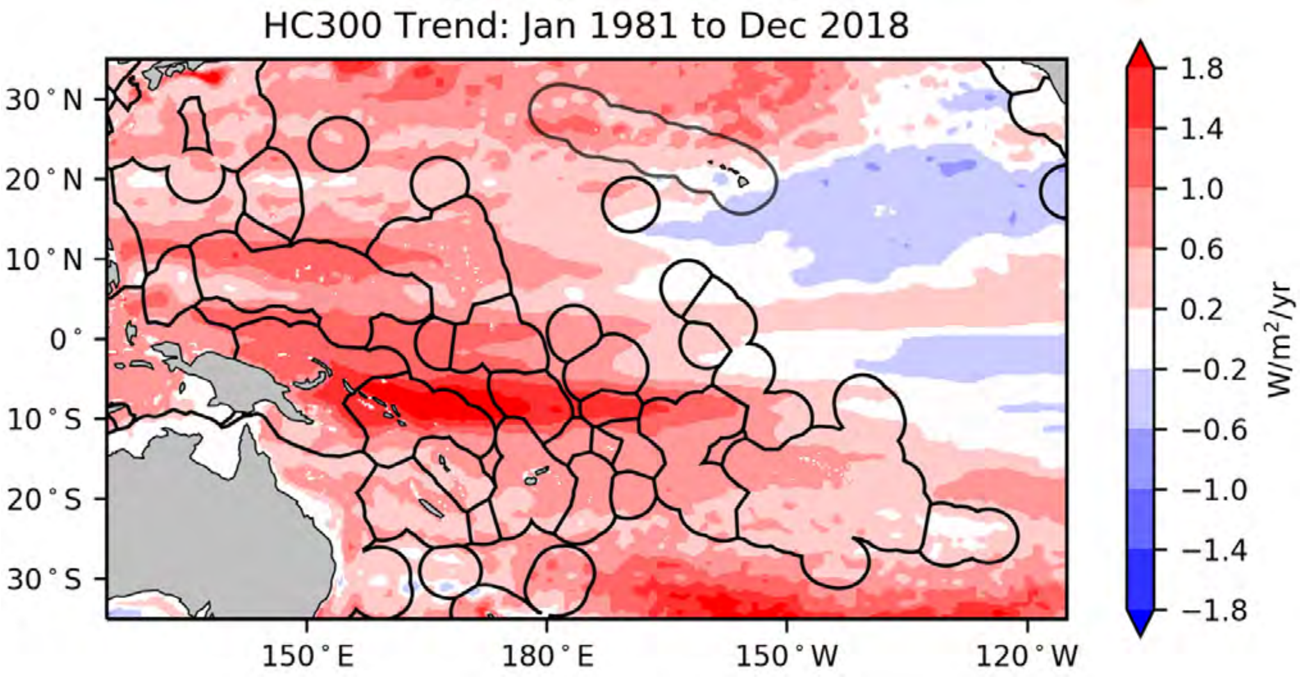


Figure 22. Heat content trends over the Pacific from January 1981 to December 2018 using monthly HC300 data from the ACCESS-S2 ocean reanalysis (Wedd et al. in prep.).

Biochemistry

Highlights

- Oceanic pH measurements collected from Station ALOHA, Hawai‘i, show a more than 12% increase in acidity over the period 1988–2020.
- Significant declines in surface ocean chlorophyll-a concentration and estimated phytoplankton size since 1998 are detectable across major portions of the Pacific Islands region.

Background

Measures of changing ocean biochemistry include changes in the pH of the ocean and phytoplankton abundance. Increased acidity (decreased pH) in the ocean results from absorption of atmospheric CO_2. Changes in chlorophyll-a concentration in the surface ocean (measured by satellites as ocean color) are used as a proxy for changes in phytoplankton abundance and biological production at the base of the ocean food chain. Ocean color observations can be combined with satellite-derived SSTs to estimate median phytoplankton size. Decreases in phytoplankton abundance and size have the potential to negatively impact ocean and coastal fisheries.

Indicator: Ocean Acidification

Ocean pH is an important indicator of the chemistry of the ocean. As the amount of CO2 in the atmosphere has risen, a substantial portion (as much as 26%) has been absorbed by the ocean. The result is that the ocean has become more acidic (that is, the ocean pH has decreased). Increasing ocean acidity can make it harder for corals and plankton to form calcium carbonate, the main mineral that makes up their hard skeletons and shells[1]. This adversely impacts coral reefs and shellfish, and threatens other marine ecosystems including pelagic fisheries.

Since October 1988, scientists working on the Hawai‘i Ocean Time-series (HOT) program have undertaken research cruises about once a month to observe the hydrography, chemistry, and biology of the water column at deep-water Station A Long-Term Oligotrophic Habitat Assessment (ALOHA) located 100 km north of Oahu, Hawai‘i[2]. Among other measurements, two measures of pH are made: directly measured pH and pH calculated from total alkalinity (TA) and dissolved inorganic carbon (DIC). The 30+ year time series at Station ALOHA represents the best available documentation of the downward trend in oceanic pH since data collection began in 1988 (Figure 23). During the period 1988 to 2020, oceanic pH has shown a linear decrease of 0.051 pH units. This corresponds to an increase of more than 12% increase in acidity over that time span[3]. Oceanic pH also exhibits short-term fluctuations of roughly 0.025 pH units up and down. The steady decline in pH, however, means that current high pH fluctuations represent conditions that were considered average or low pH at the beginning of the time series. Although oceanic pH varies over both time and space, the conditions at Station ALOHA are considered broadly representative of those across the western and central Pacific.

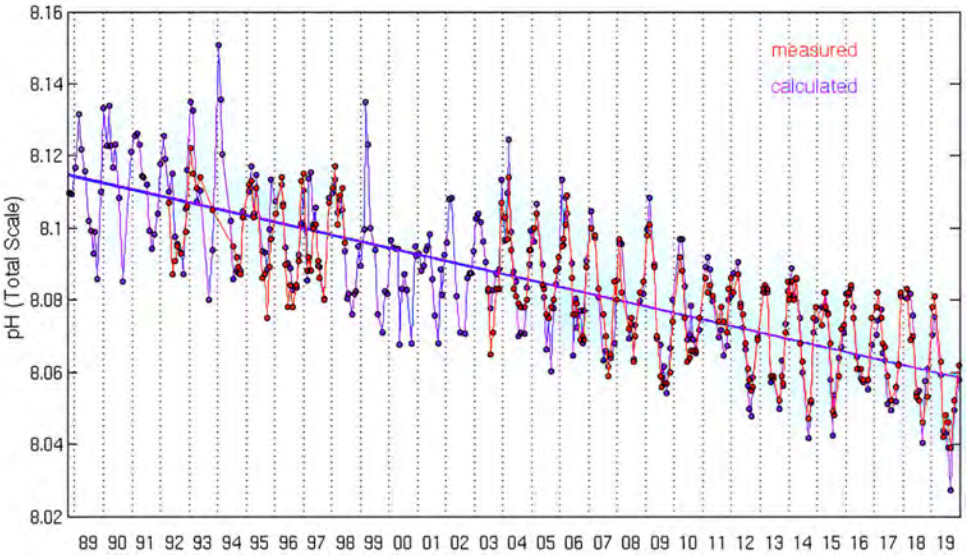
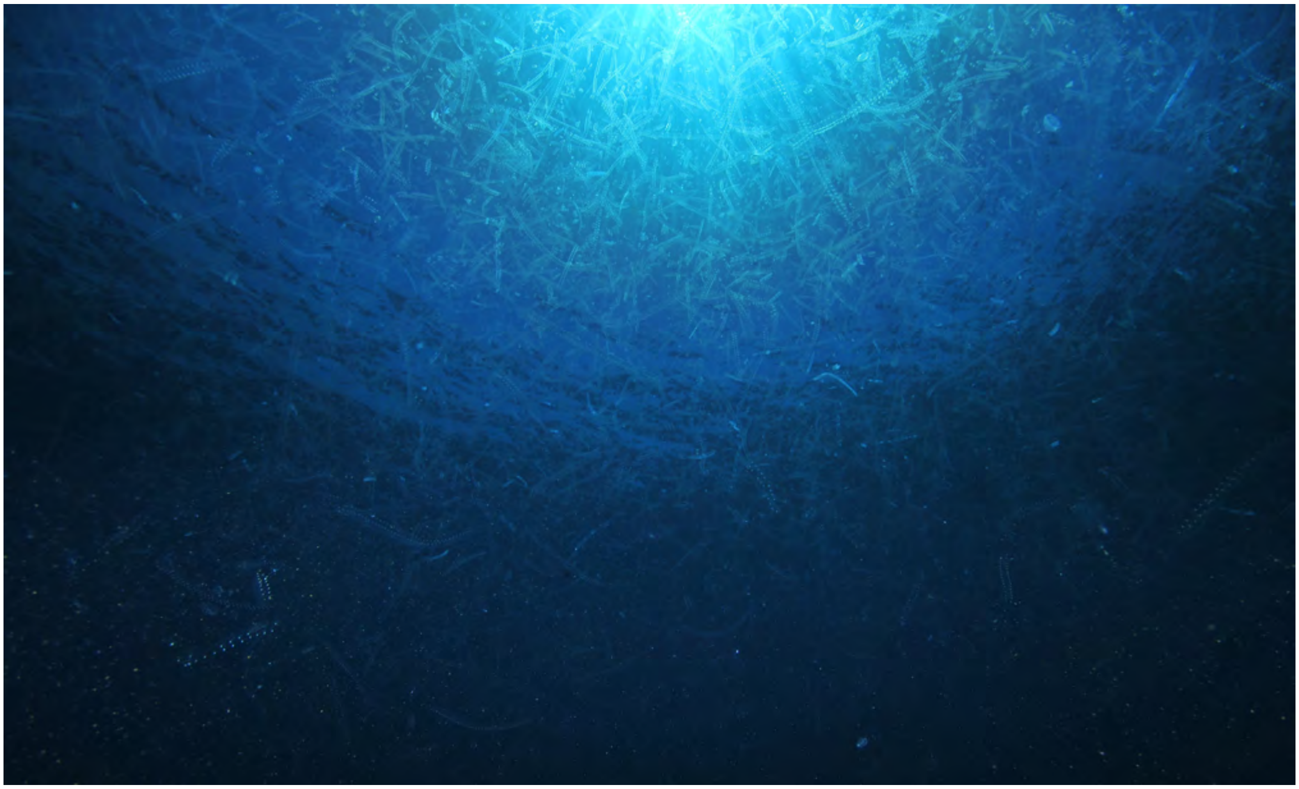


Figure 23. Measured and calculated trends in surface (0—10 m) pH at Station ALOHA, collected by the Hawai‘i Ocean Time-series (HOT). The red lines and circles represent directly measured pH from 5 m depth. The thin blue lines and circles represent pH calculated from total alkalinity (TA) and dissolved inorganic carbon (DIC). The linear fit to calculated pH is shown in thick blue line. Lower pH indicates higher acidity[4].



Dense ocean plankton near sea surface during early summer bloom. ©Adobe Stock/Dennis Poloha.

Indicator: Chlorophyll Concentration

Phytoplankton are the foundation of the marine food web. Their abundance affects food availability for all marine organisms, ranging from zooplankton to apex predators. Chlorophyll concentration is used as a proxy for phytoplankton abundance. Some climate change projections suggest a shift towards lower phytoplankton abundances, particularly in the ocean's oligotrophic gyres. Chlorophyll concentration (and phytoplankton abundance) varies greatly across the Pacific basin, with higher concentrations generally found at higher latitudes and particularly around coastlines. Chlorophyll concentrations also vary in response to natural climate variability.

Chlorophyll-a concentration is estimated from satellite remotely sensed observations of ocean color, which extend back to 1998. The basin-wide average (1998–2020) is shown below in Figure 24. Statistically significant ($p < 0.05$) declines in chlorophyll-a concentration are detectable in the North Pacific Subtropical Gyre (0.008 mg chl m-3) and the area of Equatorial Upwelling (0.025 mg chl m-3). No statistically significant trends are detected in the Western Equatorial Pacific or the South Pacific Subtropical Gyre.

Indicator: Estimated Phytoplankton Size

Phytoplankton size provides insight into ecosystem productivity with larger phytoplankton generally supporting more productive ecosystems with larger fish. Some climate change projections suggest a shift towards smaller phytoplankton, particularly in the ocean's oligotrophic gyres, potentially reducing food available to all trophic levels. Phytoplankton size varies greatly across the Pacific basin, with larger phytoplankton generally found at higher latitudes and closer to coastlines. Phytoplankton size also varies with natural climate cycles, such as ENSO, with larger phytoplankton more prevalent across the equatorial Pacific during cooler La Niña periods and vice versa during El Niño.

Estimated median phytoplankton size can be derived from satellite remotely sensed sea surface temperature and chlorophyll-a concentration (1998–2020). The regional satellite trends reflect changes in the estimated median phytoplankton size (Figure 25). Statistically significant ($p < 0.05$) declines in phytoplankton size are detectable in the North Pacific Subtropical Gyre (0.07μm); the area of Equatorial Upwelling (0.10 μm); and the Western Equatorial Pacific (0.04 μm). No statistically significant trend is detected in the South Pacific Subtropical Gyre.

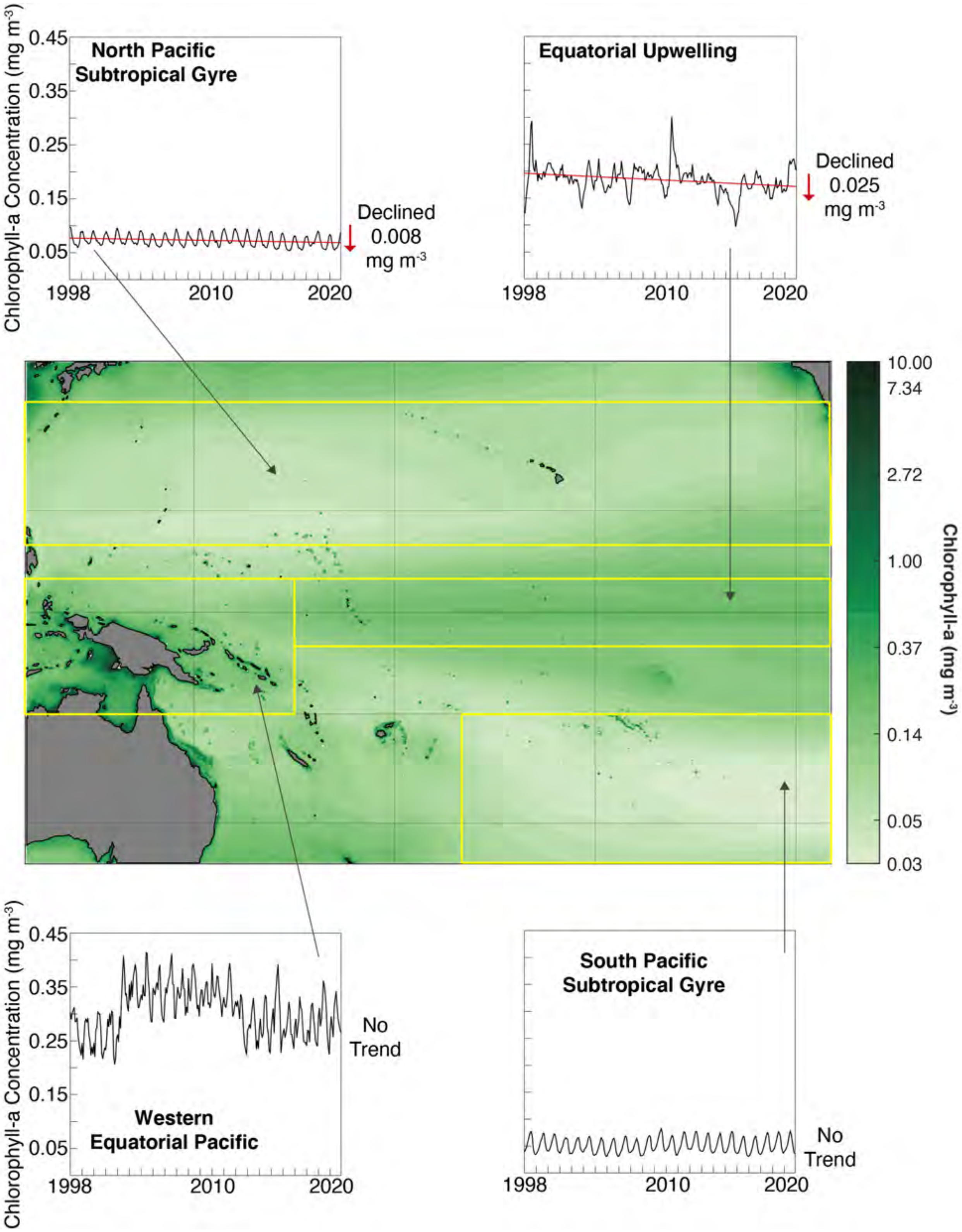


Figure 24. Time series of monthly estimated chlorophyll-a concentration (mg m^{-3}) as derived from satellite remotely sensed ocean color data. Statistically significant ($p < 0.05$) declines in chlorophyll-a concentration are detectable in two regions (red trend lines/arrows). Regional boundaries are as follows: North Pacific Subtropical Gyre: 10—30°N, 125°E—115°W; Equatorial Upwelling: 5°S—5°N, 165°E—115°W; Western Equatorial Pacific: 15°S—15°N, 125—165°E; and South Pacific Subtropical Gyre: 35°—15°S, 170—115°W.

