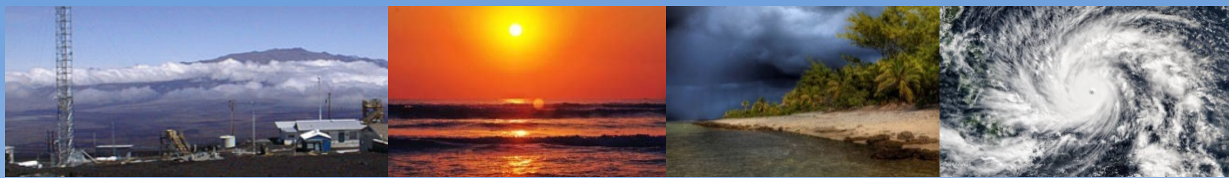
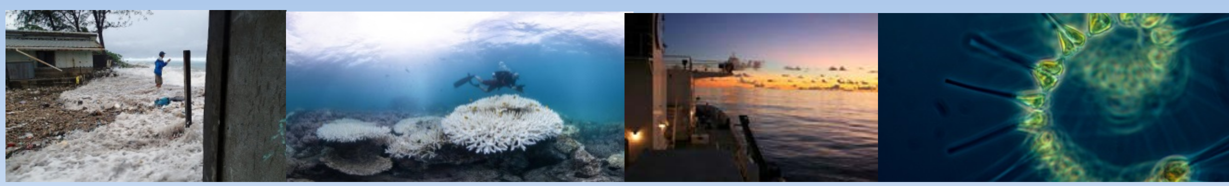


State of Environmental Conditions in Hawaii and the U.S. Affiliated Pacific Islands under a Changing Climate: 2017



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October 2017

State of Environmental Conditions in Hawaii and the U.S. Affiliated Pacific Islands under a Changing Climate: 2017

At a Glance

This report describes the current state of environmental conditions in Hawaii and the U.S. Affiliated Pacific Islands (USAPI) in terms of a set of foundational measures or *indicators* of change. This information about the trends and patterns in physical, biological, chemical, and ecological observations under a changing climate is intended to facilitate communication among and inform decisions of a broad spectrum of public and private sector stakeholders. Highlights are provided below. Background on *Hawaii and the USAPI*, information *About this Report*, and details about each of the eight indicators are provided in the sections that follow.

Main Takeaways

- Hawaii and the U.S. Affiliated Pacific Islands encompass a vast region comprised of isolated islands that are strategic to U.S. defense and contain global hotspots of marine biodiversity. These islands are exposed to environmental changes that affect every aspect of life.
- Discernable trends can be found in global to local measures of greenhouse gas concentrations, surface air temperatures, sea level, sea surface temperature, and ocean acidification. All are rising at an increasing rate. Ocean chlorophyll concentration in surface waters is decreasing.
  - Over the last 60 years the concentration of carbon dioxide (CO_2) in the atmosphere has increased by about 90 ppm (parts per million), to a value of just over 404 ppm in December of 2016.
  - In the Pacific region, land-surface temperatures have been rising at the rate of +0.17°C (0.31°F) per decade since the 1980s, slightly ahead of the global trend. Since 2005, nearly all surface stations have seen annual temperature anomalies above the long-term average.
  - Since the early 1990s, global mean sea level (GMSL) has been rising at a rate of about 3.3 mm (0.13 in) per year. Sea level has also been rising across the region, from as low as 1.1 mm (0.43 in) per year at the Honolulu tide gauge to as high as 5.4 mm (0.21 in) per year at the Kwajalein tide gauge since the early 1990s. However, regional and local sea level trends may differ significantly from the globally averaged rate over multiyear to multidecadal time scales.
  - Globally averaged sea surface temperature (SST) increased by about 1.0°C (1.8°F) over the past 100 years. Half of this rise has occurred since the early 1990s. Regionally averaged SST trends follow the globally averaged trend. Over the last 5 years almost the

entire tropical Pacific and in particular areas along the equator have seen temperatures warmer than the average over the last 30 years.
  - Globally, aragonite saturation state (a proxy for ocean acidity) has decreased at a rate of −0.03 per decade over the last 200+ years. More recent rates of change in aragonite saturation state, on the order of −0.13 per decade, are reported for the Pacific Ocean.
  - In all major mid-ocean subtropical gyres there has been an expansion of areas with low chlorophyll concentration (low biological productivity) since 1998. During the 9-year period 1998–2006, low productivity areas within the North Pacific subtropical gyre grew by 2.2% per year.
- Trends in measures of rainfall, surface winds, and tropical cyclones are not as readily apparent. Patterns of climate variability characterize these measures, and tend to mask long-term trends. Exceptions are consistent increases in the number of days with heavy precipitation and subregional changes in the number of days with high winds.
  - Precipitation patterns are highly regionalized, often with local variations in those regions. Average annual rainfall amounts over the last 50 years indicate that western Micronesia is getting wetter while eastern Micronesia is trending drier. Hawaii and parts of the Central Pacific are also drying out, but rainfall amounts are gradually increasing in the central south Pacific, an area that includes American Samoa.
  - The global frequency of tropical cyclones (TCs) appears to be showing a slow downward trend since the early 1970s. In the Pacific region long-term TC trends in frequency and intensity are relatively flat, with the record punctuated by as many active as inactive years.
- Changes in the magnitude of particular indicators may be small, but these small changes in magnitude can translate to large changes in frequency.
  - At the tide gauge at Kwajalein, high water events that occurred less than once a year, on average, in the 1960s occurred 22 times a year, on average, during the decade staring in 2005.
  - For American Samoa and Samoa the number of days per year with a Degree Heating Week (DHW) value reaching at least 1°C-week has increased has increased from 8 days during the first 10 years of the record to frequently more than 50 days during the last 10 years of the record.
- 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.

State of the Environment Scorecard

	WHERE DO WE STAND?	A LOOK AHEAD	READ MORE IN SECTION
GREENHOUSE GASES			
Carbon Dioxide	Increasing	Increasing	1
WEATHER AND CLIMATE			
Surface Temperature			2
Regional Average	Increasing	Increasing	
Frequency of Hot Days	Increasing	Increasing	
Frequency of Cold Nights	Decreasing	Decreasing	
Rainfall			3
Annual Average			
Central Pacific	Decreasing	Change*	
Western Pacific	No Change	Increasing	
South Pacific	Increasing	Increasing	
Extreme Wet Days			
Central Pacific	Decreasing	Increasing	
Western Pacific	Increasing^T	Increasing	
South Pacific	Increasing	Increasing	
Extreme Dry Days			
Central Pacific	Increasing	Change*	
Western Pacific	No Change	Change*	
South Pacific	No Change	Change*	
Surface Winds & Tropical Cyclones			4
Tradewinds	No Change	Change*	
Monsoon Winds	No Change	Change*	
Winds >Than 34 Knots			
Central Pacific	Decreasing	Change*	
Western Pacific	Increasing	Decreasing	
South Pacific	Increasing	Increasing	
Tropical Cyclone Frequency			
Central Pacific	No Change	Increasing	
Western Pacific	No Change	Decreasing	
South Pacific	No Change	Decreasing	
Tropical Cyclone Intensity			
Central Pacific	No Change	Increasing	
Western Pacific	No Change	Increasing	
South Pacific	No Change	Increasing	

	WHERE DO WE STAND?	A LOOK AHEAD	READ MORE IN SECTION
COASTS AND OCEANS			
Sea Level			5
Global	Increasing*	Increasing	
Central Pacific	Increasing	Increasing	
Western Pacific	Increasing	Increasing	
South Pacific	Increasing	Increasing	
Flood Frequency			
Central Pacific	Increasing	Increasing	
Western Pacific	Increasing	Increasing	
South Pacific	Increasing	Increasing	
Sea Surface Temperature (SST)			6
Regional SST	Increasing	Increasing	
Degree Heating Weeks	Increasing	Increasing	
Ocean Acidification			7
Global Aragonite Saturation State	Decreasing	Decreasing	
Regional pH	Decreasing*	Decreasing	
Ocean Chlorophyll Concentration			8
Chlorophyll Concentration	Decreasing*	Decreasing	

(red)	Increasing trend, likely to increase
(yellow)	No clear trend, neutral changes
(blue)	Decreasing trend, likely to decrease
*	Asterisk denotes indicator is highly variable from year-to-year
T	Highly variable from location to location

The "State of the Environment Scorecard" provides a quick snapshot of where things stand and what we might look forward to as far as changes in environmental conditions in Hawaii and the USAPI. The eight indicators of change covered in this report fall into three categories: Greenhouse Gases; Weather and Climate; and Oceans and Coasts. Some indicators are further subdivided by various sub-indicators that describe a particular measure affiliated with their overall indicator and/or by geographic location (i.e., Central, Western, or South Pacific). Patterns of change observed and projected for each indicator or sub-indicator are shown in the table as increasing, decreasing or no change and are highlighted in red, blue and yellow respectively. Also shown in the table is the section number in the report where more information can be found on each indicator.