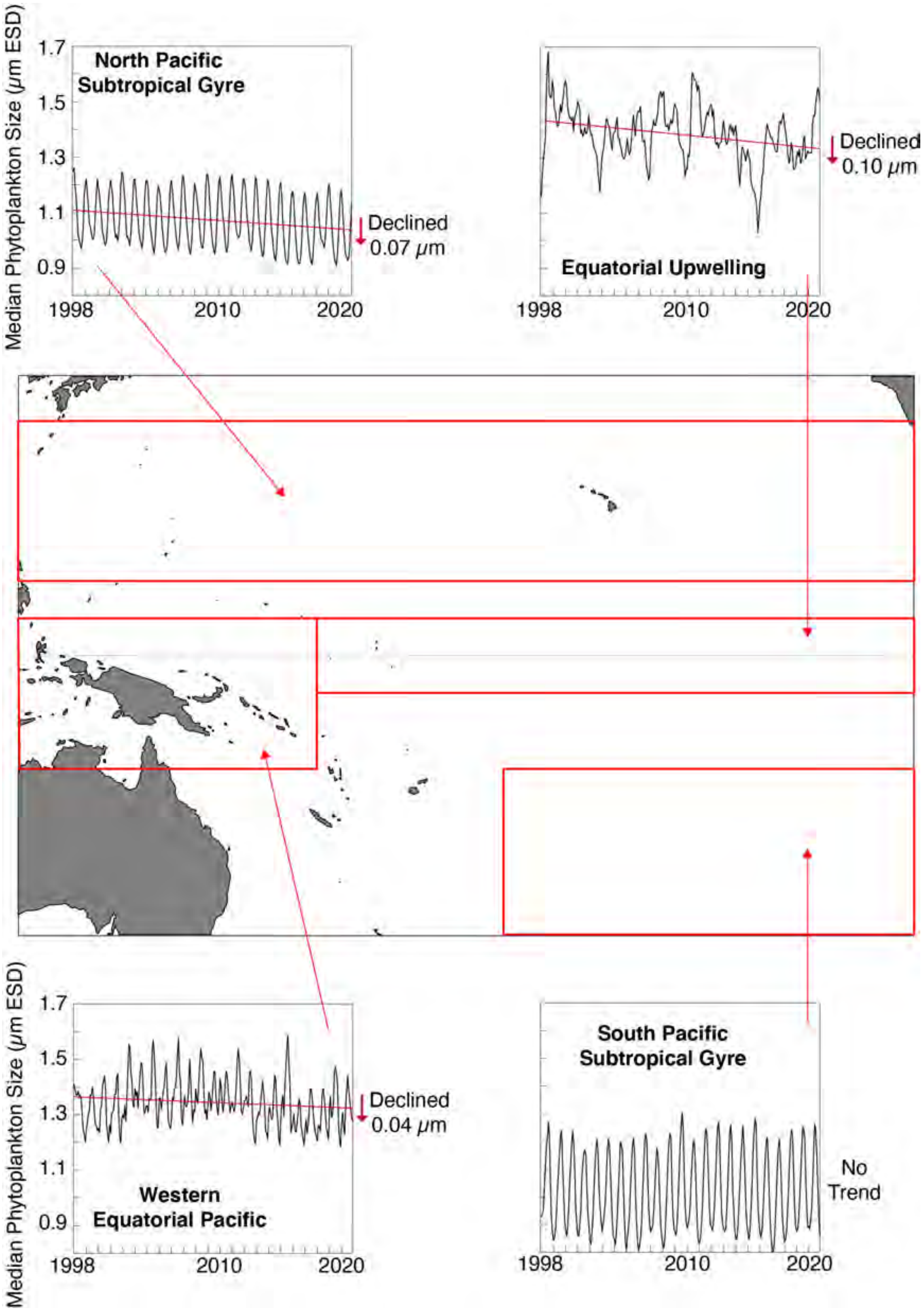


Figure 25. Time series of monthly estimated median phytoplankton size (in μm equivalent spherical diameter, ESD) as derived from satellite remotely sensed sea surface temperature and ocean color data[5]. Significant ($p < 0.05$) declines in phytoplankton size are detectable in three regions (red trend lines/arrows). Regional boundaries are as follows: North Pacific Subtropical Gyre: 10—30°N, 125E—115°W; Equatorial Upwelling: 5°S—5°N, 165°E—115°W; Western Equatorial Pacific: 15°S—15°N, 125—165°E; and South Pacific Subtropical Gyre: 35°—15°S, 170—115°W.

Future Climate

Suggested Citation:
Grose, M., Chand, S., Hernaman, V., Webb, L. (2022). *Future Climate*. In: Marra et al. (Eds.), Pacific Climate Change Monitor: 2021. The Pacific Islands-Regional Climate Centre (PI-RCC) Network Report to the Pacific Islands Climate Service (PICS) Panel and Pacific Meteorological Council (PMC). DOI: 10.5281/zenodo.6965143

Marshall Islands aerial
© Adobe Stock/Clayton

Highlights

- **Greenhouse gas concentrations** will increase but beyond the near-term the concentration depends strongly on the net greenhouse gas emissions associated with the global pathway of human development
- **Surface air temperature** will continue to rise proportional to the emission pathway, with more heat extremes affecting human health, agriculture, and ecosystems.
- **Rainfall** projections vary by region, according to the local dominant rainfall feature. A strong increase in rainfall is projected at the equator. An increase in frequency and intensity of heavy precipitation events is projected almost everywhere.
- **Tropical cyclones** are projected to have greater impact with higher rainfall rates making landfall on top of a higher sea level, as well as a greater proportion of tropical cyclones in the more intense categories and higher peak wind intensities.
- **Sea level** will continue to rise for centuries but the rise would be significantly lower and slower under low emissions pathways compared to higher ones.
- **Ocean temperature** will continue to increase, with more marine heat waves, proportional to global emissions.
- **Ocean acidification** will continue proportional to the atmospheric CO_2 concentration; oceans are projected to have reduced oxygen.

Background

Regional climate projections are generally similar for the different generations of climate models (e.g., Coupled Model Intercomparison Project Phase 5 [CMIP5] and CMIP6) and between the two recent sets of global emissions pathways (Representative Concentration Pathway [RCP] and Shared Socioeconomic Pathway [SSP]), especially when standardized to a common comparison such as a particular level of global warming (e.g., 2°C Global Warming Level). Confidence in projected change is assessed using multiple lines of evidence (process understanding, consistency between modelled and observed trends, degree of agreement among climate models) and is higher when there is agreement between those lines of evidence[1]. An impediment to confidence in some climate projections in the Pacific is the long-standing climate model biases in the simulation of important processes and patterns of mean climate and climate variability in the Pacific. Important context for interpreting climate projections include the following.

- Global surface temperature will continue to rise, and regional climate will continue to change until at least mid-century under any plausible emissions pathway the world follows. If the world reaches net zero emissions and limits further global warming some changes would stabilize such as global average temperature, but others will continue for centuries such as sea level rise.
- Natural climate drivers and internal climate variability in the Pacific include that from the ENSO and year-to-year movement of the dominant SPCZ and ITCZ. Climate variability means that there is a range of possibilities for any particular year and short-term trends (e.g., 2021–2030) may go against the long-term (multi-decadal) projected trend due to climate change.
- “Low-likelihood, high-impact outcomes” must be considered possible in terms of future climate change impacts and risks, even if we are unable to quantify their likelihood. These include the collapse of global ice sheets leading to much more rapid sea level rise, some compound extreme events, and very high warming scenarios.

Greenhouse Gas Concentrations

Future concentrations of greenhouse gases are predominantly dependent on human choices, so are explored using a scenario approach. The current international standard are the SSPs[2] (see Appendix for detailed description). Each scenario, or pathway, has a different mix of gas concentrations and different series through time and result in different levels of enhanced greenhouse effect by 2100. Figure 26 shows CO2 concentration, which is a major greenhouse gas.

Surface Air Temperature

Average air and sea temperature is projected to rise for the near term regardless of the SSP. Beyond near term, warming is proportional to the emissions pathway the world follows, from stabilization near 1.5 °C global warming since pre-industrial, through to accelerating increase (Figure 27)[3].

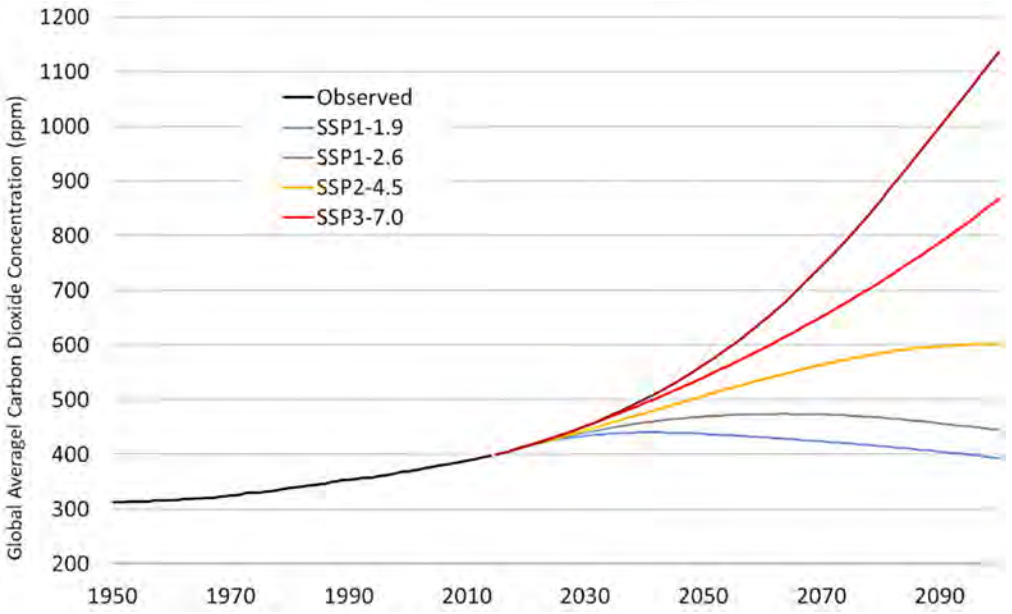
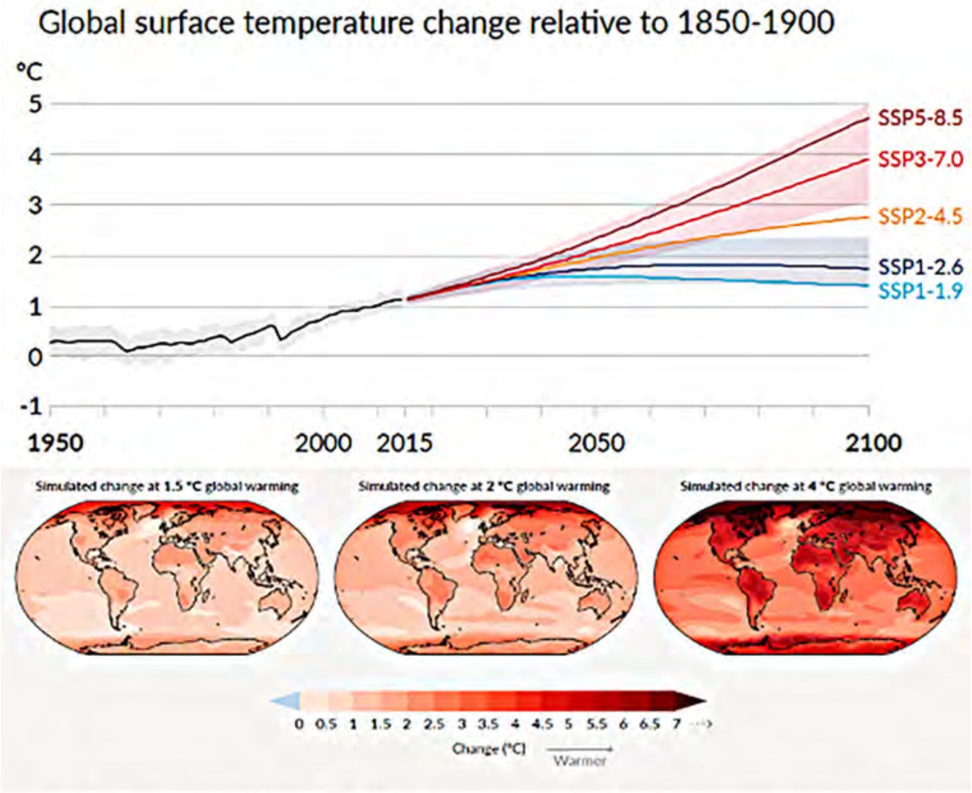


Figure 26. Observed and projected global average CO_2 concentration from the SSPs (note the SSPs also describe future changes in other greenhouse gases such as CH_4, NO_2, and halocarbons, as well as aerosols and land use).



Global warming relative to 1850-1900	Pacific Nations warming relative to 1850-1900	Pacific nations warming relative to 1986-2005
1.5 °C	Around 1.1 °C	Around 0.7 °C
2 °C	Around 1.6 °C	Around 1.0 °C
3 °C	Around 2.4 °C	Around 1.8 °C

Figure 27. Projected surface temperature change relative to 1850—1900 from the CMIP6 set of global climate models reported in the IPCC Sixth Assessment Report[3], the multi-model-mean spatial distribution of temperature change at three global warming levels (1.5, 2 and 4 °C). The table shows the central estimate of warming at these global warming levels averaged over national EEZs[4].

Regional change depends largely on the SSP, but the magnitude of warming also depends on the location on the globe. Projected warming in the Pacific region is less than the global average and much less than the Arctic and large continents. For example, if we plateau at 2 °C global warming, this means likely warming around 1.5–1.7 °C (approximately 3°F) since 1850–1900 in most Pacific nations estimated over national EEZs (including land and ocean, see Introduction Figure 1)[3,4]. Warming is typically greater over land than the ocean, therefore, warming over individual locations over land is likely to be greater and more in line with the global average than for the national EEZ.

A warmer climate means an increased frequency and intensity of extreme temperature events throughout the Pacific, and reduction in cold extremes including cool nights[5]. A warmer climate generally also means higher evaporation and transpiration. In more arid places this amplifies the drying and leads to greater aridity and for places that are wetter, the increase is offset in terms of total available water. Higher temperatures and increases in evapotranspiration both add to the impact of dry periods and droughts when they occur.

Rainfall

A persistent shift in the average rainfall is possible in many places, with greater change possible under higher emissions pathways or at higher warming levels, noting all trends appear amid very high natural variability (Figure 28)[4,6,7]. Projected rainfall changes depend largely on the dominant rainfall feature (e.g., ITCZ, SPCZ) in each subregion[4,8-14]. A substantial rainfall increase is projected along the equator linked to enhanced equatorial warming, however, the direction of change in the dominant rainfall feature and associated rainfall is less certain in most regions outside the equator. Therefore, a range of possibilities should be considered, including “storylines” approaches15 (Figure 28).

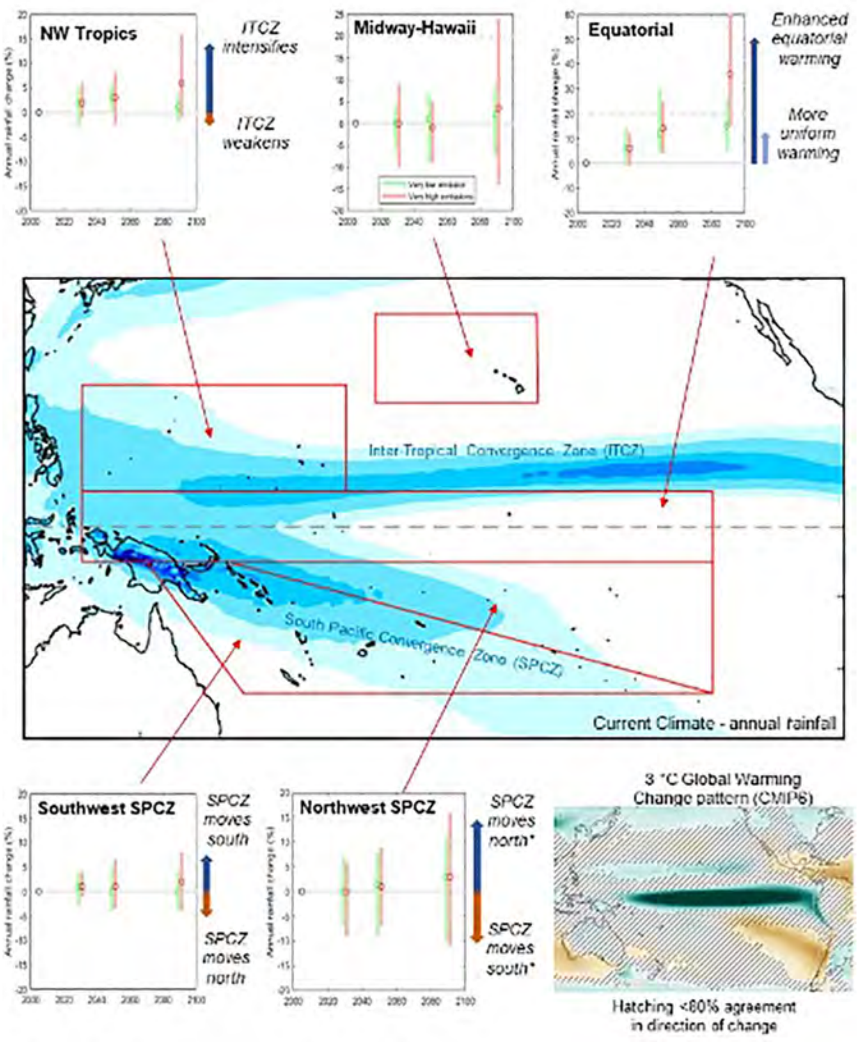


Figure 28. Range of change (%) in 2030, 2050 and 2090 relative to 1995—2014 from CMIP6 models for a low pathway (SSP1-2.6; green) and a very high pathway (SSP5-8.5; orange) Bars and markers show the 10—90% range and median of models. The central map shows the current annual rainfall (darker blue denotes higher rainfall). The map of change in the warming pattern shows model mean projection for 3 °C global warming since pre-industrial with wetter (green), drier (brown), and areas with hatching showing < 80% agreement in the direction of change. Selected storylines of changes in the dominant driver and rainfall noted next to each plot (note in the Northwest SPCZ region, the movement of the SPCZ is important but other processes also play a role). Source: Projections from IPCC Interactive Atlas[7], current rainfall from ERA5[16], storylines from NextGen Projections updated country reports[4].