State of Environmental Conditions in Hawaii and the U.S. Affiliated Pacific Islands under a Changing Climate: 2017

Table of Contents

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Hawaii and the U.S. Affiliated Pacific Islands (USAPI)

The U.S. Pacific Islands region is vast, comprising more than 2000 islands spanning millions of square miles of ocean (Figure 1).[1] The islands support about 1.9 million people, a small number by comparison to the continental United States, but their locations are strategic to U.S. defense and their biodiversity is important to the world. The islands are isolated. The largest aggregate of land in this region, the Hawaiian Archipelago, is located nearly 2,400 miles from any continental land mass, qualifying it as one of the most remote archipelagos on the globe. 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 nearly 14,000 feet, while

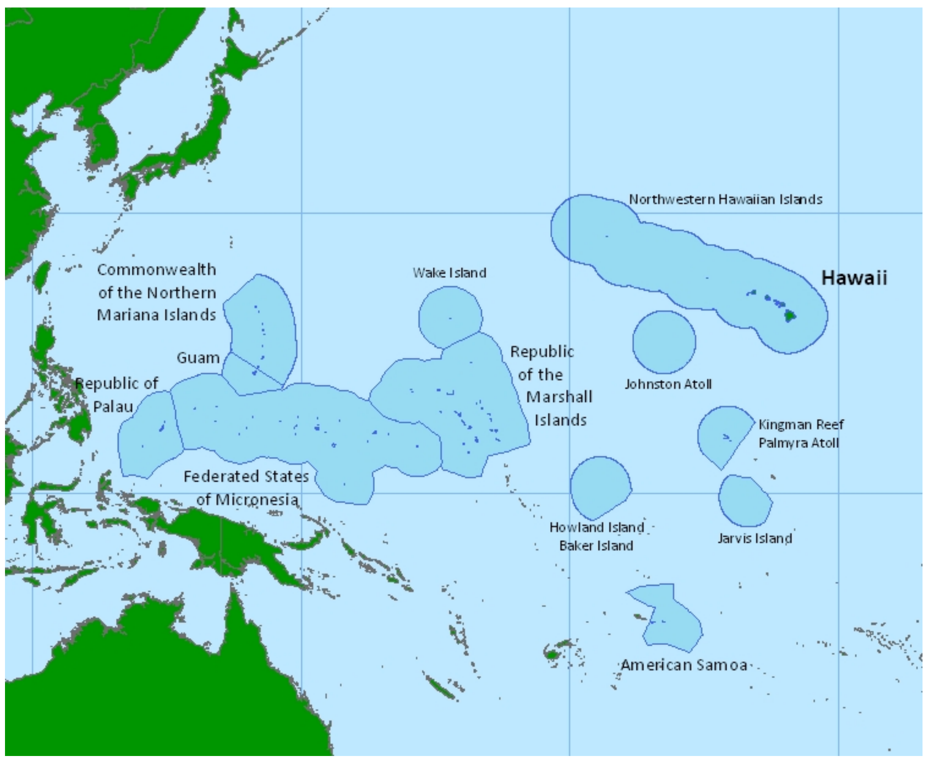

Figure 1. Hawaii and the U.S. Pacific Islands. *In its broadest sense the U.S. Pacific Islands include: the State of Hawaii and the Northwestern Hawaiian Islands (Papahānaumokuākea); the Territories of Guam and American Samoa, and the Commonwealth of the Northern Mariana Islands; the Republic of Palau, Federated States of Micronesia (including the states of Chuuk, Kosrae, Pohnpei, and Yap) and the Republic of the Marshall Islands; and the islands of the Pacific Remote Island Areas. Shading indicates each island’s Exclusive Economic Zone (EEZ).*

some of the "low" atolls peak at only a few feet above present sea level. Isolation and landscape diversity brings about some of the highest species endemism (uniqueness to geographic location) in the world, with several of the U.S. Pacific Islands considered marine biodiversity hotspots. The Pacific Islands region includes demographically, culturally, and economically varied communities. At least 20 languages are spoken in the region. 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, with multigenerational attachment to places. Tourism figures prominently in the gross domestic product of most island jurisdictions. A large U.S. military presence makes the defense sector an important source of income. Natural resources are limited, with many communities relying on agriculture and ecosystems (such as coral reefs, ocean, streams, and forests) for sustenance and revenue. Adaptive capacity in the region varies with the availability of socioeconomic and institutional resources. Typically, high islands support larger populations and infrastructure, which in turn attracts industry and allows the growth of different types of institutions.

The Pacific Islands are exposed to climate changes that affect every aspect of life. Ocean and island ecosystems are changing with warming air and ocean temperatures, shifting rainfall patterns, changing frequencies and intensities of storms and drought, decreasing base flow in streams, rising sea levels, and changing ocean chemistry. 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 atolls are particularly at risk, and the built environment on all islands is at risk from coastal flooding and erosion. Loss of habitat for endangered species such as monk seals, sea turtles, and Laysan ducks is expected along with increased coral bleaching episodes, expansion of avian malaria to higher elevations, and changes in the distribution and survival of the areas' marine biodiversity.

About this Report

Purpose

This document describes the current state of environmental conditions in Hawaii and the U.S. Affiliated Pacific Islands (USAPI). Following from and drawing upon a body of work, a set of foundational measures or *indicators* are used to assess environmental change.[2,3,4,5,6] The regional indicators described here are intended to:

- Provide meaningful regionally and locally relevant information about the status, rates, patterns and trends of key physical, biological, chemical, and ecological variables in light of a changing climate; and
- Provide such 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, thereby facilitating communication and informing decisions on management, research, and education.

Conceptual Framework

The National Climate Indicators System Report describes categories within an end-to-end system of indicators that at the broadest level includes: Greenhouse Gas Emissions and Sinks; Atmospheric Composition; Physical Climate Variability and Change; Sectors and Resources of Concern; and Adaptation and Mitigation[2]. The regional indicators employed here are much narrower in scope; they pertain almost entirely to Physical Climate Variability and Change (Figure 2).

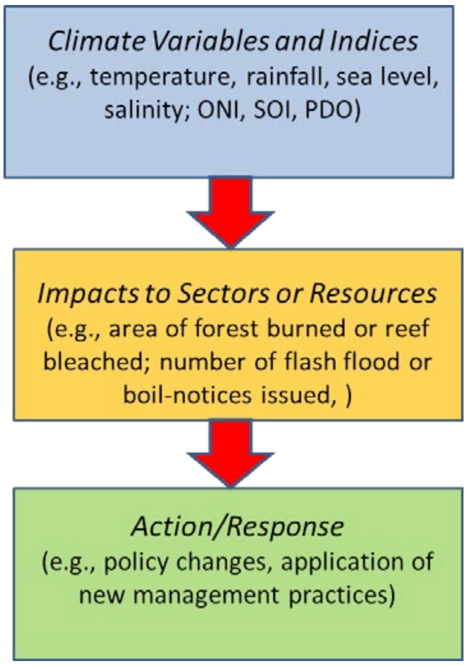

Figure 2. Categories of Indicators. *Recognizing the potential breadth of what can be encompassed within an indicators construct, only indicators that fall into the top two categories shown in the figure on the left are covered in this document. See text for details.*

Key *climate variables* fall under the top category in Figure 2. They include physical measures such as temperature, rainfall, and sea level, as well as biological, chemical, and ecological observations that are indicative of current, past, and possible future states of the climate system. Included also in this broad category are *climate indices* commonly recognized to provide information about the state of the climate [e.g., the Oceanic Nino Index (ONI) and Pacific decadal oscillation (PDO)]. Sources for information about climate variables are typically measurements obtained from in situ stations, satellites, or models. These observing systems and models provide information that can be used to characterize mean and extreme states on 1) *global, regional, subregional* or *local* scales and 2) *monthly/seasonal* to *annual/interannual* bases in terms of the magnitude, frequency, and duration (and in some cases the direction) of a particular variable.

Sector or resource-specific *impacts indicators* make up the middle category in Figure 2. This includes measures that can be used to characterize the direct and indirect impacts on assets of interest within both built and natural environments.[7] More broadly, it includes any measure that can be used to characterize an attribute relevant to assessing the state/condition of a given sector or concern (e.g., area of forest burned or reef bleached; number of flash flood or boil-notices issued). Only one impacts indicator—accumulated heat stress (on corals)—is considered in this document.

Criteria for Selection of Indicators

The following were considered as criteria for identifying a foundational set of indicators:

- Scientifically defensible;
- Links to conceptual framework;
- Defined relationship to climate change and variability;
- Regionally or locally relevant; and
- Scalable, where possible.

In addition to consulting previous work, the indicators were derived through a series of formal and informal discussions with a wide variety of stakeholders in the public and private sectors and members of the scientific community with technical expertise and practical experience related to climate change and variability. These discussions took place over a 2–3 year period. In several instances they were iterative, employing a dialog process to solicit input, generate results, collect feedback, generate new results, and so on.

The indicators described here are by no means the entire set of potential indicators that were identified. In this regard, a criterion of particular relevance with respect to the selection of the foundational set of indicators is that they could be employed almost immediately, drawing upon peer-reviewed, publicly available data from government agencies, academic institutions, and other organizations and thus requiring minimal additional research and analysis. This criterion was necessary due to the length of time required to develop, refine, or vet indicators that do not currently exist. It is envisioned that over time a more extensive set of indicators, beyond the set of foundational indicators defined below, will be established, ultimately covering the full spectrum acknowledged in the conceptual model.

The Eight Indicators of Environmental Change

A set of eight foundational indicators of environmental conditions in Hawaii and the U.S. Affiliated Pacific Islands are summarized in Table 1. Each of the indicators is grouped into one of the following broad categories: Greenhouse Gases; Weather and Climate; and Oceans and Coasts. Each indicator is considered in a separate section of this document, with each section containing the common elements:

- *Takeaways* – summarizing and highlighting important information in the section;
- *Why should we care?* – briefly noting why the given indicator is important to assessing environmental conditions under a changing climate;
- *Where are we now?* – what the indicator shows using multiple measures, reflecting different data sources and/or different ways to characterize the data;
- *What does the future hold?* – what changes in the indicator are expected over time;
- *Key Links* – additional resources on the indicator; and
- *Sources of Information* – the references cited in the section.

Informative Links

NCA http://nca2014.globalchange.gov/report/regions/hawaii-and-pacific-islands

PIRCA https://pirca.org/

NOAA Climate.gov https://www.climate.gov/

NOAA NCEI State Summaries https://statesummaries.ncics.org/hi

EPA www.epa.gov/climatechange/indicators - March 2016

PCCSP http://www.pacificclimatechangescience.org/

Table 1. The Eight Indicators of Environmental Conditions in Hawaii and the USAPI

GREENHOUSE GASES	
Atmospheric Concentration of Carbon Dioxide (CO_2)	The concentration of carbon dioxide (CO_2) in the atmosphere is a benchmark indicator of environmental conditions. Changes in CO_2 and other greenhouse gasses drive changes that cascade throughout the environment.
WEATHER AND CLIMATE	
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 trends and patterns of 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.
Surface Winds & Tropical Cyclones	Changes in wind speed can increase evaporation, thus resulting in greater water demand for agriculture. Tropical Cyclone (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.
COASTS AND OCEANS	
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.
Sea Surface 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).
Ocean Acidification (Aragonite Saturation State)	Changes in the pH in the ocean (increased acidity resulting from of the absorption of CO_2) affects marine organisms' ability to build calcium carbonate shells or skeletons. Aragonite saturation state is a measure of this changing ocean chemistry.
Ocean Chlorophyll Concentration	Changes in chlorophyll-a concentration in the surface ocean (measured in satellites as ocean color) are used as a proxy for change in phytoplankton abundance and biological production at the base of the ocean food chain. Decreases in phytoplankton abundance have the potential to negatively impact ocean and coastal fisheries.

Sources of Information

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2. Kenney, M. A, A. C. Janetos, et. al., 2014: *National Climate Indicators System Report*. National Climate Assessment and Development Advisory Committee. [Available online at http://www.globalchange.gov/sites/globalchange/files/Pilot-Indicator-System-Report_final.pdf.]

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4. PIFSC, 2016: *West Hawai'I Integrated Ecosystem Assessment: Ecosystem Trends and Status Report*. NOAA Fisheries Pacific Science Center, SP-16-004, 47 pp. [Available online at https://www.pifsc.noaa.gov/library/pubs/SP-16-004_rev.pdf.]
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This report does not attempt to identify the extent to which climate change is causing a trend in an observed indicator. Connections between human activities, climate change, and observed indicators are explored in more detail elsewhere in the scientific literature. The contents of this report are solely the opinions of the authors and do not constitute a statement of policy, decision or position on behalf of NOAA or the U.S. Government.

How to cite this report

State of Environmental Conditions in Hawaii 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

1. Atmospheric Concentration of Carbon Dioxide (CO_2)

John J. Marra, NOAA NESDIS NCEI

Takeaways

- Over the last 60 years, the concentration of carbon dioxide (CO_2) in the atmosphere has increased by about 90 ppm (parts per million), to a value of just over 404 ppm in December 2016.
- The annual average rate of increase in CO_2 since the 1960s is +1.5 ppm per year. Since the early 1990s, the rate has increased to about +2.0 ppm per year.
- In terms of CO_2 equivalents, the atmosphere in 2016 contained 489 ppm, of which 403 is CO_2 alone.
- A stable concentration of CO_2 at 550 ppm would result in an average increase in Earth's surface temperature of ~3°C (5.4°F) above the 1850–1900 average.
- The rise in CO_2 and other greenhouse gases can be attributed primarily to human activity, with emissions increasing in response to factors such as increased economic activity, population growth, and changes in land use and technology.

Source NOAA

Observations from NOAA's Mauna Loa Observatory constitute the longest record of direct measurements of CO_2 in the atmosphere. Observations were started by C. David Keeling of the Scripps Institution of Oceanography in March 1958 at a NOAA facility there.[1] NOAA started its own CO_2 measurements in May 1974, and the two observations data sets have run in parallel ever since.[2] The annual growth rate measured at Mauna Loa is not the same as the global growth rate, but it is quite similar and therefore is often used as the global value. From NOAA ESRL https://www.esrl.noaa.gov/gmd/obop/mlo/.

Why should we care?

The concentration of carbon dioxide (CO_2) in the atmosphere is a benchmark indicator of climate change. Rising concentrations of CO_2 and other "greenhouse gases" (e.g., methane, nitrous oxide, 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 thousands of years.

Where are we now?

Global

The annual mean concentration of CO_2, at NOAA's Mauna Loa Observatory in Hawaii, is considered a global indicator of climate change (Figure 1.1). In 1959, the onset year of observations, the annual mean concentration of CO_2 at Mauna Loa was 315.97 ppm. It passed 350 ppm in 1988 and 400 ppm in 2015. The annual mean concentration of CO_2 at Mauna Loa in 2016 was 404.21 ppm. That corresponds, roughly, to an increase of about 90 ppm over the last 60 years, or +1.5 ppm per year.[3] The rate over the last 25 years, since the early 1990s, is higher, about +2.0 ppm per year, and in 2015 and 2016, the annual mean rate of growth of CO_2 was +3 ppm. This rise in CO_2 can be attributed primarily to human activity, with CO_2 emissions increasing in response to factors such as increased economic activity, population growth, and changes in land use and technology.[4]