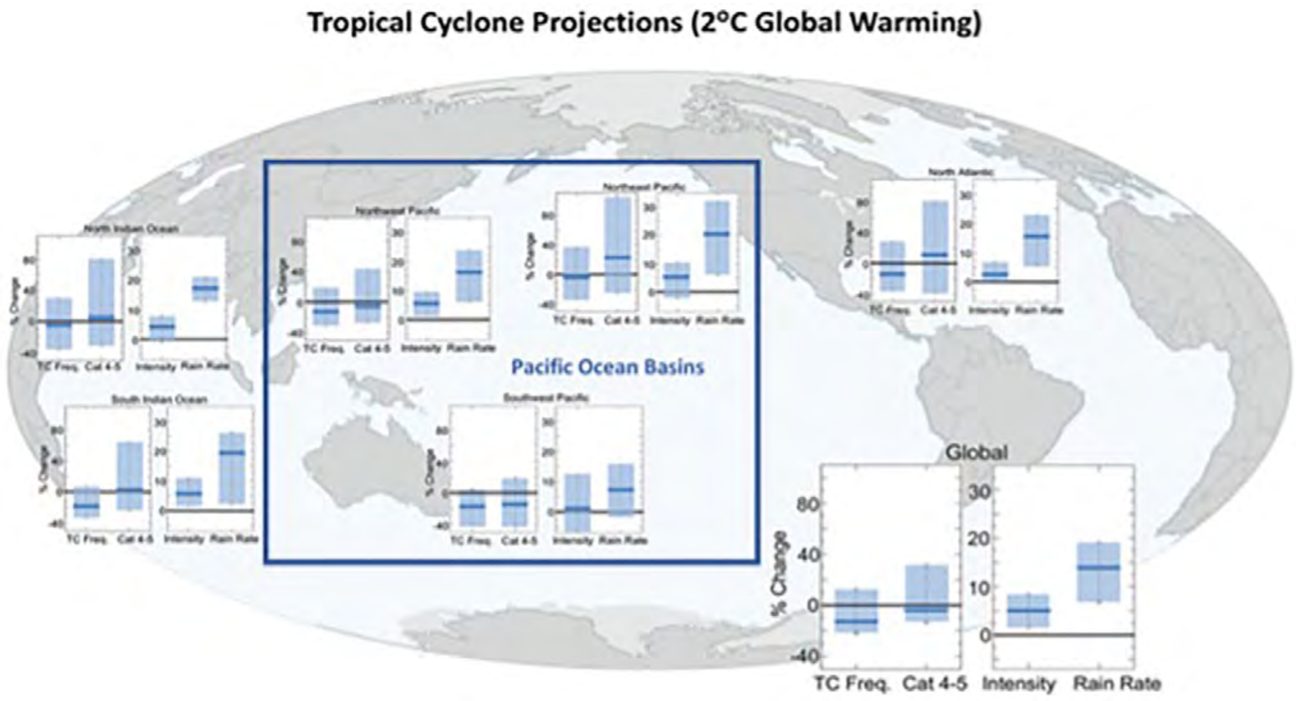


Figure 29: TC activity projection for a 2°C global warming (Pacific Ocean basins are highlighted). For each basin, the bars on the left indicate a likely change in the total number of TCs and severe (category 4—5) TCs, and bars on the right indicate likely changes in the average intensity of TCs and associated rainfall. Shown are the median (blue line) and the 10th—90th-percentile ranges (blue bars). Source: Knutson et al. 2020[17]; see NextGen Tropical Cyclone report[4] for more.

Warmer climate conditions result in an increase in hourly to daily intense rainfalls[5]. This includes heavy rainfall that leads to pluvial (rainfall-based) flooding which, in turn, includes both flash floods and urban floods. This is projected to occur even in places where the average rainfall doesn't increase. Maximum 1-day precipitation is projected to increase almost everywhere, by a minimum of 5–7% per degree of warming. However, in some cases it may increase by much more due to other processes, including changes to the dynamics of tropical cyclones. As well as pluvial floods, increases in extreme rainfall can drive an increase in fluvial (river) floods for some locations.

Tropical Cyclones

The overall effect of tropical cyclones is expected to increase with further warming through:

- Increase in peak wind intensity;
- A greater proportion of tropical cyclones in the intense categories (Cat 3-5)—the net result of a reduced number of total tropical cyclones in the south and an increase in the north (Figure 29);
- Higher rain rates due to warmer sea and air temperatures; and
- Making landfall on a higher sea level.

Sea Level

The global average sea level is projected to continue to rise this century under any emissions pathway, but less under lower greenhouse gas pathways (a *likely* range 0.28–0.55 m [0.9–1.8 feet] by 2090 under the very low SSP1-1.9) and more under higher pathways (likely range 0.63–1.01 m [2.0–3.3 feet] under SSP5-8.5)[5,6]. Due to deep uncertainty in ice sheet processes, a rise above this *likely* range can't be ruled out: approaching 2 m (6.6 feet) by 2100 under the very high SSP5-8.5[3]. Sea level is not expected to plateau in this century, even if emissions stabilize, and further sea level rise is projected for hundreds of years in the future.

Due to regional influences, sea level is projected to rise slightly faster in the Pacific than the global average, but lower than some areas of the world (Figure 30). Locally, vertical land subsidence could also lead to higher observed sea level rise.

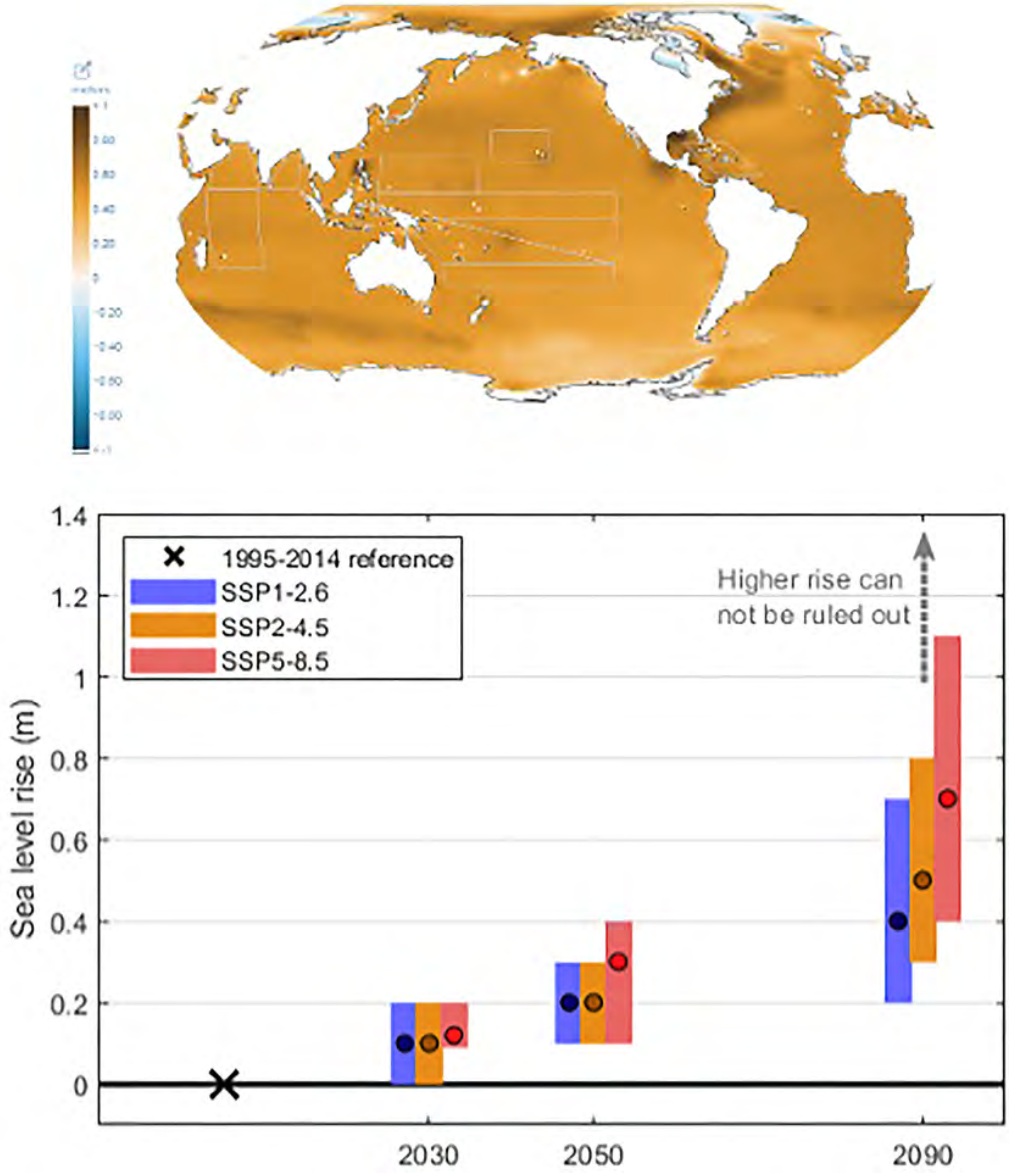


Figure 30. Projected sea level rise. The map shows the global spatial pattern of projected sea level rise under a medium emissions pathway (SSP2-4.5) by the end of the 21st Century (2080—2099 relative to 1995—2014). The bars show the range of *likely* sea level rise averaged over the Pacific Small Islands regions as marked on the map for three SSPs (bars show the 5—95% range and median). Source: IPCC Interactive Atlas[6].

The total water level during extreme sea level events is a function of the mean sea level, but also seasonal or interannual variability such as the ENSO, tides, storm surge, wave setup, and wave runup. A significant increase in extreme sea level events in the Pacific is projected, primarily as a function of the mean sea level. There may be changes in storm strength and waves that offset or enhance the effect of rising sea levels.

Ocean Temperature

Sea surface temperature is projected to increase in the Pacific, with a similar dependence to SSPs as for air temperature. Higher sea temperature on average means more marine heat waves (see above). A recent analysis of the western and central Pacific[18] indicated that under a low emissions pathway (SSP2.6), marine heat waves in the lowest intensity category of "Moderate" are projected to increase from recent historical (1995–2014) values of 10–50 days per year (dpy) to >100 dpy by 2050, with >200 dpy nearer the equator (Figure 31). This increases by about 100 dpy under the high emissions pathway (SSP8.5): 200 dpy of Moderate MHW intensities are projected across most of the region by 2050, with >300 dpy nearer the equator. Furthermore, marine heat waves in the "Severe" intensity category are much more frequent under the high emissions pathway (Figure 31).

Ocean Chemistry

Observed changes to ocean chemistry in the Pacific are projected to continue during the 21st century (Figure 32), with projected decreases of 0.3 pH in much of the Pacific under a high emissions pathway and widespread decreases in oxygen concentration except for along the equator (Figure 32, modified from Frölicher et al. [2016][19]). Much smaller decreases are projected under a low emissions pathway (Figure 32).

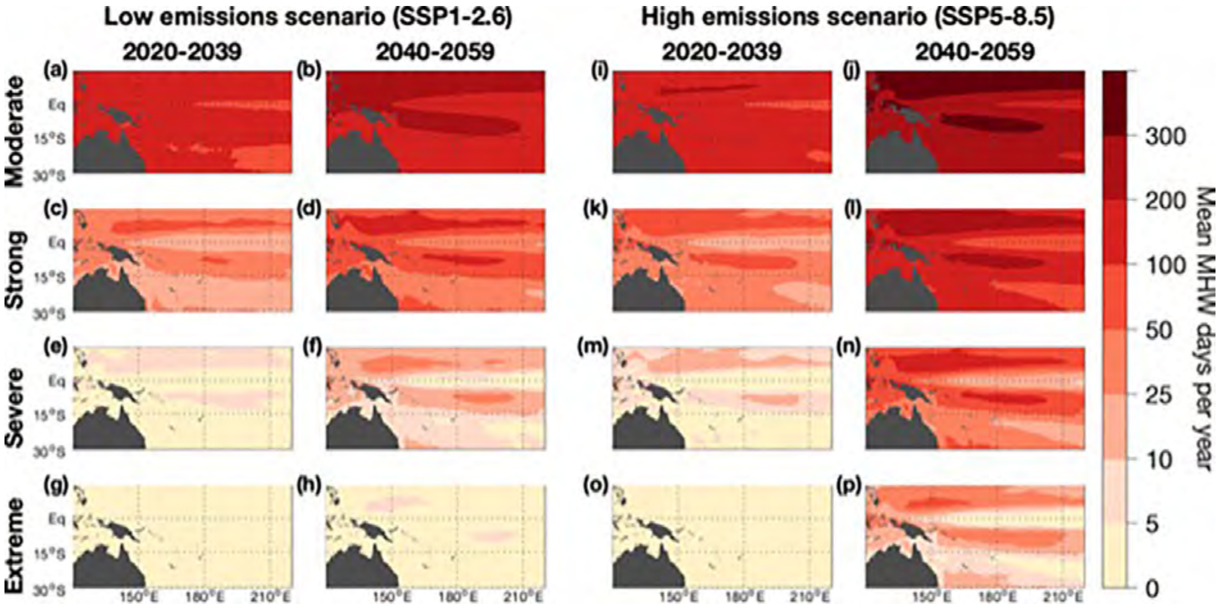
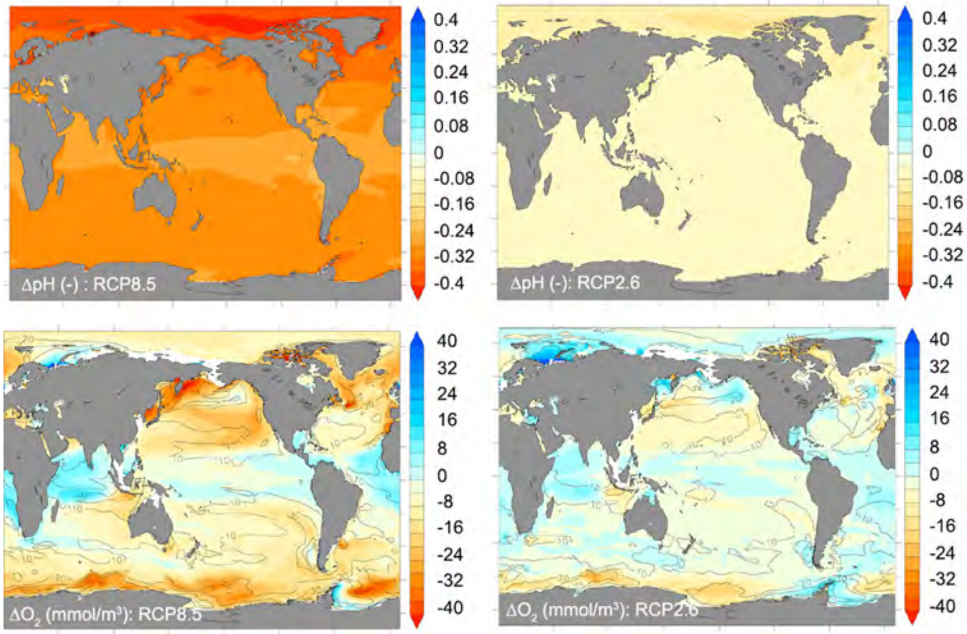


Figure 31. Projected increase in the mean number of marine heat wave days per year. For each of four intensity categories (Moderate, Strong, Severe, and Extreme) by 2030 and 2050 under low (SSP1-2.6; left panels) and high (SSP5-8.5; right panels) emissions pathways relative to a baseline of 1995—2014. Source: Holbrook et al. (2022)[18].

Figure 32. Projected multimodel mean change in surface ocean pH (top row) and oxygen concentration (bottom row; averaged over 100—600 m depth), under a high (RCP8.5; left column) and low (RCP2.6; right column) emissions pathway by the year 2085 (2076—2095) relative to a baseline of 1985—2004. Source: modified from Frölicher et al. (2016)[19].