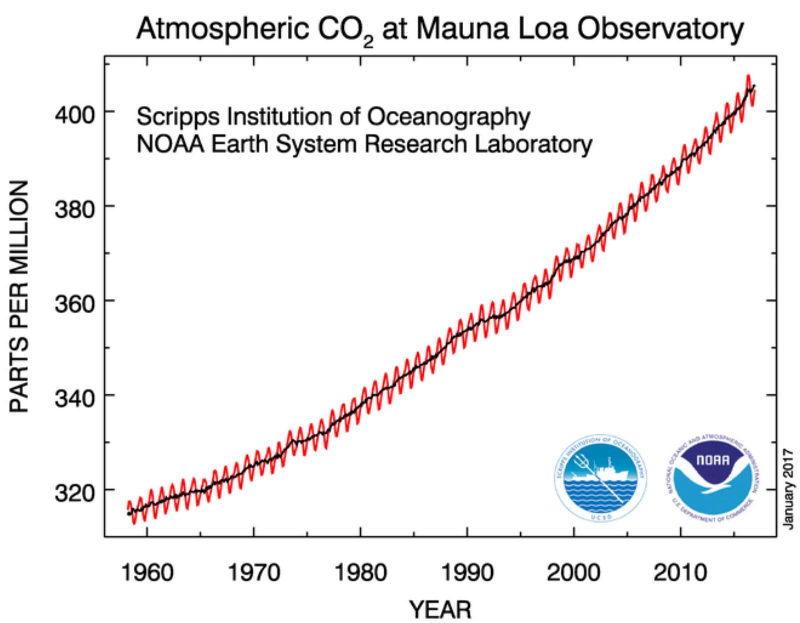

Figure 1.1. Monthly Mean Concentration of Atmospheric CO_2 at Mauna Loa since 1959. The carbon dioxide data (red curve), measured as the mole fraction (ppm) in dry air, on Mauna Loa, Hawaii. The black curve represents the seasonally corrected data. The annual oscillations at Mauna Loa are due to the 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/.

Annual Greenhouse Gas Index

The Annual Greenhouse Gas Index (AGGI) is a simple measure of the abundance of greenhouse gases in the atmosphere.[3] The index was designed to enhance the connection between scientists and society by providing a normalized standard that can be easily understood and followed. In 2016, the AGGI was 1.40 (Figure 1.2). Expressed as a greenhouse gases volume equivalent, in 2016 the atmosphere contained 489 ppm. CO_2 alone accounts for more than 80% (403 ppm) of this value; the rest comes from other gases. It took ~240 years for the AGGI to go from 0 to 1 (i.e., to reach the 1990 100% value). Since 1990, the AGGI has increased by 40%.

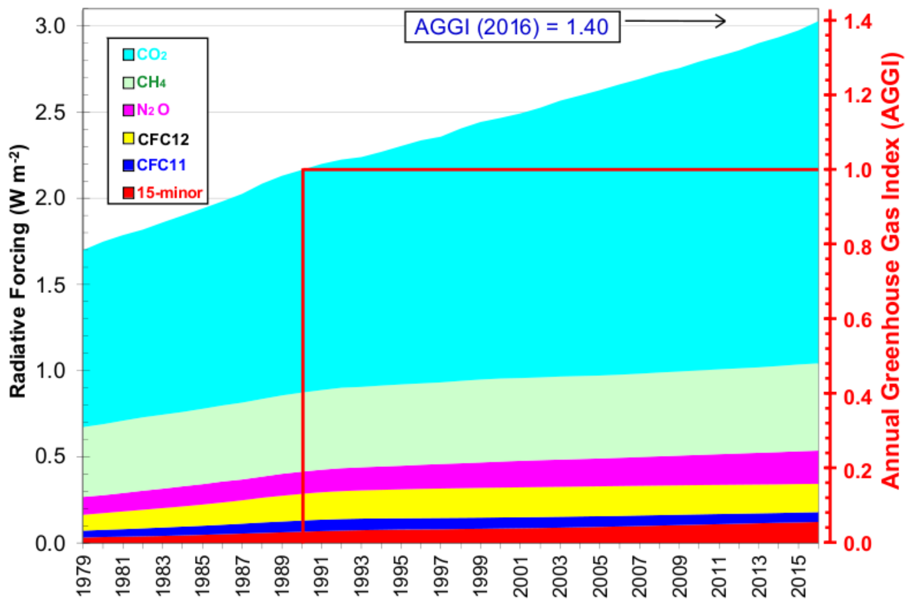

Figure 1.2. Radiative forcing, relative to 1750, of all the long-lived greenhouse gases and a set of 15 minor long-lived halogenated gases. NOAA's AGGI, which is indexed to 1 for the year 1990, is shown on the right axis. The AGGI is been defined as the ratio of the total direct radiative forcing due to long-lived greenhouse gases for any year for which adequate global measurements exist to that which was present in 1990. 1990 was chosen because it is the baseline year for the Kyoto Protocol; https://www.esrl.noaa.gov/gmd/aggi/aggi.html.

What does the future hold?

As part of their Fifth Assessment Report, the Intergovernmental Panel on Climate Change (IPCC) identified four representative concentration pathways (RCPs) to characterize a broad range of potential climate outcomes.[5,6] Each RCP is defined in terms of its total radiative forcing (cumulative measure of human emissions of GHGs from all sources) pathway and level by 2100 resulting from different combinations of economic, technological, demographic, policy, and institutional futures. RCP2.6, the lowest of the four scenarios, has a peak in CO_2 concentrations around 2050, followed by a modest decline to around 400 ppm CO_2 (approximately its current value), by the end of the century. Under RCP8.5, the highest of the four scenarios (a.k.a. the 'business as usual' scenario), CO_2 concentrations are in excess of 900 ppm by the end of the century. RCP4.5 and RCP6.0, the middle scenarios, correspond to CO_2 concentrations around 500–600 ppm by 2100. Stabilization of CO_2 at a concentration of 550 ppm is estimated to result in a ~3°C (5.4°F) increase in Earth's average temperature above the 1850–1900 average.

Key Links

NOAA ESRL https://www.esrl.noaa.gov/gmd/ccgg/trends/

EPA https://www.epa.gov/ghgemissions/overview-greenhouse-gases

IPCC http://www.ipcc.ch/report/ar5/

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2. Surface Temperature

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Takeaways

- 2016 was the hottest year on record, beating the previous record (set in 2015) by 0.2°C (0.36°F).
- Since the early 1980s, global temperatures have been rising at the rate of 0.16°C (0.29°F) per decade.
- In the Pacific region, land surface temperatures have been rising at the rate of 0.17°C (0.30°F) per decade since the 1980s, slightly ahead of the global trend.
- Since 2005, nearly all surface stations have seen annual temperature anomalies above the long-term average.
- The number of hot days has increased across the region since the 1990s. Hot days are based on distributions that correspond to temperatures of about 32°C (90°F).
- The number of very cold nights, defined as less than 18°C (65°F), has decreased substantially across the region since the 1990s. This is in alignment with the steady rise in sea surface temperatures, which acts to keep minimum temperatures elevated (see chapter 6).
- By 2055, much of the equatorial Pacific could see 2.0°C rises over the 1981-2010 period, with at least 1.5°C (2.7°F) rises in the major atolls of RMI, FSM, and Palau.

Surface air temperatures have been on the rise since the late 1990s. Increased frequency of heat waves and warmer nights have led to greater human health impacts across the region.

Why should we care?

More frequent and intense extreme heat events can lead to human health issues, agricultural damage, and changes in the phenology of plants. Warming surface temperatures, when combined with clear skies and only a light breeze, can result in even warmer sea surface temperatures and exacerbate coral bleaching. Warming temperatures, both during the day and at night, also lead to an increase in energy usage to maintain indoor comfort.

Where are we now?

Global

Since global records began in 1880, 2016 was the warmest year on record, with a global anomaly just shy of 1.0°C (1.8°F), eclipsing that of 2015 (the previous warmest year on record) by nearly 0.20°C (0.36°F), as compared against the 1981-2010 period. The 2016 warmth was contributed to by the existence of El Niño and was the second consecutive year the global average surface temperature reached 1.0°C (1.8°F) above the long-term average[4].

Global surface temperatures are now about 1.4°C (2.5°F) warmer than the early part of the 20th century (Figure2.1). As of December 2016, the rate of temperature rise as measured by both land and ocean observing systems since 1980 is 0.16°C/decade (0.29°F/decade). This is based on the 1981–2010 normal period, as defined by the World Meteorological Organization[1]. Since 1978, the global temperature anomaly has been above normal, with the 2016 anomaly being the highest on record (since 1880), at 0.9°C (1.6°F) over the 1981-2010 period.

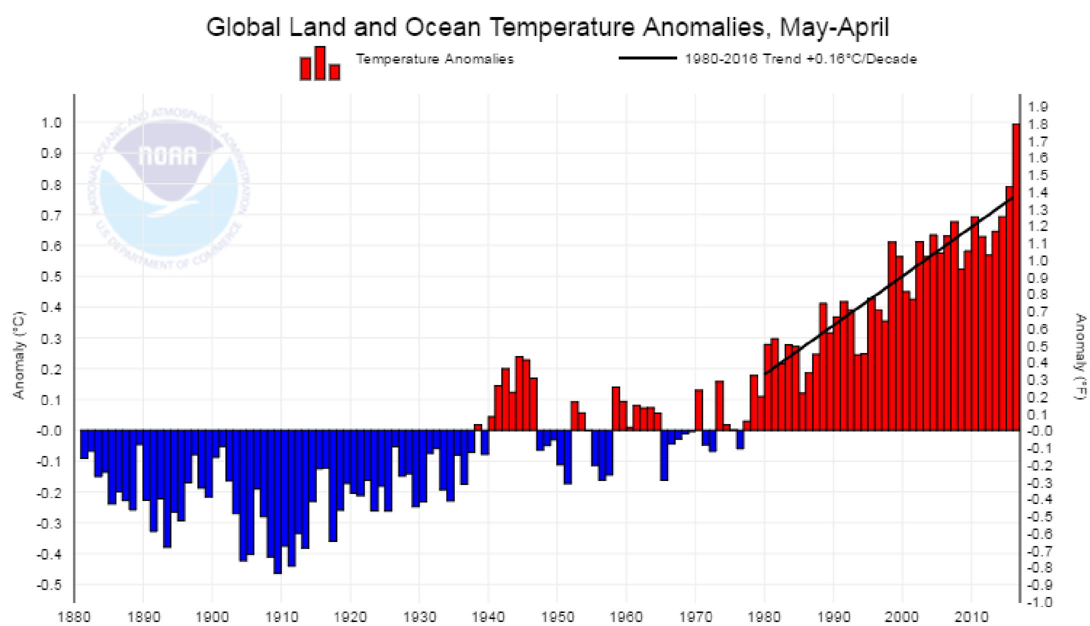


Figure 2.1 Global Surface Temperature Anomalies since 1880. The black line represents the linear trend since 1980, which shows an increase of 0.16°C (0.29°F) per decade. NCEI - https://www.ncdc.noaa.gov/cag/

Regional

In the regional area of Oceania, defined as 40°N to 40°S and 130°W to 125°E, the surface temperature anomalies have also been rising as shown in Figure 2.2, with the black line representing the long-term linear trend (0.11°C per decade; 0.20°F). In this region, every year since 1985 has been above normal, with the warmest year of 2013 being 1.3°C (2.3°F) above normal. The land surface temperature anomalies in Oceania are generally at or above the global anomalies. This translates to a rising trend of 0.17°C/ decade (0.3°F/decade) since 1980.

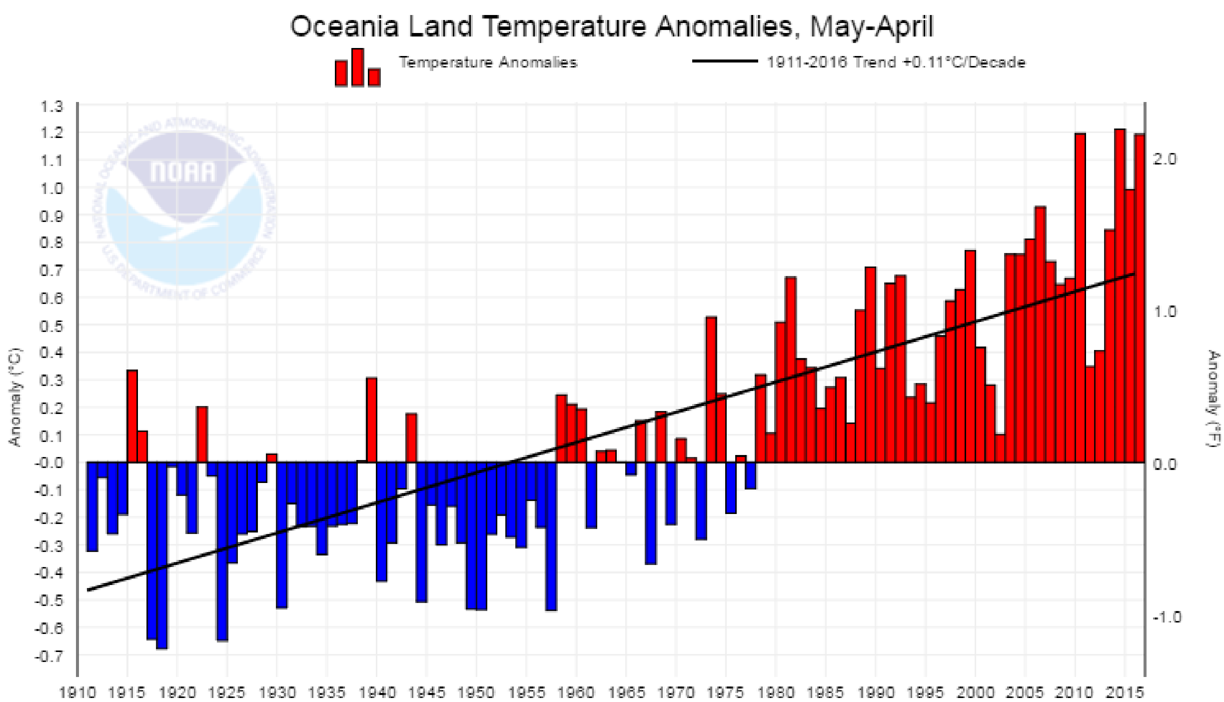


Figure 2.2. Land-Surface temperature trends in Oceania since 1910. The black line represents the long-term linear trend, which shows an increase of 0.11°C (0.20°F) per decade since 1910.
NCEI https://www.ncdc.noaa.gov/cag/

Local – Magnitude

Interpretation of historical temperature records in the US-API is difficult. Changes of station location, physical changes at the sites, and even instrumentation changes have had large impacts on the record. While most stations exhibit a long-term warming trend of both MAX and MIN temperature (MAX T and MIN T) over their period of record.

- For Honolulu (2.3), average annual (May–April) temperatures have been steadily rising since the late 1940s. Even then, there were cooler than average years as recently as 2012 and 2013. The hottest year for Honolulu occurred in 1995 with an anomaly exceeding 1.0°C (1.8°F) above the 1981-2010 average.
- For Hilo (2.4), the long-term trend has been positive despite the recent cool years between 2008–2013. However, 2016 was the warmest year since 1948, exceeding 1.0°C (1.8°F) above the 1981-2010 average.

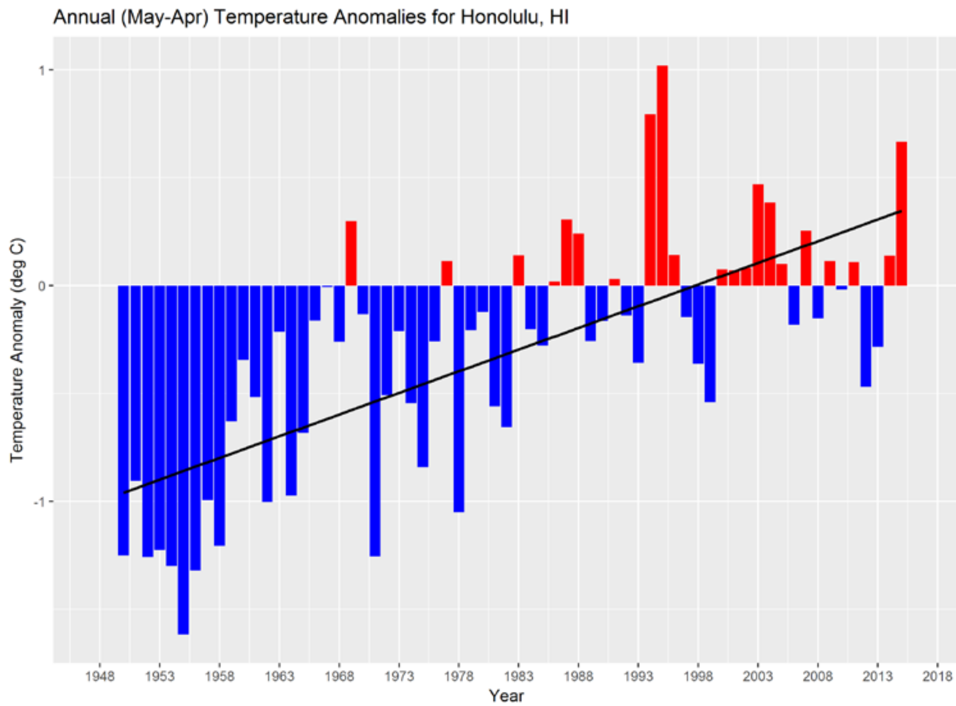


Figure 2.3. Local Surface Temperature Trends for Honolulu. The plot shows the annual average temperature anomaly for Honolulu, with the long-term linear trend indicated by the solid black line. Data from GHCN-Daily. Original figure created by Michael Kruk, NCEI.