Observed and Expected Impacts on Key Sectors

Suggested Citation:

Keener, V.W.+, Warrick, O.+ Brewington, L., Grecni, Z. (2022). Observed and Expected Impacts on Key Sectors. In: Marra et al. (Eds.), Pacific Climate Change Monitor: 2021. The Pacific Islands-Regional Climate Centre Network (PI-RCC) Report to the Pacific Islands Climate Service (PICS) Panel and Pacific Meteorological Council (PMC). DOI: 10.5281/zenodo.6965143

+ indicates equal first-authorship

School of bigeye trevally © Adobe Stock/divedog

Highlights

- Agriculture and Food Security—Increasing air temperature will have negative impacts to agroforestry and crops, and increased invasive species, pests, and diseases. Increasing sea level will lead to increasing saltwater intrusion/thinning freshwater lens impacts impacting local food production and security
- Disaster Risk Management—Increasing TC intensity will result in more extreme rainfall and flooding, coastal erosion, wave inundation, freshwater contamination, and risks to human safety. Increasing air temperature will cause more frequent extreme heat events-related illness in vulnerable populations.
- Energy—Increasing air temperatures will lead to increasing demand. Increasing storm intensity and rising sea levels will result in increased impacts to electric infrastructure.
- Health—Increases in air temperature, storm intensity, and rising sea levels will lead to increased incidence of heat-related illness and vector-borne disease, and threats to physical safety. This will contribute to increases in mental health-related illness.
- Water—Decreasing rainfall, in some areas, will reduce the quantity of freshwater resources. Increasing sea level will lead to increasing saltwater intrusion/thinning freshwater and reduction in water quality. Increases in heavy rainfall leading to increased land-based pollution in ground and surface waters will all adversely affect water quality. Increasing severity of storms and rising sea levels will adversely affect water and wastewater infrastructure.
- Fisheries and Aquaculture—Increasing surface and sea surface temperatures, increasing acidification, and decreasing chlorophyll concentration will lead to reduced commercial and subsistence catch due to shifting fisheries, reduced fish size, and degraded coral reefs.
- Tourism—Increasing storm intensity and rising sea levels will result in increased land-based pollution and beach erosion. In addition, changes in ocean conditions will result in degraded coral reefs and open-ocean fishing habitat, which will adversely impact tourism and recreation-based activities.

Photo Credit: Christopher Shuler, UHM WRRC

Background

The SPREP Pacific Roadmap for Strengthened Climate Services (SPREP, 2019) details the seven most relevant key sectors to guide climate services development in the island nation states and territories of the Pacific. The Roadmap was developed from the World Meteorological Organization's Global Framework for Climate Services (WMO GFCS) and is aligned with the Pacific Islands Meteorological Strategy (PIMS) from 2017–2026, which focuses on improving climate services across the region. For regional alignment, this report focuses on broad current and future climate impacts in these seven key sectors as informed by the climate indicators sections of the Pacific Climate Change Monitor. While many climate impacts cross multiple sectors and different Pacific Islands, this section identifies broad trends and risks across the region.

Agriculture and Food Security

Increasing average air temperature, nighttime temperatures, and evapotranspiration, will negatively impact production of staple food crops, export commodities, and agroforestry across the region[1-5]. For example, sugar yield in Fiji could decline by 2–14% under end-of-century scenarios ranging from 0.5 to 1.5°C baseline conditions in 1995[6]. Livestock—an important protein source in Pacific islands—is particularly vulnerable to heat stress[1].

As sea level rise and wave overwash increase saltwater intrusion into aquifers on islands, some areas are experiencing increased soil salinity with negative impacts on local food production and food security[7,8,9].

Photo Credit: Alexis Wolfgramm from Ministry of Marine Resources, Cook Islands.

In 2015, Category 5 TC Pam caused losses and damages to the agricultural sector in Vanuatu valued at 64.1% of GDP[10]. A greater proportion of severe TCs will repeatedly damage agricultural productivity in Pacific islands with flow-on effects for food and nutritional security, and increased reliance on imported food[11].

Climate change will directly affect the spread and degree of infestation of insect pests on agriculture across the region. Important regional pests including nematodes, leaf miners, and weevils, have all been shown to spread under higher temperatures or drought conditions[2].

Cultural food security is threatened as climate change affects the provision of subsistence foods and foods that enable Indigenous peoples to sustain the connection with cultural and social practices and traditions[2,5,12].

Disaster Risk Management

Future increases in the proportion of intense tropical cyclones throughout the Pacific islands' region will exacerbate impacts currently experienced including: riverine flooding, coastal inundation and erosion (compounded in places by higher sea levels and degradation of coral reefs), and wind damage to housing and infrastructure[7,13-19]. Some Pacific atoll islands are likely to experience storm-related wave overwash over their entire surface annually by 2060–2070 under a high emissions scenario (RCP 8.5), which may significantly reduce habitability due to repeated contamination of freshwater resources and damage to infrastructure[7].

Increasing exposure of Pacific populations to climate change-related coastal hazards is compounded by high-density population concentration on the coast and human modification of coastal environments[16,20,21]. In Kiribati, the Marshall Islands, and Tuvalu more than 95% of infrastructure is located in the low elevation coastal zone[21, 22]. In 2015, flooding in Tuvalu and Kiribati triggered by distant severe TC Pam affected or destroyed up to 98% of households in some islands, inundating entire settlements and causing severe coastal erosion in some locations[15,23]. In the absence of substantial adaptation measures, monetary investment, and sustainable urban planning, damage to housing and infrastructure is likely to increase from severe-category TCs, extreme rainfall events, and SLR[21,24].

Where more frequent and/or intense climate extremes are expected, economic and humanitarian risk increases[25]. In Fiji, where there is a trend towards heavier rainfall events, a high intensity rainfall event in 2012 led to severe flooding in the Western Division of Viti Levu, which displaced thousands and caused damage estimated at FJD$70 million[26]. In 2016, severe TC Winston caused losses in Fiji equivalent to more than 20% of GDP[27]. In Hawai'i where a drying trend is present, the 2007–2014 drought cost an estimated US $44.5 million in lost production from ranching[28]. In addition, investment in economic development declines after severe weather events as resources are diverted to clean up and recovery.

Impacts and risks from multiple climate change-related extremes are worse for the most vulnerable. Informal settlements are highly vulnerable to riverine and coastal flooding, storm surge, and TCs due to high exposure and difficulties in enforcing building regulations[29,30]. Women and people with special needs are frequently disproportionately affected, for example, because they have less ability to access economic alternatives[13].

Energy

Demand for electricity to run air conditioning has increased significantly over the last 65 years at a regional scale[31]. Trends towards more extreme temperatures suggests that this demand for electricity will continue to increase. Energy is used to pump and distribute freshwater. An increase in hot days will increase the need for water, as well as evaporative loss, resulting in increased energy use to supply water demand[32].

Energy infrastructure is exposed to increased damages from more intense and/or frequent extremes such as TCs, high winds, riverine flooding, storm surge, and coastal inundation. Most Pacific countries have a high reliance on imported fuel and are therefore highly vulnerable to supply chain interruptions caused by climate extremes such as storms and floods. Additionally, this reliance comes at a very high cost to energy users, contributing to vulnerability of populations that have typically high rates of poverty[33].

Health

Direct human health impacts from climate change in Pacific Islands include threats to human safety from more intense or frequent extreme weather events such as TCs or drought and increased heat-related illness[34]. Increasing coastal storm intensity for example, threatens physical safety via flooding and landslide events[35]. Additionally, infrastructure such as healthcare facilities and schools on the coasts or in low-lying areas will be increasingly affected and need repairs and updates to building and energy codes[9]. When extreme events overlap with King Tides and disease outbreaks, the health sector response will be disrupted.

Indirect impacts on health include increased risk of vector-borne and water borne disease (e.g., dengue, filariasis, or leptospirosis) incidence in almost all Pacific Island countries and increased food and water insecurity from altered rainfall patterns, flood, and drought[34,36]. High temperatures are observed to increase the risk of hospitalizations for cardiovascular, renal and respiratory disorders. Non-communicable diseases are already a leading cause of death in many Pacific Islands[37,38]. Climate change challenges prevention and management of non-communicable disease because hot weather can make it unsafe to exercise and compromised local food systems may result in greater reliance on less nutritious, imported foods. Increasing extreme events, displacement, and migration from climate change will also pose mental health risks to impacted populations[39].

Frontline communities will experience disparities in health, climate exposure, and risks depending on varying and compounding factors (e.g., urban vs. rural areas, low-lying areas, socioeconomic status, age, disability, minority and class status, property-ownership). Children, the elderly, and those with chronic disabilities are at greater risk for heat illness, including dehydration, heat stress, fever, and respiratory problems. As the frequency and intensity of hot days increases across the region, these populations will be disproportionately impacted[9,34,40-43].

Climate impacts on subsistence food systems may lead to an increased dependence on imported foods that have less nutritional value, already a public health stressor for Pacific Islands contending with high rates of non-communicable diseases, including diabetes[44].

Water

Freshwater quality and quantity will be impacted by increasing air temperature and evaporation, changing seasonal rainfall patterns, increasing intensity of storms, sea level rise, and the ways in which these trends overlap with climate and non-climate disasters.

Access to freshwater can be a problem on islands with limited land storage. Local and regional drought are strongly correlated with El Niño events in the western Pacific and La Niña in the central equatorial Pacific and islands. Increases in the strength of El Niño and La Niña events have been observed, and some of their impacts are projected to increase[45,46]. Communities may need to rely on mobile desalination systems more often[5,47]. Uncertainty associated with future rainfall will make it more challenging to successfully manage surface water for both ecological as well as social uses[48].

As sea level continues to rise, groundwater aquifers will be threatened by both increased wave overwash events and a narrowing freshwater transition lens, decreasing freshwater security. These impacts are being experienced across the region, but are more severe on atolls[7,32].

Extreme rainfall events have become more common across the region, causing increased runoff, erosion, flooding, brown water events, and decreased water quality[49].

Fisheries and Aquaculture

Fisheries and aquaculture provide an important source of household income and employment in the region[50]. Commodity fisheries, such as pearls, shrimp, and seaweed, also provide thousands of people with part- or full-time work[51]. Fisheries, particularly reef fisheries, provide social and cultural value, and are a significant source of nutrition.

Declines in localized upwelling systems in the tropical Pacific, as a result of shifting currents and higher temperatures and acidification, may lead to reduced primary productivity with a cascading effect on higher trophic levels[50]. Over half of Pacific Island nations are projected to experience greater than 50% declines in maximum catch potential of exploited fishes and invertebrates by 2100, with the largest declines occurring in the western tropical Pacific (under RCP8.5)[52]. Pacific Island economies are projected to experience an average 20% decline in purse-seine tuna catches by 2050, an average annual loss in regional tuna-fishing access fees of US $90 million (under RCP8.5)[53]. Pelagic fish catches are projected to slightly increase to the east of 170° E (under A2)[54]. The projected eastward redistribution of skipjack and yellowfin tuna could result in opportunities for French Polynesia and Pacific Island nations in the subtropics, e.g., Vanuatu and Fiji, to obtain increased economic benefits (under RCP8.5)[54,55].

Widespread coral bleaching is expected to occur annually by the 2050s across the region (under RCP8.5), and declines in pH will further degrade corals[56]. Decline in reef-associated species have been observed associated with coral bleaching[57].

In Pacific Islands that possess mangroves and seagrass, capture-fisheries species (e.g., sea cucumber and lobster) have close associations with these habitats, either as a food source or preferred habitat. Melanesian seagrass habitats are valued at US $151.4 billion with long-term carbon sequestration alone estimated at approximately US $760/ha/yr[58,59]. Increasing ocean temperatures, rainfall, and storm frequency threaten seagrass ecosystem resilience and function[60].

Freshwater pond aquaculture to produce tilapia, carp, and milkfish for food security is likely to benefit from projected increases in temperature and rainfall throughout much of the Pacific, with the exception of the southwest Pacific, which may experience more extreme wet and dry periods[51,61]. The production of livelihood commodities in coastal waters are expected to incur production losses (under A2)[51].

Tourism

A global analysis of climate change vulnerability in the tourism sector found that Small Island Developing States, particularly those in the Pacific who are economically more reliant on tourism, have the highest vulnerability to the impacts of climate change[62].

Degraded coral reefs are a major risk for local operators in many Pacific islands, which are also vulnerable to multiple climate change-related coastal hazards[63,64]. Globally, 9% of all coastal tourism value is found in countries with coral habitats, with a total value estimated at US $36 billion[65]. Mangrove areas are ideally situated for ecotourism opportunities, but are threatened both by overfishing and coastal development pressures as well as rising sea levels and air and sea temperatures[66]. Seagrass ecosystems benefit tourism by improving water clarity when located near dive sites as well as contributing substantially to Pacific Island livelihoods[67,68]. Higher sea temperatures combined with other anthropogenic stresses may result in loss of Pacific islands seagrass habitat of between 5–30% by 2100[60]. The inundation of low-lying coastal land, erosion of beaches and shorelines, and saltwater intrusion into freshwater lenses endangers coastal infrastructure, which is particularly crucial for islands with few economic alternatives to tourism[69].

Future increases in the proportion of intense tropical cyclones and trends towards heavier rainfall events and flash floods may influence tourists' travel choices[70]. TC Pam caused US $51.7 million total damage to the tourism subsector, with total losses during the subsequent six months estimated at US $31.5 million[71]. Increases in extreme events globally can affect visitor numbers to Pacific islands, compounding vulnerability to global shocks such as COVID-19.

Case Study 1: Climate change projections to inform black pearl production vulnerability in the Cook Islands:

Climate change projections have been employed in a recent study to inform black pearl production vulnerability in the Cook Islands. This assessment indicates the production of pearls is already impacted by marine heat waves and tropical cyclones. Vulnerability is likely to rise due to projected increases in marine heat waves and ocean acidification by 2050 especially under a high emission scenario. While the projected decrease in cyclone frequency would reduce vulnerability, the projected change in average cyclone intensity, combined with sea level rise and increased rainfall rates would increase cyclone impacts. The projected rise in sea level is expected to increase the exposure of people living on atolls such as Manihiki, where black pearls are produced, especially under a high emission scenario. Work undertaken in the study can inform some of the proposed initiatives outlined in the Draft National Aquaculture Development Plan 2020–2025 (Ministry of Marine Resources and SPC Pacific Community 2020), with measures to address these issues outlined in the Draft Cook Islands Pearl Industry Strategic Plan, e.g., pearl farming technologies: spat collection methods; conditioning time; shell cleaning; identifying potential future farming locations; predation issues; and oyster nutrition driven by nutrient availability (MMR and SPC 2012).

Case Study 2: Collaborative groundwater modeling to increase freshwater resilience under a changing climate in American Samoa.

In many small islands' contexts, limited human and financial resources constrain the ability of public water utilities to evaluate and model future water quantity and quality under changing climate projections. The impacts of climate on freshwater supply are often evaluated infrequently by external consultants or researchers, which fails to increase island modeling capacity. In American Samoa, an innovative partnership between the University of Hawai‘i Water Resources Research Center (WRRC), American Samoa Power Authority (ASPA), and Pacific Regional Sciences & Assessments (Pacific RISA) program uses social networking, cloud-computing and an open-source collaborative GitHub framework to collect weather and streamflow data and create water budget and groundwater recharge estimates. Researchers and ASPA staff work together to develop and maintain the models in an accessible, transparent, and stakeholder driven way, which are then used to inform water and power management decisions considering both current and future climate projections.

Also see PIRCA case study: "Collaborating for Success: Sustaining Water Supply on a Pacific Island"

Acknowledgements

The lead authors wish to thank the contributing authors, who gave of their time and drew upon their wealth of technical expertise and practical experience to provide invaluable input to individual sections. We express our gratitude to the external reviewers—Jerome Aucan, Yuriy Kuleshov, Scott Power, Claire Spillman, and also to members of the steering committee—Faapisa Aiono, Terry Atalifo, Zulfikar Begg, Omar Baddour, Seluvaia Finaulahi, and Victoire Laurent—for their constructive comments throughout the development of the report. The lead authors wish to acknowledge with special regard the endorsement of PMC and NMHs of this effort. We look forward to working with them and other stakeholders in the region over the coming months to help make use of this information, in particular how this effort can contribute to the development of individual country reports that contain such information.

Appendix: Traceable Accounts

The Pacific Islands

Sources of Information and Further Reading

1. Britannica. https://www.britannica.com/place/Pacific-Islands.
2. Keener, V.W., J. J. Marra, M. L. Finucane, D. Spooner, & M. H. Smith (Eds.) (2012): Climate Change and Pacific Islands: Indicators and Impacts. Report for the 2012 Pacific Islands Regional Climate Assessment (PIRCA). Washington, DC: Island Press.
3. Leong, J.A., J. J. Marra, M. L. Finucane, T. Giambelluca, M. Merrifield, S. E. Miller, J. Polovina, E. Shea, M. Burkett, J. Campbell, P. Lefale, F. Lipschultz, L. Loope, D. Spooner, and B. Wang (2014): Hawai‘i and U.S. Affiliated Pacific Islands. Climate Change Impacts in the United States: The Third National Climate Assessment. Ch. 23 National Climate Assessment, J. M. Melillo, T.C. Richmond, and G. W. Yohe (Eds.), U.S. Global Change Research Program, 537-556. doi:10.7930/J0W66HPM. http://nca2014.globalchange.gov/report/regions/hawaii-and-pacific-islands.
4. IPCC AR5 Climate Change (2014): Impacts, Adaptation, and Vulnerability, Chapter 29, Small Islands (Nurse et al. 2014). https://www.ipcc.ch/report/ar5/wg2/.

- CSIRO climate change information for the Pacific. https://www.csiro.au/en/research/environmental-impacts/climate-change/pacific-climate-change-info.
- Pacific Islands Regional Climate Assessment. https://pirca.org/.
- IPCC (2021): Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (Eds.), Cambridge University Press. In Press. https://www.ipcc.ch/report/ar6/wg1/.
- Keener, V., D. Helweg, S. Asam, S. Balwani, M. Burkett, C. Fletcher, T. Giambelluca, Z. Grecni, M. Nobrega-Olivera, J. Polovina, and G. Tribble (2018): Hawai‘i and U.S.-Affiliated Pacific Islands. In Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 1242–1308. doi: 10.7930/NCA4.2018.CH27. https://nca2018.globalchange.gov/chapter/27/
- CSIRO State of the Climate 2020. https://www.csiro.au/en/research/environmental-impacts/climate-change/state-of-the-climate.

About this Report

Sources of Information and Further Reading

1. WMO State of the Global Climate 2020. https://public.wmo.int/en/our-mandate/climate/wmo-statement-state-of-global-climate.
2. Pacific Islands Regional Climate Assessment (PIRCA) Climate Change Reports. https://pirca.org/category/publications/reports/.
3. State of Environmental Conditions in Hawai‘i and the U.S. Affiliated Pacific Islands under a Changing Climate:2017: Coordinating Authors: J.J. Marra and M.C. Kruk. Contributing Authors: M. Abecassis; H. Diamond; A. Genz; S.F. Heron; M. Lander; G. Liu; J. T. Potemra; W.V. Sweet; P. Thompson; M.W. Widlansky; and P. Woodworth-Jefcoats. September, 2017. NOAA NCEI.
4. Australia CSIRO State of the Climate 2020. https://www.csiro.au/en/research/environmental-impacts/climate-change/state-of-the-climate.
5. U.S. EPA Climate Change Indicators in the USA. https://www.epa.gov/climate-indicators.

Greenhouse Gases

Data and Methods

Atmospheric Concentration of Carbon Dioxide, Other Greenhouse Gasses

The **red** line in Figure 3 represents the monthly mean values of CO2measured by NOAA on Mauna Loa, Hawaii, centered on the middle of each month. The **black** line is a moving average of seven adjacent seasonal cycles centered on the month to be corrected, except for the first and last three and one-half years of the record, where the seasonal cycle was averaged over the first and last seven years, respectively. Measurements take into account that successive daily means are not fully independent; the CO_2 deviation on most days has some similarity to that of the previous day. If there is a missing month, its interpolated value is shown in blue.

Data are reported as a dry air mole fraction defined as the number of molecules of carbon dioxide divided by the number of all molecules in air, including CO_2 itself, after water vapor has been removed. The mole fraction is expressed as parts per million (ppm). Example: 0.000400 is expressed as 400 ppm.

The Mauna Loa data are being obtained at an altitude of 3400 m in the northern subtropics and may not be the same as the globally averaged CO_2 concentration at the surface. Data collection was started by C. David Keeling of the Scripps Institution of Oceanography in March of 1958. Source: https://gml.noaa.gov/ccgg/trends/.

The Cape Grim baseline carbon dioxide data in Figure 5 shows both the annual cycle and the long-term trend. Carbon dioxide concentrations in air masses at are measured jointly by BOM/CSIRO. They been measured using a technique called cavity ring-down spectroscopy (CRDS) since 2013. These instruments can detect the concentration of CO_2 by measuring the amount infrared laser light absorbed by an air sample compared to a reference or calibration air sample. Prior to 2013, Non-Dispersive Infrared (NDIR) gas analyzers were used to measure CO_2. Carbon dioxide is measured in parts per million molar (ppm). Cape Grim Baseline Air Pollution Station (CG BAPS) first began measuring the composition of the atmosphere in April 1976. Source: https://www.csiro.au/en/research/natural-environment/atmosphere/latest-greenhouse-gas-data.

The AGGI is a measure of the climate-warming influence of long-lived trace gases in the atmosphere (e.g., carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and halogenated compounds—mainly CFCs) and how that influence has changed since the onset of the industrial revolution. Air samples are collected through the NOAA Global Greenhouse Gas Reference Network, which provides samples from up to 80 global background air sites, including some collected at 5-degree latitude intervals from ship routes. Weekly data are used from the most remote sites to create smoothed north-south latitude profiles from which global averages and trends are calculated.

To determine the total radiative forcing of the greenhouse gases for the AGGI, the IPCC (Ramaswamy et al. 2001) recommended using expressions to convert changes in greenhouse gas global abundance relative to 1750 to instantaneous radiative forcing. This empirical expression is derived from atmospheric radiative transfer models and generally has an uncertainty of about 10%. By contrast, uncertainties in the measured global average abundances of the long-lived greenhouse gases are much smaller (<1%). Only direct forcing from these gases has been included. Model-dependent feedbacks, for example, due to water vapor and ozone depletion, are not included. Other spatially heterogeneous, short-lived, climate forcing agents, such as aerosols and tropospheric ozone, are highly variable and have uncertain global magnitudes and also are not included here to maintain accuracy. Source: https://gml.noaa.gov/aggi/aggi.html.

Sources of Information and Further Reading

1. U.S. EPA Climate Indicators: Greenhouse Gases. https://www.epa.gov/climate-indicators/greenhouse-gases.
2. IPCC (2021): *Climate Change 2021: The Physical Science Basis*. In Masson-Delmotte, V., et al. (Eds.), *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press. In Press. https://www.ipcc.ch/report/ar6/wg1/.
3. Wyrtki, K. (1975): El Niño—The dynamical response of the equatorial Pacific Ocean to atmospheric forcing. *Journal of Physical Oceanography*, 5, 572-584.
4. Mantua, N.J., S.R. Hare, Y. Zhang, J.M. Wallace, and R.C. Francis (1997): A Pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin of the American Meteorological Society*, 78, 1069-1079.

5. NOAA ESRL Monitoring Laboratory. https://gml.noaa.gov/ccgg/trends/.
6. CSIRO Cape Grim Greenhouse Gas Data. https://www.csiro.au/en/research/natural-environment/atmosphere/latest-greenhouse-gas-data.
7. NOAA ESRL Monitoring Laboratory. https://gml.noaa.gov/aggi/.

- Battle, M., M. Bender, T. Sowers, P.P. Tans, J.H. Butler, J.W. Elkins, J.T. Ellis, T. Conway, N. Zhang, P. Lang, and A.D. Clarke (1996): Atmospheric gas concentrations over the past century measured in air from firn at the South Pole. *Nature*, 383, 231-235. doi: 10.1029/2005JD006035.
- Bruhwiler, L., S. Basu, J.H. Butler, A. Chatterjee, E. Dlugokencky, M.A. Kenney, A. McComiskey, S.A. Montzka, and D. Stanitski (2021): Observations of greenhouse gases as climate indicators. *Climatic Change*, 165, 1-2. doi: 10.1007/s10584-021-03001-7.
- Butler, J. H., and S. A. Montzka, (2017): The NOAA Annual Greenhouse Gas Index (AGGI). NOAA Earth System Research Laboratory. https://www.esrl.noaa.gov/gmd/aggi/aggi.html.
- Dunn, R.J.H., D.M. Stanitski, N. Gobron, and K.M. Willett, (2020): Chapter 2: Global Climate, Overview. *Bulletin of the American Meteorological Society*, 101(8), S9-S127. doi: 10.1175/BAMS-D-20-0104.1.
- Etheridge, D.M., L.P. Steele, R.L. Langenfelds, and R.J. Francey (1996): Natural and anthropogenic changes in atmospheric CO2 over the last 1000 years from air in Antarctic ice and firn. *Journal of Geophysical Research*, 101, 4115-4128.
- Etheridge, D.M., L.P. Steele, R.J. Francey, and R.L. Langenfelds (1998): Atmospheric methane between 1000 A.D. and present: Evidence of anthropogenic emissions and climate variability. *Journal of Geophysical Research*,103, 15,979-15,993.
- Hofmann, D.J., J.H. Butler, E.J. Dlugokencky, J.W. Elkins, K. Masarie, S.A. Montzka, and P. Tans (2006): The role of carbon dioxide in climate forcing from 1979-2004: Introduction of the Annual Greenhouse Gas Index. *Tellus* B, 58B, 614-619.
- Keeling, C.D., R.B. Bacastow, A.E. Bainbridge, C.A. Ekdahl, P.R. Guenther, L.S. Waterman, and J.F.S. Chin (1976): Atmospheric carbon dioxide variations at Mauna Loa Observatory, Hawai'i. *Tellus*, 28, 538-551. doi: 10.3402/tellusa.v28i6.11322.
- Lan, X., P. Tans, B.D. Hall, G. Dutton, J. Muhle, J.W. Elkins, and I. Vimont (2021): Long-lived greenhouse gases. *Bulletin of the American Meteorological Society*, 102, 8, S83-S87. doi: 10.1175/BAMS-D-21-0098.1.
- Ramaswamy, V., et al. (2001): Radiative forcing of climate change. In *Climate Change 2001: The Scientific Basis*, Ch. 6, Cambridge Univ. Press, Cambridge UK and New York, NY USA.

Atmosphere—Surface Temperature, Rainfall, Tropical Cyclones (TCs) and Surface Winds

Data and Methods

Mean temperature, Amount of hot days, Amount of cold nights. Total wet-day rainfall, Consecutive dry days, Heavy rainfall

Daily temperature and rainfall data primarily sourced from the Bureau of Meteorology Pacific Climate Change Data Portal for the period 1951–2015, with updates to 2020 from the following sources.

- CliDE databases (updates from 2015)
- GHCND for the U.S. states and territories (complete record)
- GHCND for the U.S. affiliates in the north Pacific (from 2015)
- MeteoFrance New Caledonia and French Polynesia (from 2015)
- Australia Bureau of Meteorology Climate Data Online (from 2015)
- New Zealand NIWA's Cliflo (from 2015).

Quality control for U.S. states and territories undertaken via GHCND. No further QC applied. For the remaining records QC checks have been applied to data obtained from the Pacific Climate Change Data Portal.

- Annual mean daily mean temperature index calculated using Climpact package (https://climpact-sci.org/), which calculates the WMO ET-SCI indices. Annual mean daily mean temperature = Annual mean daily maximum temperature – Annual mean daily minimum temperature (Units: °C/decade).

- Annual amount of hot days index calculated using Climpact package (https://climpact-sci.org/), which calculates the WMO ET-SCI indices. Annual amount of hot days = Percentage of days when daily maximum temperature > 90th percentile (Units: %/decade).
- Annual amount of cold nights index calculated using Climpact package (https://climpact-sci.org/), which calculates the WMO ET-SCI indices. Annual amount of cold nights = Percentage of days when daily minimum temperature < 10th percentile (Units: %/decade).
- Annual total rainfall on wet day index calculated using Climpact package (https://climpact-sci.org/), which calculates the WMO ET-SCI indices. Annual total rainfall on wet days = Annual sum of daily rainfall >= 1.0 mm (Units: mm/decade).
- Annual consecutive dry days index calculated using Climpact package (https://climpact-sci.org/), which calculates the WMO ET-SCI indices. Annual consecutive dry days = Annual number of consecutive dry days when rainfall < 1.0 mm within a calendar year (Units: days/decade).
- Maximum 1-day rainfall calculated using Climpact package (https://climpact-sci.org/), which calculates the WMO ET-SCI indices. Annual maximum 1-day rainfall = maximum amount of rainfall received in 24 hours within a calendar year (Units: mm/decade).

Linear annual and seasonal trends are calculated using the nonparametric Kendall's tau-based slope estimator. This method has notable advantages over the more commonly used least squares estimate. It is nonparametric and is less affected by outliers, making it well suited to meteorological and hydrological time series. The significance of the trend is determined using Kendall's test. Trends are presented in the form of a bubble over the station. The size/color of the bubble is proportional to the magnitude of the trend. Filled circles are significant at the 95% level.

Total TCs, Severe TCs, Surface Wind Speed

TC wind thresholds follow the U.S. Saffir-Simpson Hurricane Wind Scale.

- Tropical Cyclone >= 34 knots
- Cat 1 >= 64 knots
- Cat 2 >= 83 knots
- Cat 3 >= 96 knots
- Cat 4 >= 113 knots
- Cat 5 >= 137 knots

TC data from 1981 to 2020 is derived from the International Best Track Archive for Climate Stewardship (IBTrACS)[2,3]. Python v3 code is used to extract the data and make all the plots. The code is publicly available via GitHub with supported libraries. For counting, TC spurs were ignored, which would have resulted in an erroneous double-count. IBTrACS is the basis for the three subregions: Western North Pacific; Central North Pacific; and Western South Pacific.

Wind data[4] from 1981–2020 is derived from the National Centers for Environmental Prediction-Department of Energy Atmospheric Model Intercomparison Project re-analysis covering the satellite period 1979 to the present. Data are provided by the Climate Diagnostics Center in Boulder, Colorado, with a spatial and temporal resolution of T62, 28 levels, at 6 hourly intervals, Trend lines are calculated using the nonparametric Kendall's tau-based slope estimator. Pacific subregions are based on RMSC areas of responsibility. Linear annual and seasonal trends are calculated using the nonparametric Kendall's tau-based slope estimator. The significance of the trend is determined using Kendall's test.

Sources of Information and Further Reading

Temperature and rainfall

1. Jones, D.A., et al. (2013): An updated analysis of homogeneous temperature data at Pacific Island stations. *Australian Meteorological and Oceanographic Journal*, 63(2), 285-302. https://doi.org/10.22499/2.6302.002.
2. Whan, K., et al. (2014): Trends and variability of temperature extremes in the tropical Western Pacific. *International Journal of Climatology*, 34(8). https://doi.org/10.1002/joc.3861.

3. McGree, S., N. Herold, L. Alexander, S. Schreider, Y. Kuleshov, E. Ene, S. Finaulahi, K. Inape, B. Mackenzie, H. Malala, A. Ngari, B. Prakash, and L. Tahani (2019): Recent changes in mean and extreme temperature and precipitation in the western Pacific Islands. *Journal of Climate*, 32(16), 4919-4941. https://doi.org/10.1175/JCLI-D-18-0748.1.
4. Wang G, Power SB, McGree S. (2016): Unambiguous warming in the western tropical Pacific primarily caused by anthropogenic forcing. *International Journal of Climatology*, 36(2). https://doi.org/10.1002/joc.4395.
5. Dutheil, C., M. Bador, M. Lengaigne, J. Lefèvre, N. Jourdain, J. Vialard, S. Jullien, A. Peltier, and C. Menkes (2019): Impact of surface temperature biases on climate change projections of the South Pacific Convergence Zone. *Climate Dynamics*, 1-23. https://doi.org/10.1007/s00382-019-04692-6.
6. IPCC (2021). Climate Change 2021: The Physical Science Basis. In Masson-Delmotte, V., et al. (Eds.), *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press. In Press.
7. Chen, Y.R., and P.-S. Chu (2014): Trends in precipitation extremes and return levels in the Hawaiian Islands under a changing climate. *International Journal of Climatology*, 29, 3913-3925. https://doi.org/10.1002/joc.3950.
8. Frazier, A.G., and T.W. Giambelluca (2017): Spatial trend analysis of Hawaiian rainfall from 1920 to 2012. *International Journal of Climatology*, 37(5), 2522-2531. https://doi.org/10.1002/joc.4862.
9. Clilverd, H.M., Y.-P. Tsang, D.M. Infante, A.J. Lynch, and A.M. Strauch (2019): Long-term streamflow trends in Hawai'i and implications for native stream fauna. *Hydrological Processes*, 33(5), 699-719. https://doi.org/10.1002/hyp.13356.
10. Whan, K., B. Timbal, and J. Lindesay (2014): Linear and nonlinear statistical analysis of the impact of sub-tropical ridge intensity and position on south-east Australian rainfall. *International Journal of Climatology*, 34(2), 326-342. https://doi.org/10.1002/joc.3689.
11. Dey, R., S.C. Lewis, J.M. Arblaster, and N.J. Abram (2019): A review of past and projected changes in Australia's rainfall. *WIREs Climate Change*, 10(3), e577. https://doi.org/10.1002/wcc.577.
12. Timbal, B., and W. Drosdowsky (2013): The relationship between the decline of Southeastern Australian rainfall and the strengthening of the subtropical ridge. *International Journal of Climatology*, 33(4), 1021-1034. https://doi.org/10.1002/joc.3492.
13. Fyfe, J.C., N.P. Gillett, and G.J. Marshall (2012): Human influence on extratropical Southern Hemisphere summer precipitation. *Geophysical Research Letters*, 39(L23711). https://doi.org/10.1029/2012GL054199.
14. Australian Bureau of Meteorology, CSIRO. (2011): *Climate Change in the Pacific: Scientific Assessment and New Research. Volume 1: Regional Review. Volume 2: Country Reports.* Melbourne, Australia.
15. Keener, V.W., J.J. Marra, M.L. Finucane, D. Spooner, and M.H. Smith (2012): *Climate Change and Pacific islands: Indicators and Impacts Pacific Islands Regional Climate Assessment (PIRCA)*. Island Press: Washington D.C.
16. Folland, C.K., J.A. Renwick, M.J. Salinger, and A.B. Mullan (2002): Relative influences of the Interdecadal Pacific Oscillation and ENSO on the South Pacific Convergence Zone. *Geophysical Research Letters*, 29(13), 21-24. https://doi.org/10.1029/2001GL014201.
17. Salinger, M.J., S. McGree, F. Beucher, S.B. Power, and F. Delage (2014): A new index for variations in the position of the South Pacific convergence zone 1910/11–2011/2012. *Climate Dynamics*, 1-12. https://doi.org/10.1007/s00382-013-2035-y.