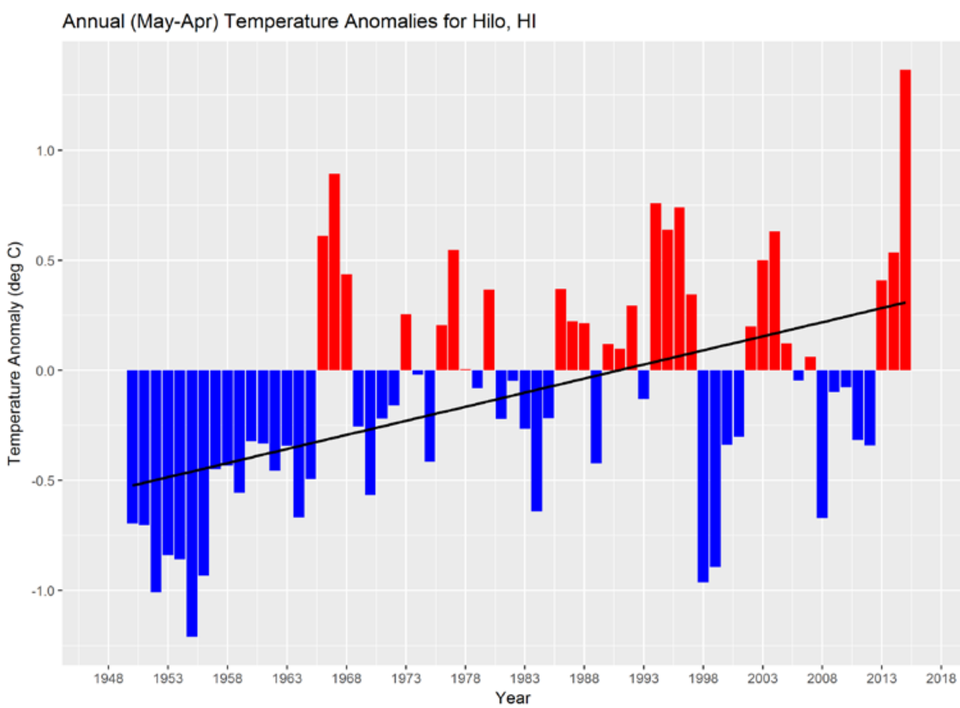
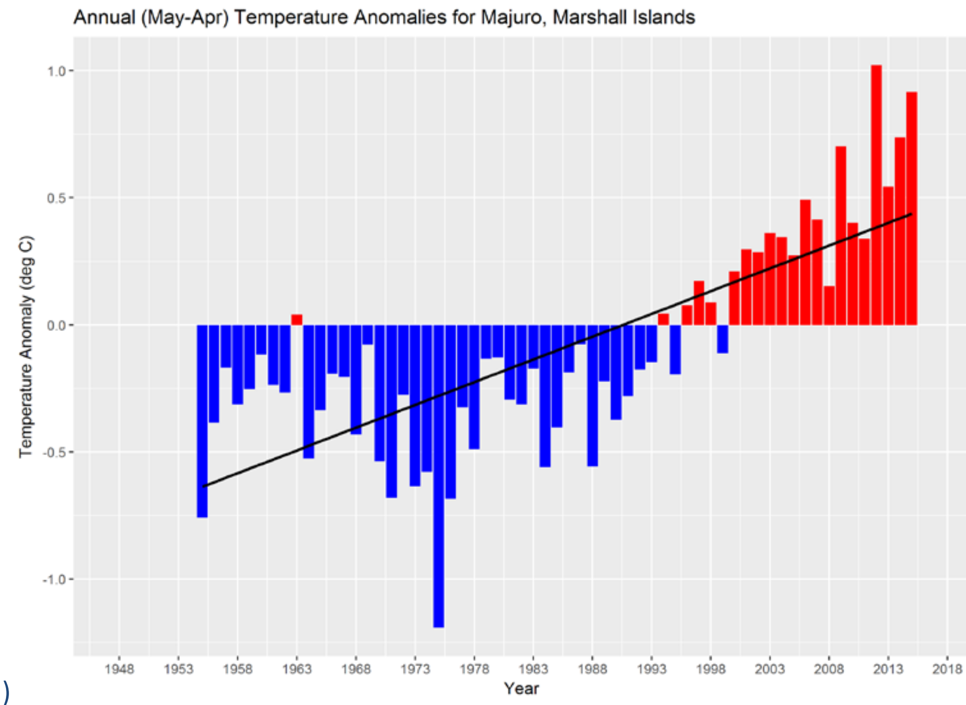
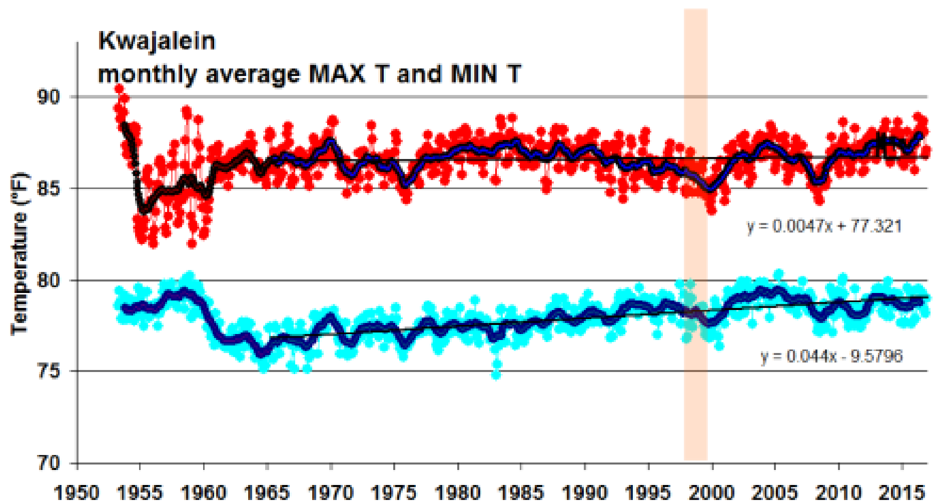


Figure 2.4. Local Surface Temperature Trends for Hilo. The plot shows the annual average temperature anomaly for Hilo, with the long-term linear trend indicated by the solid black line. Data from GHCN-Daily. Original figure created by Michael Kruk, NCEI.



a)



b)

Figure 2.5. Local Surface Temperature Trends for Majuro and Kwajalein. Plot (a) shows the annual average temperature anomaly for Majuro, with the long-term linear trend indicated by the solid black line. Plot (b) shows the monthly average maximum and minimum temperatures for Kwajalein. Data from GHCN-Daily. Original figure created by Michael Kruk, NCEI and Mark Lander, UoG.

- For Majuro (2.5a), the bar graph showing only warmer than average years since 1999 is very closely aligned with sea surface temperature trends in the Western Pacific (see chapter 7). Prior to 1999, nearly every year was below normal. The result is a dramatic upward trend in average annual temperatures. For Kwajalein (2.5b), the warm temperatures of the 1950s appear to be unreliable as they deviate significantly from the rest of the time series. Then after 1960, the

MIN T starts at a low level and rises steadily throughout the rest of the period of record, gaining about 1°C (1.8°F).The MAX T exhibits a smaller warming trend of less than 0.5°C (0.9°F).