- Pacific Islands Regional Climate Assessment (PIRCA) Reports Palau, Guam, CNMI, American Samoa. 2020–2021 East-West Center, Honolulu, HI. https://pirca.org/category/publications/.
- Australian Bureau of Meteorology (BoM), and Commonwealth Scientific and Industrial Research Association (CSIRO) (2014): *Climate Variability, Extremes and Change in the Western Tropical Pacific: New Science and Updated Country Reports 2014*. Australian Bureau of Meteorology and Commonwealth Scientific and

Industrial Research Organisation, 372 pp. http://www.pacificclimatechangescience.org/wp-content/uploads/2014/07/PACCSAP_CountryReports2014_WEB_140710.pdf.

Total TCs, Severe TCs, Surface Wind Speed

1. Davarzani, H., K. Smits, R.M. Tolene, and T. Illangasekare (2014): Study of the effect of wind speed on evaporation from soil through integrated modeling of the atmospheric boundary layer and shallow subsurface. *Water Resources Research,* 50(1), 661-680.
2. Knapp, K.R., M.C. Kruk, D.H. Levinson, H.J. Diamond, and C.J. Neumann (2010): The International Best Track Archive for Climate Stewardship (IBTrACS): Unifying tropical cyclone best track data. *Bulletin of the American Meteorological Society*, 91, 363–376, doi: 10.1175/2009BAMS2755.1.
3. Kruk, M.C., K.R. Knapp, and D.H. Levinson (2010): A technique for combining global tropical cyclone best track data. *Journal of Atmospheric and Oceanic Technology*, 27(4), 680-692.
4. Kanamitsu, M., W. Ebisuzaki, J. Woollen, S.-K. Yang, J.J. Hnilo, M. Fiorino, and G.L. Potter (2002): NCEPDOE AMIP-II Reanalysis (R-2). *Bulletin of the American Meteorological Society*, 83, 1631-1643, https://doi.org/10.1175/BAMS-83-11-1631.
5. Lu, J., G.A. Vecchi, and T. Reichler (2007): Expansion of the Hadley cell under global warming. *Geophysical Research Letters*, 34(6).
6. Kruk, M.C., K. Hilburn, and J.J. Marra (2015): Using microwave satellite data to assess changes in storminess over the Pacific Ocean. *Monthly Weather Review*, 143(8), 3214-3229.

Ocean—Sea Level, Sea Surface Temperature and Ocean Heat Content, Ocean Chemistry

Data and Methods

Regional and Local Sea Level Trends, Annual Counts of Flood Frequency

Sea level trends are from satellite altimetry and island tide gauges since the beginning of the satellite record (1993–2020).

Minor flood frequency is calculated as the total number of minor flood days per year measured by tide gauges since 1980 (1980–1920). A minor flood day is defined as a day in which the elevation of the sea at the tide gauge exceeded the elevation associated with the 0.5 year return interval of a given station based on extreme value analysis (stationary GPD on detrended daily data). Results are set relative to the 1991-2009 epoch (centered on 2005 MHHW datum). No corrections were made for seismic-induced vertical land motion. Any effects of tsunamis and tropical cyclones were not removed.

Tide gauge data is from the from the UHSLC Fast-Delivery database, http://uhslc.soest.hawaii.edu/data/?fd

Satellite data is from the SSALTO/DUACS multimission dataset distributed by the European Copernicus Marine Environment Monitoring Service (CMEMS). https://www.aviso.altimetry.fr/en/data/product-information/information-about-mono-and-multi-mission-processing/ssaltoduacs-multimission-altimeter-products.html.

Thirty-one TG stations met either Level 1 or Level 2 data criteria and had at least 70% coverage between 1980 and 2020. Level 1 criteria requires the TG to have years with 80% of the record, missing no more than 2 months; months with 80% of days, missing no more than 5 days and no more than 3 consecutive days; and days with at least 4 regularly spaced observations (i.e., every 6 hours). Level 2 criteria requires the TG to have years with 75% of the record, missing no more than 3 months; months with 75% of days; and days with at least 1 observation in every 6 hour interval. A year is defined as May 1–April 30.

Mean Sea Surface Temperature, Ocean Heat Waves

Sea surface temperature data were obtained from the Asia-Pacific Data Research Center (APDRC) at the University of Hawaiʻi (http://apdrc.soest.hawaii.edu).

The Physical Sciences Division at NOAA produces an SST product based on optimum interpolation (OI) analysis. The product, NOAA OI.v2 SST is produced weekly on a one-degree grid. The analysis uses *in situ* and satellite SST plus SST simulated by sea-ice cover. Before the analysis is computed, the satellite data are adjusted for biases using the method of Reynolds[a] and Reynolds and Marsico[b]. Monthly averages used here are derived by a linear interpolation of the weekly optimum interpolation (OI) version 2 fields to daily fields then averaging the daily values over a month. The temporal coverage of the monthly data used is from January 1982 through December 2021 (although data are updated each month to present).

[a] Reynolds, R.W. (1988): A real-time global sea surface temperature analysis. *Journal of Climate*, 1, 75–87.
[b] Reynolds, R.W., and D.C. Marsico (1993): An improved real-time global sea surface temperature analysis. *Journal of Climate*, 6, 114–119.

Marine heat wave information is derived from daily Optimally Interpolated Sea Surface Temperature (OISSTv2.1) that was obtained from the National Oceanic and Atmospheric Administration (NOAA).

Time series plots are from the marine heat wave tracker (http://www.marineheatwaves.org/tracker.html), which uses the climatology period 1982 to 2011. Marine heat wave maps use the climatology period 1981 to 2010.

Heat content data down to 300 meters were obtained from the monthly ACCESS-S2 reanalysis from Bureau of Meteorology (1981-2018).

Ocean Acidification

All HOT pH data were collected using the spectrophotometric method of Clayton and Byrne (1993) and are reported at a constant temperature of 25°C. The +0.0047 unit correction suggested by DelValls and Dickson (1998) has NOT been applied to any HOT data. The 1992–1993 HOT pH data were originally reported on the Seawater Scale, while later data have all been reported on the Total Scale. For the sake of consistency, the 1992–1993 pH data have as of today been converted to the Total Scale according to Lewis and Wallace (1998). The Total Scale values are approximately 0.01 pH units higher than the Seawater Scale values they replace. The cruises affected are HOT 36-47 and HOT 49-50. Prior to 1992, on HOT 23-32, pH measurements were made using a pH electrode calibrated with NBS buffers and were reported on the NBS Scale. Potentiometric measurements of pH are inherently less precise than spectrophotometric measurements. Moreover, the relationship between the NBS Scale and the Total Scale is not exact and depends on characteristics of the electrode employed. Given these difficulties, we have not attempted to correct the pre-1992 data to the Total Scale. They are available in the raw data files via FTP and remain as reported on the NBS Scale, but have been assigned a questionable quality flag and thus are not accessible through HOT-DOGS. https://hahana.soest.hawaii.edu/hot/methods/ph.html.

Chlorophyll Concentration

Trends were calculated using (1) NOAA's CoralTemp sea surface temperature, and (2) the European Space Agency's OC-CCI data, both hosted by NOAA's OceanWatch. These data were used to estimate median phytoplankton size following the methods of Barnes et al. (2011).

Sources of Information and Further Reading

Regional and Local Sea Level Trends, Annual Counts of Flood Frequency

1. Oppenheimer, M., et al. (2019): Sea level rise and implications for low-lying islands, coasts and communities. In Pörtner, H.-O., et al. (Eds.), *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*. In press.
2. Storlazzi, C.D., S.B. Gingerich, A.P. van Dongeren, O.M. Cheriton, P.W. Swarzenski, E. Quataert, C.I. Voss, D.W. Field, H. Annamalai, G.A. Piniak, and R. McCall (2018): Most atolls will be uninhabitable by the mid-21st century because of sea-level rise exacerbating wave-driven flooding. *Science Advances*, 4(4), eaap9741. https://doi.org/10.1126/sciadv.aap9741.
3. Gingerich, S.B., C.I. Voss, and A.G. Johnson (2017): Seawater-flooding events and impact on freshwater lenses of low-lying islands: Controlling factors, basic management and mitigation. *Journal of Hydrology*, 551, 676688. doi:10.1016/j.jhydrol.2017.03.001.
4. Wairiu, M. (2017): Land degradation and sustainable land management practices in Pacific Island Countries. *Regional Environmental Change*, 17, 1053-1064. https://doi.org/10.1007/s10113-016-1041-0.
5. Fox-Kemper, B., et al. (2021): Ocean, cryosphere and sea level change. In Masson-Delmotte, V., et al. (Eds.), *Climate Change 2021: The Physical Science Basis*. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. In Press. https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter_09.pdf.
6. Climate Change: Global Sea Level NOAA Climate.gov. https://www.climate.gov/news-features/understanding-climate/climate-change-global-sea-level.

7. Sweet, W.V., R.E. Kopp, C.P. Weaver, J. Obeysekera, R.M. Horton, E.R. Thieler, and C. Zervas (2017): Global and regional sea level rise scenarios for the United States. NOAA Technical Report NOS CO-OPS 083. Silver Spring, Maryland: U.S. Department of Commerce, NOAA, National Ocean Service, Center for Operational Oceanographic Products and Services. https://doi.org/10.7289/V5/TR-NOS-COOPS-083.
8. Sweet, W.V., et al. (2022): Global and regional sea level rise scenarios for the United States: Up-dated mean projections and extreme water level probabilities along U.S. coastlines. NOAA Technical Report NOS 01. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD, 111 pp. https://oceanservice.noaa.gov/hazards/sealevelrise/noaa-nos-techrpt01-global-regional-SLR-scenarios-US.pdf.
9. Di Lorenzo, E., K.M. Cobb, J.C. Furtado, N. Scheider, B.T. Anderson, A. Bracco, M.A. Alexander, and D.J. Vimont (2010): Central Pacific El Niño and decadal climate change in the North Pacific Ocean. *Nature Geosciences*, 3, 762-765, doi: 10.1038/NGEO984.
10. Becker, M., B. Meyssignac, W. Llovel, A. Cazenave, and T. Delcroix (2012): Sea level variations at tropical Pacific islands since 1950. *Global and Planetary Change*, 80-81, 85–98, doi: 10.1016/j.gloplacha.2011.09.004.
11. Hamlington, B.D., R.R. Leben, K.-Y. Kim, R.S. Nerem, L.P. Atkinson, and P.R. Thompson (2015): The effect of the El Niño-Southern Oscillation on U.S. regional and coastal sea level. *Journal of Geophysical Research-Oceans*, 120, 3970-3986, doi: 10.1002/2014JC010602.
12. Moon, J.-H., Y.T. Song, and H. Lee (2015): PDO and ENSO modulations intensified decadal sea level variability in the tropical Pacific. *Journal of Geophysical Research-Oceans*, 120, 8229-8237, doi: 10.1002/2015JC011139.
13. Widlansky, M.W., A. Timmerman, and W. Cai (2015): Future extreme sea level seesaws in the tropical Pacific. *Science Advances*, 1, e1500560, doi: 10.1126/sciadv.1500560.
14. Long, X., M.J. Widlansky, F. Schloesser, P.R. Thompson, H. Annamalai, M.A. Merrifield, and H. Yoon (2020): Higher sea levels at Hawai'i caused by strong El Niño and weak trade winds. Journal of Climate, 33(8), 3037-3059. https://dx.doi.org/10.1175/jcli-d-19-0221.1.
15. Feng, M., Y. Li, and G. Meyers (2004): Multidecadal variations of Fremantle sea level: Footprint of climate variability in the tropical Pacific. *Geophysical Research Letters*, 31, L16302. https://doi.org/10.1029/2004GL019947.
16. Merrifield, M.A., and P.R. Thompson (2018): Interdecadal sea level variations in the Pacific: Distinctions between the tropics and extratropics. *Geophysical Research Letters*, 45(13), 6604-6610. https://doi.org/10.1029/2018GL077666.
17. Hamlington, B.D., and P.R. Thompson (2015): Considerations for estimating the 20th century trend in global mean sea level. *Geophysical Research Letters*, 42, 4102-4109. http://onlinelibrary.wiley.com/doi/10.1002/2015GL064177/full.
18. Martínez-Asensio, A., G. Wöppelmann, V. Ballu, M. Becker, L. Testut, A.K. Magnan, V.K.E. Duvat (2019): Relative sea-level rise and the influence of vertical land motion at Tropical Pacific Islands. *Global and Planetary Change*, 176, 132-143. https://doi.org/10.1016/j.gloplacha.2019.03.008.
19. Han, S.-C., J. Sauber, F. Pollitz, and R. Ray (2019): Sea level rise in the Samoan Islands escalated by viscoelastic relaxation after the 2009 Samoa-Tonga earthquake. *Journal of Geophysical Research-Solid Earth*, 124, 4142-4156. https://doi.org/10.1029/2018JB017110.
20. Sweet, W.V., and J.J. Marra (2015): 2014 State of nuisance tidal flooding. Supplement to *State of the Climate: National Climate Report* for August 2015. https://www.ncdc.noaa.gov/monitoring-content/sotc/national/2015/aug/sweet-marra-nuisance-flooding-2015.pdf.
21. Thompson, P.R., M.J. Widlansky, B.D. Hamlington, M.A. Merrifield, J.J. Marra, G.T. Mitchum, and W. Sweet (2021): Rapid increases and extreme months in projections of United States high-tide flooding. *Nature Climate Change*. https://doi.org/10.1038/s41558-021-01077-8.

22. Hoeke, R.H., K.L. McInnes, J.C. Kruger, R.J. McNaught, J.R. Hunter, and S.G. Smithers (2013): Widespread inundation of Pacific islands triggered by distant-source wind-waves. *Global and Planetary Change*, 108, 128-138. https://doi.org/10.1016/j.gloplacha.2013.06.006.
23. Merrifield, M.A., J.M. Becker, M. Ford, and Y. Yao (2014): Observations and estimates of wave-driven water level extremes at the Marshall Islands. *Geophysical Research Letters*, 41, 7245-7253, doi: 10.1002/2014GL061005.
24. Quataert, E., C.D. Storlazzi, A. van Rooijen, O.M. Cheriton, and A.R. van Dongeren (2015): The influence of coral reefs and climate change on wave-driven flooding of tropical coastlines. Geophysical Research Letters, 1-9. doi: 10.1002/2015GL064861.
25. Moftakhari, H.R., A. AghaKouchak, B.F. Sanders, and R.A. Matthew (2017): Cumulative hazard: The case of nuisance flooding. *Earth's Future*, 5, 214-223, doi: 10.1002/2016EF000494.

- BOM http://www.bom.gov.au/australia/tides/
- NASA https://sealevel.nasa.gov/understanding-sea-level/key-indicators/global-mean-sea-level
- NOAA COOPS https://tidesandcurrents.noaa.gov/sltrends/sltrends.html
- University of Hawai‘i Sea Level Center https://uhslc.soest.hawaii.edu/

Mean Sea Surface Temperature, Ocean Heat Waves

1. van Hooidonk, R., et al. (2016): Local-scale projections of coral reef futures and implications of the Paris Agreement. *Scientific Reports*, 6, 39666. https://doi.org/10.1038/srep39666.
2. Namias, J., and R.M. Born (1970): Temporal coherence in north Pacific sea-surface temperature patterns. *Journal of Geophysical Research*, 75, 5952-5955.
3. Deser, C., M. Alexander, S.-P. Xie, and A.S. Phillips (2010): Sea surface temperature variability: patterns and mechanisms. *Annual Review of Marine Science*, 2, 115-43.
4. Shea, D. (2018): NINO SST Indices (NINO 1+2, 3, 3.4, 4: ONI and TNI). https://climatedataguide.ucar.edu/climate-data/nino-sst-indices-nino-12-3-34-4-oni-and-tni.
5. Reynolds, R.W., et al. (2007): Daily high-resolution blended analyses for sea surface temperature, *Journal of Climate*, 20, 5473-5496.
6. Huang, B., C. Liu, V. Banzon, E. Freeman, G. Graham, B. Hankins, T. Smith, and H.-M. Zhang (2021): Improvements of the Daily Optimum Interpolation Sea Surface Temperature (DOISST) Version 2.1. *Journal of Climate*, 34, 2923-2939. doi: 10.1175/JCLI-D-20-0166.1.
7. Banzon, V., T.M. Smith, T.M. Chin, C. Liu, and W. Hankins (2016): A long-term record of blended satellite and in situ sea-surface temperature for climate monitoring, modelling and environmental studies. Earth System Science Data, 165-176. doi: 10.5194/essd-8-165-2016.
8. Zou, Y. and X. Xi (2021): An ongoing cooling in the eastern Pacific linked to eastward migrations of the southeast Pacific subtropical anticyclone. *Environmental Research Letters*, 16, 034020.
9. Hobday, A.J., Alexander, L.V., Perkins, S.E., Smale, D.A., Straub, S.C., Oliver, E.C.J., Benthuysen, J., Burrows, M.T., Donat, M. G., Feng, M., Holbrook, N.J., Moore, P.J., Scannell, H.A., Gupta, A.S., Wernberg, T. (2016): A hierarchical approach to defining marine heatwaves. *Progress in Oceanography*, 141, 227-238. doi: 210.1016/j.pocean.2015.1012.1014.
10. Hobday, A.J., Oliver, E.C.J., Gupta, A.S., Benthuysen, J.A., Burrows, M.T., Donat, M.G., Holbrook, N.J., Moore, P.J., Thomsen, M.S., Wernberg, T., Smale, D.A. (2018): Categorizing and naming marine heatwaves. *Oceanography*, 31(2). doi: 10.5670/oceanog.2018.5205.

- BOM http://www.bom.gov.au/climate/ahead/about/model/access.shtml.
- NASA https://climate.nasa.gov/vital-signs/global-temperature/.
- NOAA https://www.psl.noaa.gov/data/gridded/.
- NOAA OISST https://www.ncei.noaa.gov/products/optimum-interpolation-sst.
- Marine heat wave tracker http://www.marineheatwaves.org/tracker.html.
- Marine heat wave software https://github.com/ecjoliver/marineHeatWaves.
- APDRC http://apdrc.soest.hawaii.edu/datadoc/noaasst.php.

- Bulgin, C.E., C.J. Merchant, and D. Ferreira (2020): Tendencies, variability and persistence of sea surface temperature anomalies. *Scientific Reports*, 10, 7986. https://doi.org/10.1038/s41598-020-64785-9.
- Merchant, C. J., et al. (2019): Satellite-based time-series of sea-surface temperature since 1981 for climate applications. *Scientific Data*, 6. https://doi.org/10.1038/s41597-019-0236-x.

Ocean Acidification, Chlorophyll Concentration, and Estimated Phytoplankton Size

1. Feely, R.A., S.R. Alin, B. Carter, N. Bednarsek, B. Hales, F. Chan, T.M. Hill, B. Gaylord, E. Sanford, R.H. Byrne, C.L. Sabine, D. Greeley, and L. Juranek (2016): Chemical and biological impacts of ocean acidification along the west coast of North America. *Estuarine, Coastal and Shelf Science*, 183, 260-270.
2. UH SOEST HOT promo video. https://hahana.soest.hawaii.edu/hot/promo/promoVids.html.
3. NOAA PMEL primer on pH. https://www.pmel.noaa.gov/co2/story/A+primer+on+pH.
4. UH SOEST HOT Trends. https://hahana.soest.hawaii.edu/hot/trends/trends.html.
5. Barnes, C., X. Irigoien, J.A.A. De Oliveira, D. Maxwell, and S. Jennings (2011): Predicting marine phytoplankton community size structure from empirical relationships with remotely sensed variables. *Journal of Plankton Research*, 33(1), 13-24.

- Cao, L., and K. Caldeira (2008): Atmospheric CO2 stabilization and ocean acidification. *Geophysical Research Letters*, 35, L19609. doi:10.1029/2008GL035072.
- Clayton, T.D., and R.H. Byrne (1993): Spectrophotometric seawater pH measurements: total hydrogen ion concentration scale calibration of m-cresol purple and at-sea results. *Deep-Sea Research Part I*, 40, 2115-2129.
- DelValls, T.A., and A.G. Dickson (1998): The pH of buffers based on 2-amino-2-hydroxymethyl-1,3-propanediol (tris) in synthetic seawater. *Deep-Sea Research Part I*, 45, 1541-1554.
- Lewis, E., and D.W.R. Wallace (1998): Program developed for CO2 system calculations. ORNL/CDIAC-105. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee. doi: 10.1016/j.ecss.2016.08.043.
- Polovina, J.J., and P.A. Woodworth (2012): Declines in phytoplankton cell size in the subtropical oceans estimated from satellite remotely-sensed temperature and chlorophyll, 1998–2007. *Deep Sea Research Part II: Topical Studies in Oceanography*, 77, 82-88.
- Woodworth-Jefcoats, P.A., J.J. Polovina, J.P. Dunne, and J.L. Blanchard (2013): Ecosystem size structure response to 21st century climate projection: Large fish abundance decreases in the central North Pacific and increases in the California Current. *Global Change Biology*, 19, 724-733. doi: 10.1111/gcb.12076.

Future Climate

Data and Methods

Confidence in projected changes is assessed from multiple lines of evidence using the semi-quantitative system used in IPCC assessments1. Evidence includes:

- Physical processes;
- Past trends and their formal attribution;
- Evaluation of climate models; and
- Agreement between climate models

Confidence in some projections for the Pacific is lower than other regions due to long-standing model biases such as the cold tongue and double ITCZ bias (see Grose et al. 2014[20] and Grose et al. 2020[21]).

Projections are given for the Shared Socio-economic Pathways (SSPs), each with a narrative about human development then a number quantifying the amount of enhanced greenhouse effect by 2100. The narrative and the greenhouse effect for the most common ('Tier 1') combinations are as follows.

Shared Socio-economic Pathway	Narrative	Tier 1 Combinations
SSP1—Sustainability	Pervasive shift to sustainable path, lower challenges to both mitigation and adaptation	SSP1-1.9 (1.9 Wm^{-2}) SSP1-2.6
SSP2—Middle of the Road	Trends largely following historical path, medium challenges	SSP2-4.5
SSP3—Regional Rivalry	Regional conflicts and nationalism, high challenges	SSP3-7.0
SSP4—Inequality	Unequal investment, growing gaps, low challenges to mitigation, high challenges to adaptation	
SSP5—Fossil-fueled Development	Market-driven path, rapid growth	SSP5-8.5

The rainfall climate of most regions in the Pacific is dominated by a single feature such as the ITCZ, SPCZ or Asia-Australia Monsoon, and the future change in this main feature is the dominant source of uncertainty. Another dominant feature in terms of future change is the degree of 'enhanced equatorial warming' leading to rainfall increase at the equatorial region. The more important nature of the change in each feature (e.g., in latitude or in terms of strength of the feature) is reported in CSIRO and SPREP (2021)[4] and based on the literature.

- SPCZ—change in latitude and orientation (Brown et al. 2013, 2020)[9-10]
- ITCZ—strengthening or weakening (Byrne et al. 2018)[11]
- Equatorial warming—enhanced or more uniform spatial pattern (Grose et al. 2015)[12], affecting equatorial region but also the northeast SPCZ region
- Asia-Australia monsoon—enhancement or weakening (Narsey et al. 2020)[13]

Sources of Information and Further Reading

1. Mastrandrea, M.D., C.B. Field, T.F. Stocker, O. Edenhofer, K.L. Ebi, D.J. Frame, H. Held, E. Kriegler, K.J. Mach, P.R. Matschoss, G.-K. Plattner, G.W. Yohe, and F.W. Zwiers (2010): *Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties*. Intergovernmental Panel on Climate Change.
2. Meinshausen, M., et al. (2019): The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500. *Geoscientific Model Development*, 2019, 1-77. doi: 10.5194/gmd-13-3571-2020.
3. Masson-Delmotte, V., et al. (2021): *Climate Change 2021: The Physical Science Basis*. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Cambridge University Press.
4. CSIRO and SPREP (2021): 'NextGen' projections for the western tropical Pacific: Current and future climate for Fiji. Final report to the Australia-Pacific Climate Partnership for the Next Generation Climate Projections for the Western Tropical Pacific project. Commonwealth Scientific and Industrial Research Organisation (CSIRO) and Secretariat of the Pacific Regional Environment Programme (SPREP), CSIRO Technical Report, Melbourne, Australia. https://doi.org/10.25919/5gh8-qt86 (https://www.rccap.org).
5. Seneviratne, S.I., X. Zhang, M. Adnan, W. Badi, C. Dereczynski, A. Di Luca, S. Ghosh, I. Iskandar, J. Kossin, S. Lewis, F. Otto, I. Pinto, M. Satoh, S.M. Vicente-Serrano, M. Wehner, and B. Zhou (2021): Weather and climate extreme events in a changing climate supplementary material. In Masson-Delmotte, V., et al. (Eds.), *Climate Change 2021: The Physical Science Basis*. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. https://www.ipcc.ch/.

6. Gutiérrez, J.M., et al. (2021): Atlas. In Masson-Delmotte, V., et al. (Eds.), *Climate Change 2021: The Physical Science Basis*. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. In Press.
7. Gutiérrez, J.M., et al. (2021): Atlas. In Masson-Delmotte, V., et al. (Eds.), *Climate Change 2021: The Physical Science Basis*. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. http://interactive-atlas.ipcc.ch/.
8. State of Hawaiʻi Climate Change portal 2021. https://climate.hawaii.gov/.
9. Brown, J.R., R.A. Colman, A.F. Moise and I.N. Smith (2013): The western Pacific monsoon in CMIP5 models: Model evaluation and projections. *Journal of Geophysical Research-Atmospheres*, 118(22), 2013JD020290.
10. Brown, J.R., M. Lengaigne, B.R. Lintner, M.J. Widlansky, K. van der Wiel, C. Dutheil, B.K. Linsley, A.J. Matthews, and J. Renwick (2020): South Pacific convergence zone dynamics, variability and impacts in a changing climate. *Nature Reviews Earth and Environment*.
11. Byrne, M.P., A.G. Pendergrass, A.D. Rapp, and K.R. Wodzicki (2018): Response of the intertropical convergence zone to climate change: Location, width, and strength. *Current Climate Change Reports*, 4(4), 355-370.
12. Grose, M.R., J. Bhend, S. Narsey, A.S. Gupta, and J.R. Brown (2015): Can we constrain CMIP5 rainfall projections in the tropical Pacific based on surface warming patterns? *Journal of Climate*, 27(24), 9123-9138.
13. Narsey, S.Y., J.R. Brown, R.A. Colman, F. Delage, S.B. Power, A.F. Moise, and H. Zhang (2020): Climate change projections for the Australian monsoon from CMIP6 models. *Geophysical Research Letters*, 47(13), e2019GL086816.
14. Dhage, L., and M.J. Widlansky (2022): Assessment of 21stcentury changing sea surface temperature, rainfall, and sea surface height patterns in the tropical Pacific Islands using CMIP6 greenhouse warming projections. *Earth's Future*. https://doi.org/10.1029/2021EF002524.
15. Shepherd, T. G., et al. (2018): Storylines: an alternative approach to representing uncertainty in physical aspects of climate change. *Climatic Change*, 151(3), 555-571.
16. Hersbach, H., et al. (2020): The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, 146(730), 1999-2049.
17. Knutson, T., et al. (2020): Tropical cyclones and climate change assessment: Part II: Projected response to anthropogenic warming. *Bulletin of the American Meteorological Society*, E303-E322. https://doi.org/10.1175/BAMS-D-18-0194.1.
18. Holbrook, N.J., V. Hernaman, S. Koshiba, J. Lako, J.B. Kajtar, P. Amosa, and A. Singh (2022): Impacts of marine heat waves on tropical western and central Pacific Island nations and their communities. *Global and Planetary Change*, 208, 103680.
19. Frölicher, T.L., K.B. Rodgers, C.A. Stock, and W.W.L. Cheung (2016): Sources of uncertainties in 21st century projections of potential ocean ecosystem stressors. *Global Biogeochem. Cycles*, 30(8), 1224-1243. doi: 10.1002/2015GB005338.
20. Grose, M.R., J.N. Brown, S. Narsey, J.R. Brown, B.F. Murphy, C. Langlais, A. Sen Gupta, A.F. Moise, and D.B. Irving (2014): Assessment of the CMIP5 global climate model simulations of the western tropical Pacific climate system and comparison to CMIP3. *International Journal of Climatology*, 34(12), 3382-3399.
21. Grose, M.R., et al. (2020): Insights from CMIP6 for Australia's future climate. *Earth's Future*, 8(5), e2019EF001469 (includes an assessment of the cold tongue bias in the Pacific in CMIP6).

Observed and Expected Impacts

Sources of Information and Further Reading

1. Bell, J., and M. Taylor (2015): Building climate-resilient food systems for Pacific Islands. 2015-15. Program Report 2015-15. WorldFish, Penang, Malaysia. http://pubs.iclarm.net/resource_centre/2015-15.pdf.
2. Taylor, M., A. McGregor, and B. Dawson, Eds. (2016): *Vulnerability of Pacific Island Agriculture and Forestry to Climate Change*. Noumea Cedex, New Caledonia, 559 pp. http://www.pacificfarmers.com/wp-content/uploads/2016/07/Vulnerability-of-Pacific-Island-agriculture-and-forestry-to-climate-change.pdf.
3. Bell, J.D., et al. (2021): Pathways to sustaining tuna-dependent Pacific Island economies during climate change. *Nature Sustainability*, 4, 900-910. https://doi.org/10.1038/s41893-021-00745-z.
4. Friday, J.B., K. Friday, and C. Elevitch (2017: Appendix A: Regional summaries: Hawai‘i and the U.S.-Affiliated Pacific Islands. In Schoeneberger, M. M., G. Bentrup, and T. Patel-Weynand (Eds.), *Agroforestry: Enhancing Resiliency in U.S. Agricultural Landscapes Under Changing Conditions*. U.S. Department of Agriculture, Forest Service, Washington, DC, p. 147-153. https://www.fs.usda.gov/treesearch/pubs/55775.
5. Keener, V., D. Helweg, S. Asam, S. Balwani, M. Burkett, C. Fletcher, T. Giambelluca, Z. Grecni, M. Nobrega-Olivera, J. Polovina, and G. Tribble (2018): Hawai‘i and U.S.-Affiliated Pacific Islands. In Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (Eds.), *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment*. U.S. Global Change Research Program, Washington, DC, USA, Volume II, pp. 1242-1308. doi: 10.7930/NCA4.2018.CH27.
6. McGree, S., S. Schreider, Y. Kuleshov, and B. Prakash (2020): On the use of mean and extreme climate indices to predict sugar yield in western Fiji. *Weather and Climate Extremes*, 29, 100271. https://doi.org/10.1016/j.wace.2020.100271.
7. Storlazzi, C.D., S.B. Gingerich, A. Dongeren, O.M. van, Cheriton, P.W. Swarzenski, E. Quataert, C.I. Voss, D.W. Field, H. Annamalai, G.A. Piniak, and R. McCall (2018): Most atolls will be uninhabitable by the mid-21st century because of sea-level rise exacerbating wave-driven flooding. *Science Advances*, 4, eaap9741. https://doi.org/10.1126/sciadv.aap9741.
8. Wairiu, M. (2017): Land degradation and sustainable land management practices in Pacific Island Countries. *Regional Environmental Change*, 17, 1053-1064. https://doi.org/10.1007/s10113-016-1041-0.
9. Keener, V., Z. Grecni, C. Shuler, K. Anderson Tagarino, and W. Miles (2021): Climate change in American Sāmoa: Indicators and considerations for key sectors. Report for the Pacific Islands Regional Climate Assessment. East-West Center, Honolulu, HI. https://doi.org/10.5281/zenodo.4663397.
10. Nalau, J., J. Handmer, and M. Dalesa (2017): The role and capacity of government in a climate crisis: Cyclone Pam in Vanuatu. In Leal Filho, W. (Ed.), *Climate Change Adaptation in Pacific Countries: Fostering Resilience and Improving the Quality of Life.* Climate Change Management, Springer, Cham. https://doi.org/10.1007/978-3-319-50094-2_9.
11. Haynes, E., et al. (2020): Food sources and dietary quality in small island developing states: Development of methods and policy relevant novel survey data from the Pacific and Caribbean. *Nutrients*, 12(11), 3350. doi: 10.3390/nu12113350.
12. McNaught, R., O. Warrick, and A. Cooper (2014): Communicating climate change for adaptation in rural communities: A Pacific study. *Regional Environmental Change*, 14(4), 1491-1503. https://doi.org/10.1007/s10113-014-0592-1.
13. Brown, P., A. Daigneault, and D. Gawith (2017): Climate change and the economic impacts of flooding on Fiji. *Climate and Development*, 9(6), 493-504. https://doi.org/10.1080/17565529.2016.1174656.