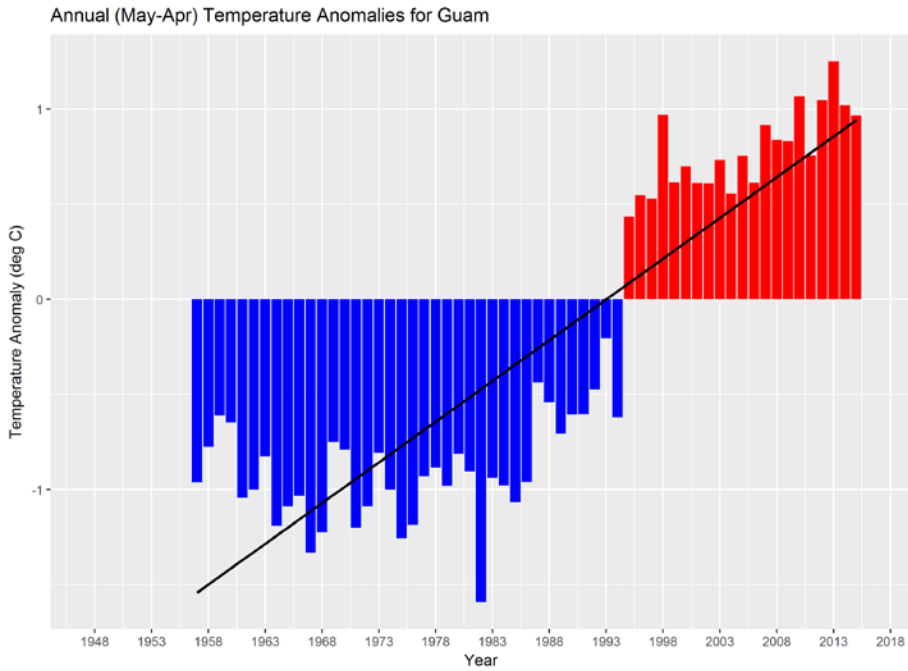
- For Guam (2.6), historical temperature records are available for three sites: Andersen Air Force Base (AAFB), the NOAA Weather Service Meteorological Observatory (WSMO), and the Naval Air Station (NAS)—now Weather Forecast Office (WFO), Guam. WSMO was deactivated in 1995 when NOAA stood up the WFO at the NAS site at the Guam International Airport. The temperature records at the WFO are not suitable for climate studies. The official record is a concatenation of WSMO and WFO records that yield grossly unreliable trends. Known instrumentation errors remain in the record. The AAFB record is deemed a “cleaner” record, and as such, MAX T and MIN T show warming in the first half of the record, with slight cooling thereafter. The cooling trend is most pronounced in the AAFB MIN T, which has lost about 0.5°C (0.9°F) since the late 1980s.
- For Yap (2.7), the historical record at the WFO, Yap Island, contains a clear artifact of station metadata: in April 2008, the station was moved to a new building at the southwest side of the runway at the Yap International Airport. This caused an immediate jump of +2.2°C (+4.0°F) in the MIN T. The MAX T was also similarly affected with changes to its magnitude and its variability. Another unusual behavior noted at Yap is a substantial long-term cooling trend of the MIN T (prior to 2008), while at the same time a slower rise of the MAX T was observed.
- For Pago Pago (2.8), the MIN T rises sharply (almost 4°F from 1966 to 1998), and thereafter exhibits a cooling trend. The MAX T has no appreciable trend from 1966 through 1993, then rises abruptly to a sharp peak in 1998, and thereafter undergoes cooling in concert with the cooling of the MIN T.

Local – Frequency

With data extending back to 1948 in most cases, there exists a strong climate record from which extremes in the distribution can be derived. This section examines the frequency and trends in hot days (maximum temperature exceeding the 95th percentile of the distribution), and cold nights (minimum temperatures colder than the 5th percentile of the distribution). This roughly corresponds to daytime temperatures warmer than 32.0°C (90.0°F) and nighttime minimums below 18.0°C (65.0°C).

- For Honolulu (2.9a), the number of hot days has increased from 5 per year in 1948 to 15 per year by 2016, representing a 200% increase. The most was 72 days in 1997. The number of cold nights has decreased, from an average of 30 per year in the early 1950s, to 15 per year today. For comparison purposes, there were a total of 65 nights that were very cold in 1963.
- For Hilo (2.9b), the number of hot days averaged just under 10 in 1950 to near 20 in 2016, or a doubling of occurrences in the last 70 years. Meanwhile, the number of cold nights has dropped dramatically, from 30 days per year in the late 1940s, to under 10 in 2015. In fact, 2016 marked the fewest cold night events on record with only 5.
- For Majuro (2.9c), the number of hot days has increased 2500% since 1950. In fact, many years in the 1950s saw zero hot days, whereas 2016 saw 46 days above the 95th percentile. The number of very cold nights has dropped to near zero (from a peak of 30 days per year in the

1950s). Since 2003, Majuro has only recorded a total of 13 cold nights. Six years since 2003 have recorded zero cold nights.



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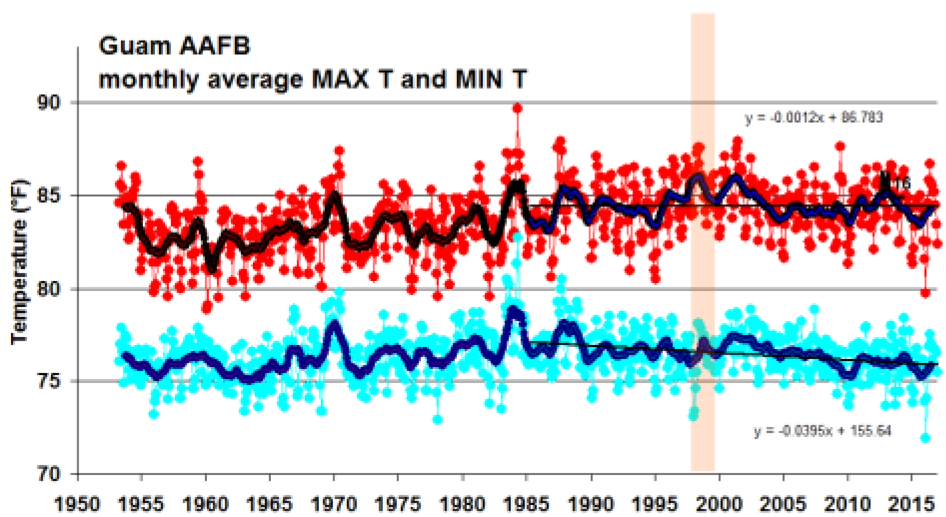
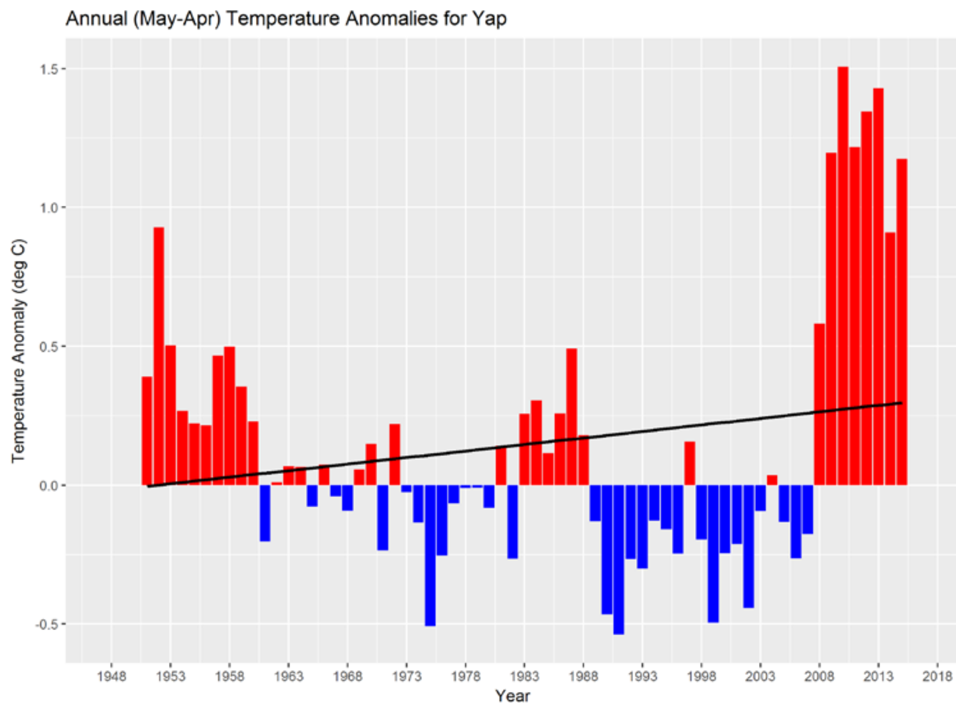


b)

Figure 2.6. Local Surface Temperature Trends for Guam. Plot (a) shows the annual average temperature anomaly, with the long-term linear trend indicated by the solid black line. Plot (b) shows the monthly average maximum and minimum temperatures. Data from GHCN-Daily. Original figure created by Michael Kruk, NCEI and Mark Lander, UoG.