14. Rey, T., L. le De, F. Leone, and D. Gilbert (2017): An integrative approach to understand vulnerability and resilience post-disaster: The 2015 Cyclone Pam in urban Vanuatu as case study. *Disaster Prevention and Management*, 26(3), 259-275. https://doi.org/10.1108/DPM-07-2016-0137.
15. Hoeke, R.K., H. Damlamian, J. Aucan, and M. Wandres (2021): Severe flooding in the atoll nations of Tuvalu and Kiribati triggered by a distant Tropical Cyclone Pam. *Frontiers in Marine Science*, 7, 539646. https://doi.org/10.3389/fmars.2020.539646.
16. Salmon, Camille, Virginie KE Duvat, and Victoire Laurent (2019): "Human-and Climate-Driven Shoreline Changes on a Remote Mountainous Tropical Pacific Island: Tubuai, French Polynesia Human-and Climate-Driven Shoreline Changes on a Remote Mountainous Tropical Pacific." Anthropocene Review 25. https://doi.org/10.1016/j.ancene.2019.100191ï.
17. Winter, G., et al. (2020): Steps to develop early warning systems and future scenarios of storm wave-driven flooding along coral reef-lined coasts. *Frontiers in Marine Science*, 7, 199. https://doi.org/10.3389/fmars.2020.00199.
18. Beetham, E., P.S. Kench, and S. Popinet (2017): Future reef growth can mitigate physical impacts of sea-level rise on atoll islands. *Earth's Future*, 5(10), 1002-1014. https://doi.org/10.1002/2017EF000589.
19. Ahmed, I., and T. McDonnell (2020): Prospects and constraints of post-cyclone housing reconstruction in Vanuatu drawing from the experience of Tropical Cyclone Harold. *Progress in Disaster Science*, 8, 100126. https://doi.org/10.1016/j.pdisas.2020.100126.
20. Romine, B.M., and C.H. Fletcher (2013): A summary of historical shoreline changes on beaches of Kauai, O'ahu, and Maui, Hawai'i. *Journal of Coastal Research*, 288, 605-614. https://doi.org/10.2112/JCOASTRES-D-11-00202.1.
21. Kumar, L., and S. Taylor (2015): Exposure of coastal built assets in the South Pacific to climate risks. *Nature Climate Change*, 5(11), 992-996. https://doi.org/10.1038/nclimate2702.
22. Andrew, N.L., P. Bright, L. de la Rua, S.J. Teoh, and M. Vickers (2019): Coastal proximity of populations in 22 Pacific island countries and territories. PLOS ONE, 14 (9), e0223249. https://doi.org/10.1371/journal.pone.0223249.
23. Taupo, T., and I. Noy (2016): At the very edge of a storm: The impact of a distant cyclone on atoll islands at the very edge of a storm. *Economics of Disasters and Climate Change*, 1, 143-166. https://ssrn.com/abstract=2898124https://ssrn.com/abstract=2898124.
24. Fakhruddin, S. H.M., M. S. Babel, and A. Kawasaki (2015): Assessing the vulnerability of infrastructure to climate change on the islands of Samoa. *Natural Hazards and Earth System Sciences*, 15(6), 1343-1356. https://doi.org/10.5194/nhess-15-1343-2015.
25. Lee, D., H. Zhang, and C. Nguyen. (2018): The economic impact of natural disasters in Pacific island countries: Adaptation and preparedness. International Monetary Fund Working Paper no. 2018/108, 37 pp. https://www.imf.org/en/Publications/WP/Issues/2018/05/10/The-Economic-Impact-of-Natural-Disasters-in-Pacific-Island-Countries-Adaptation-and-45826
26. Kuleshov, Y., S. McGree, D. Jones, A. Charles, A. Cottrill, B. Prakash, T. Atalifo, S. Nihmei, and F.L.S.K. Seuseu. (2014): Extreme weather and climate events and their impacts on island countries in the Western Pacific: Cyclones, floods and droughts. *Atmospheric and Climate Sciences*, 4(5), 803-818. https://doi.org/10.4236/acs.2014.45071.
27. Mansur, A., J. Doyle, and O. Ivaschenko (2017): Social protection and humanitarian assistance nexus for disaster response: Lessons learnt from Fiji's Tropical Cyclone Winston. World Bank Group, Social Protection & Labor, Discussion Paper no. 1701, 52 pp. https://documents1.worldbank.org/curated/en/143591490296944528/pdf/113710-NWP-PUBLIC-P159592-1701.pdf
28. Frazier, A.G. (2019): Economic costs of drought in Hawai'i. http://dlnr.hawaii.gov/drought/.

29. Butcher-Gollach, C. (2015): Planning, the urban poor and climate change in small island developing states (SIDS): Unmitigated disaster or inclusive adaptation? *International Development Planning Review*, 37(2), 225-248. https://doi.org/10.3828/idpr.2015.17.
30. Chandra, A., and P. Gaganis (2016): Deconstructing vulnerability and adaptation in a coastal river basin ecosystem: A participatory analysis of flood risk in Nadi, Fiji Islands. *Climate and Development*, 8(3), 256-269. https://doi.org/10.1080/17565529.2015.1016884.
31. McGree, S., N. Herold, L. Alexander, S. Schreider, Y. Kuleshov, E. Ene, S. Finaulahi. (2019): Recent changes in mean and extreme temperature and precipitation in the western Pacific islands. *Journal of Climate*, 32(16), 4919-4941. https://doi.org/10.1175/JCLI-D-18-0748.1.
32. Gingerich, S.B., C.I. Voss, and A.G. Johnson (2017): Seawater-flooding events and impact on freshwater lenses of low-lying islands: Controlling factors, basic management and mitigation. *Journal of Hydrology*, 551, 676688. doi: 10.1016/j.jhydrol.2017.03.001.
33. Feinstein, C. (2014): SIDS—towards a sustainable energy future. Presented at WB-UN High Level Dialogue on Advancing Sustainable Development in Small Island Developing States, World Bank Group, June 13, 2014. https://www.worldbank.org/content/dam/Worldbank/SIDS%20Towards%20Sustainable%20Energy%20Future.pdf.
34. World Health Organization, Western Pacific Region (2015): Human health and climate change in Pacific Island countries. WHO Press, Geneva, Switzerland, 145 pp. https://www.who.int/publications/i/item/human-health-and-climate-change-in-pacific-island-countries.
35. Anderson, D.L., P. Ruggiero, F.J. Mendez, P.L. Barnard, L.H. Erikson, A.C. O'Neill, M. Merrifield, A. Rueda, L. Cagigal, and J. Marra (2021): Projecting climate dependent coastal flood risk with a hybrid statistical dynamical model. *Earth's Future*, 9, e2021EF002285. https://doi.org/10.1029/2021EF002285.
36. Morrow, G., and K. Bowen (2014): Accounting for health in climate change policies: a case study of Fiji. *Global Health Action*, 7, 1. doi: 10.3402/gha.v7.23550.
37. World Health Organization (2011): Noncommunicable diseases country profiles. Geneva: World Health Organization.
38. Ichiho, H.M., J.W. Gillan, and N. Aitaoto (2013): An assessment of non-communicable diseases, diabetes, and related risk factors in the Territory of Guam: a systems perspective. *Hawai'i Journal of Medical and Public Health*, 72, 68-76.
39. Gibson, K.E., J. Barnett, N. Haslam, and I. Kaplan (2020): The mental health impacts of climate change: Findings from a Pacific Island atoll nation. *Journal of Anxiety Disorders*, 73, 102237. https://doi.org/10.1016/j.janxdis.2020.102237.
40. Sarofim, M. C., et al. (2016): Ch. 2: Temperature-related death and illness. The impacts of climate change on human health in the United States: A scientific assessment, U.S. Global Change Research Program, pp. 43-68. http://dx.doi.org/10.7930/J0MG7MDX.
41. Miles, W., Z. Grecni, P. Matsutaro, P. Colin, V. Keener, and Y. Golbuu (2020): Climate change in Palau: Indicators and considerations for key sectors. Report for the Pacific Islands Regional Climate Assessment. East-West Center, Honolulu, HI. https://doi.org/10.5281/zenodo.4124259.
42. Grecni, Z., W. Miles, R. King, A. Frazier, and V. Keener (2020): Climate change in Guam: Indicators and considerations for key sectors. Report for the Pacific Islands Regional Climate Assessment. East-West Center, Honolulu, HI. https://doi.org/10.58281/zenodo.4037481.
43. Grecni, Z., W. Miles, R. Greene, E. Derrington, and V. Keener (2021): Climate change in the Commonwealth of the Northern Marianas Islands: Indicators and considerations for key sectors. Report for the Pacific Islands Regional Climate Assessment. East-West Center, Honolulu, HI. https://doi.org/10.5281/zenodo.4426942.
44. Savage, A., L. McIver, and L. Schubert (2020): Review: The nexus of climate change, food and nutrition security and diet-related non-communicable diseases in Pacific island countries and territories. *Climate and Development*, 12(2), 120-133. https://doi.org/10.1080/17565529.2019.1605284.

45. Cai, W., S. Borlace, M. Lengaigne, P. van Rensch, M. Collins, G. Vecchi, A. Timmermann, A. Santoso, M.J. McPhaden, L. Wu, M.H. England, G. Wang, E. Guilyardi, and F.-F. Jin (2014): Increasing frequency of extreme El Niño events due to greenhouse warming. *Nature Climate Change*, 4(2), 111-116. doi: 10.1038/nclimate2100.
46. Cai, W., G. Wang, A. Santoso, M.J. McPhaden, L. Wu, F.-F. Jin, A. Timmermann, M. Collins, G. Vecchi, M. Lengaigne, M.H. England, D. Dommenget, K. Takahashi, and E. Guilyardi (2015): Increased frequency of extreme La Niña events under greenhouse warming. *Nature Climate Change*, 5(2), 132-137. doi: 10.1038/nclimate2492.
47. Murphy, B.F., S.B. Power, and S. McGree (2014): The varied impacts of El Niño-Southern Oscillation on Pacific island climates. *Journal of Climate*, 27(11), 4015-4036. https://doi.org/10.1175/JCLI-D-13-00130.1.
48. Strauch, A.M. (2020): Evaluating the management of a tropical reservoir: Implications of climate change for water availability. *Pacific Science*, 74(2), 115-135. https://doi.org/10.2984/74.2.2.
49. Kruk, M.C., A.M. Lorrey, G.M. Griffiths, M. Lander, E.J. Gibney, H.J. Diamond, and J.J. Marra (2015): On the state of the knowledge of rainfall extremes in the western and northern Pacific basin. *International Journal of Climatology*, 35(3), 321-336. doi:10.1002/joc.3990.
50. Johnson, J.E., J.D. Bell, V. Allain, Q. Hanich, P. Lehodey, B.R. Moore, S. Nicol, T. Pickering, and I. Senina (2017): The Pacific Island region: Fisheries, aquaculture and climate change. In Phillips, B.F., and M. Pérez-Ramírez (Eds.), *Climate Change Impacts on Fisheries and Aquaculture: A Global Analysis*, Volume I, First Edition.
51. Pickering, T.D., B. Ponia, C.A. Hair, P.C. Southgate, E.S. Poloczanska, L.D. Patrona, A. Teitelbaum, C.V. Mohan, M.J. Phillips, J.D. Bell, and S.D. Silva (2011): Chapter 11: Vulnerability of aquaculture in the tropical Pacific to climate change. In Bell, J.D., Secretariat of the Pacific Community (Eds.), *Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change*. Secretariat of the Pacific Community, Noumea, New Caledonia.
52. Asch, R.G., W.W.L. Cheung, and G. Reygondeau (2018): Future marine ecosystem drivers, biodiversity, and fisheries maximum catch potential in Pacific Island countries and territories under climate change. *Marine Policy*, 88, 285-294. https://doi.org/10.1016/j.marpol.2017.08.015.
53. Bell, J.D., A. Ganachaud, P.C. Gehrke, S.P. Griffiths, A.J. Hobday, O. Hoegh-Guldberg, J.E. Johnson, R. Le Borgne, P. Lehodey, J.M. Lough, R.J. Matear, T.D. Pickering, M.S. Pratchett, A.S. Gupta, I. Senina, and M. Waycott (2013): Mixed responses of tropical Pacific fisheries and aquaculture to climate change. *Nature Climate Change*, 3, 591–599. https://doi.org/10.1038/nclimate1838.
54. Bell, J.D., J. Albert, G. Amos, C. Arthur, M. Blanc, D. Bromhead, S.F. Heron, A.J. Hobday, A. Hunt, D. Itano, P.A.S. James, P. Lehodey, G. Liu, S. Nicol, J. Potemra, G. Reygondeau, J. Rubani, J. Scutt Phillips, I. Senina, and W. Sokimi (2018): Operationalising access to oceanic fisheries resources by small-scale fishers to improve food security in the Pacific Islands. *Marine Policy*, 88, 315-322. https://doi.org/10.1016/j.marpol.2017.11.008.
55. Barange, M., T. Bahri, M.C.M. Beveridge, K.L. Cochrane, S. Funge Smith, F. Poulain, Food and Agriculture Organization of the United Nations (2018): Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options. https://www.fao.org/3/i9705en/i9705en.pdf.
56. Van Hooidonk, R., J. Maynard, J. Tamelander, J. Gove, G. Ahmadia, L. Raymundo, G. Williams, S.F. Heron, and S. Planes (2016): Local-scale projections of coral reef futures and implications of the Paris Agreement. *Scientific Reports*, 6, 39666. https://doi.org/10.1038/srep39666.
57. Magel, J., S. Dimoff, and J. K. Baum (2020): Direct and indirect effects of climate change-amplified pulse heat stress events on coral reef fish communities. *Ecological Applications*, 30(6). doi: 10.1002/eap.2124.
58. Hoegh-Guldberg, O., and T. Ridgway (2016): Reviving Melanesia's ocean economy: The case for action. Global Change Institute/WWF Oceania, p. 1-64. ISBN, ISBN (978-2-940529-43-8).

59. Gonzalez, R., V. Ram-Bidesi, G. Leport, N. Pascal, L. Brander, L. Fernandes, J. Salcone, and A. Seidl (2015): National marine ecosystem service valuation: Fiji. MACBIO (GIZ/IUCN/SPREP) Suva, Fiji. 91 pp.

60. Brodie, G., and A. de Ramon N'Yeurt (2018): Effects of climate change on seagrasses and seagrass habitats relevant to the Pacific Islands. Suva.

61. Lough, J.M., G.A. Meehl, and M.J. Salinger (2011): Observed and projected changes in surface climate of the tropical Pacific. In Bell, J.D., J.E. Johnson, and A.J. Hobday (Eds.), *Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change*, Secretariat of the Pacific Community, Noumea, New Caledonia. pp. 40-99.

62. Scott, D., C.M. Hall, and S. Gössling (2019): Global tourism vulnerability to climate change. *Annals of Tourism Research*, 77, 49-61. https://doi.org/10.1016/j.annals.2019.05.007.

63. Mcleod, E., J. Hinkel, A.T. Vafeidis, R.J. Nicholls, N. Harvey, and R. Salm (2010): Sea-level rise vulnerability in the countries of the Coral Triangle. *Sustainability Science*, 5, 207-222. https://doi.org/10.1007/s11625-010-0105-1.

64. Parsons, M., C. Brown, J. Nalau, and K. Fisher (2018): Assessing adaptive capacity and adaptation: Insights from Samoan tourism operators. *Climate and Development*, 10(7), 644-663. https://doi.org/10.1080/17565529.2017.1410082.

65. Spalding, M., L. Burke, S.A. Wood, J. Ashpole, J. Hutchison, and P. zu Ermgassen (2017): Mapping the global value and distribution of coral reef tourism. *Marine Policy*, 82, 104-113. https://doi.org/10.1016/j.marpol.2017.05.014.

66. IUCN (2013): Impacts of projected climate change on mangrove and coastal ecosystems and community livelihoods in Solomon Islands, Vanuatu, Fiji, Tonga, Samoa. 46 pp. https://www.iucn.org/sites/dev/files/impacts_of_projected_climate_change_on_mangrove_and_coastal_ecosystems_and_community_livelihood.pdf.

67. Barbier, E. B. (2020): Progress and challenges in valuing coastal and marine ecosystem services. *Review of Environmental Economics and Policy*.

68. McKenzie, L.J., R.L. Yoshida, J.W. Aini, S. Andréfouet, P.L. Colin, L.C. Cullen-Unsworth, A.T. Hughes, C.E. Payri, M. Rota, C. Shaw, P.A. Skelton, R.T. Tsuda, V.C. Vuki, and R.K.F. Unsworth (2021): Seagrass ecosystems of the Pacific Island Countries and Territories: A global bright spot. *Marine Pollution Bulletin*, 167, 112308. https://doi.org/10.1016/j.marpolbul.2021.112308.

69. Oppenheimer, M., B.C. Glavovic , J. Hinkel, R. van de Wal, A.K. Magnan, A. Abd-Elgawad, R. Cai, M. CifuentesJara, R.M. DeConto, T. Ghosh, J. Hay, F. Isla, B. Marzeion, B. Meyssignac, and Z. Sebesvari (2019): Sea level rise and implications for low-lying islands, coasts and communities. In Pörtner, H.-O., D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, and N.M. Weyer (Eds.), *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*.

70. Wolf, F., W.L. Filho, P. Singh, N. Scherle, D. Reiser, J. Telesford, I.B. Miljković, P.H. Havea, C. Li, D. Surroop, and M. Kovaleva (2021): Influences of climate change on tourism development in small Pacific Island states. *Sustainability*, 13, 4223. https://doi.org/10.3390/su13084223.

71. Government of Vanuatu (2015): Vanuatu post disaster needs assessment: Tropical Cyclone Pam, March 2015. Port Vila.

Case Studies

- Secretariat of the Pacific Regional Environment Programme (2019): Pacific Roadmap for Strengthened Climate Services, 2021–2026. Apia, Samoa, 4pp.
- Ministry of Marine Resources and SPC Pacific Community (2012): Cook Islands Aquaculture Development Plan 2012-2016. Noumea.
- Shuler, C.K., and M. Comeros-Raynal (2020): Ridge to Reef Management Implications for the Development of an Open-Source Dissolved Inorganic Nitrogen Loading Model in American Sāmoa. *Environmental Management*, 66(3), 498-515. https://doi.org/10.1007/s00267-020-01314-4.
- Shuler, C.K., L. Brewington, and A.I. El-Kadi (2021): A participatory approach to assessing groundwater recharge under future climate and land-cover scenarios, Tutuila, American Sāmoa. *Journal of Hydrology: Regional Studies*, 34, 100785. https://doi.org/10.1016/j.ejrh.2021.100785.

Visit the WMO RA-V Pacific Regional Climate Centre (RCC) Network page at https://www.pacificmet.net/rcc