- For Guam (2.9d), a dramatic increase in the number of very hot days is shown, with near zero days in the early 1950s to a recent maximum of 120 days in 2016! A similarly incredible drop is evident in the number of cold nights, from an average of 40 per year in 1950 to zero since 2005.



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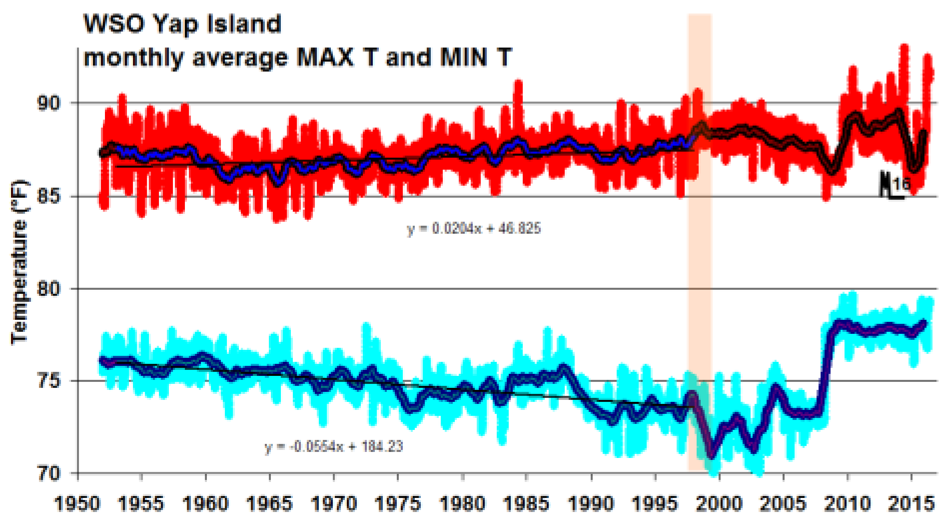
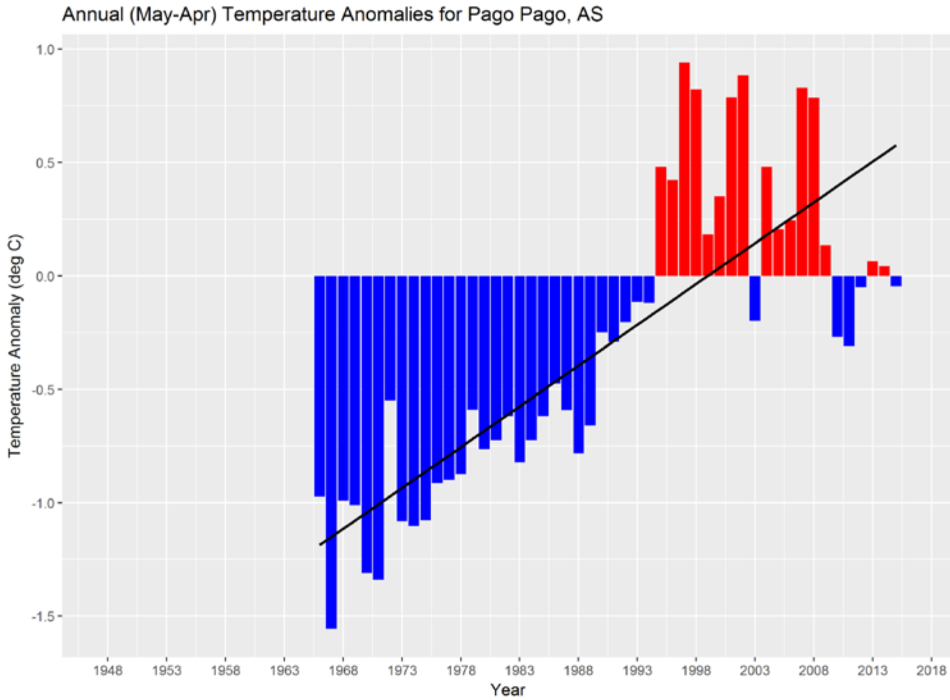


b)

Figure 2.7. Local Surface Temperature Trends for Yap. Plot (a) shows the annual average temperature anomaly, with the long-term linear trend indicated by the solid black line. Plot (b) shows the monthly average maximum and minimum temperatures. Original figure created by Michael Kruk, NCEI and Mark Lander, UoG.



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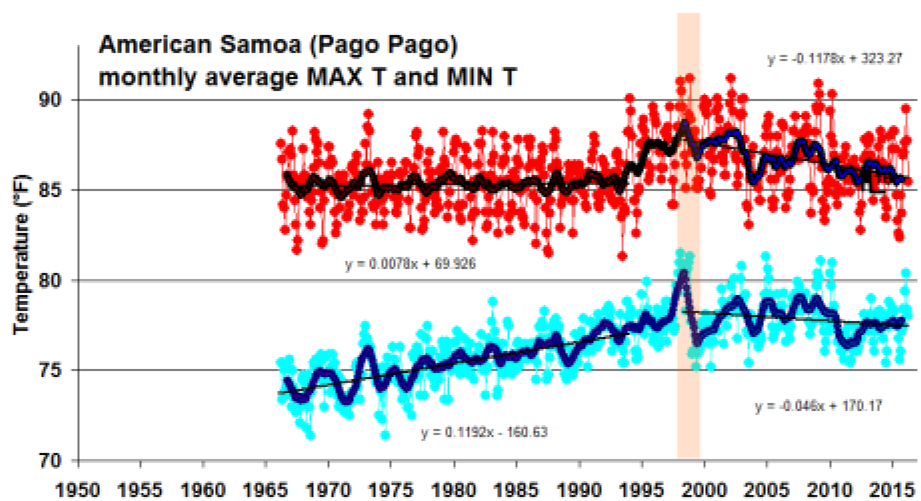
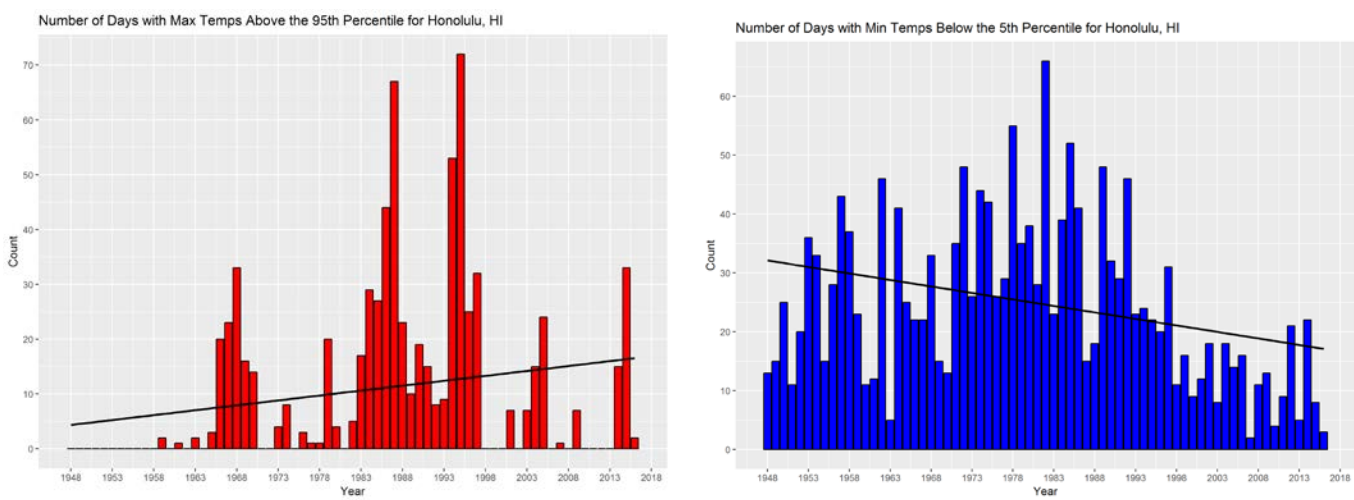


b)

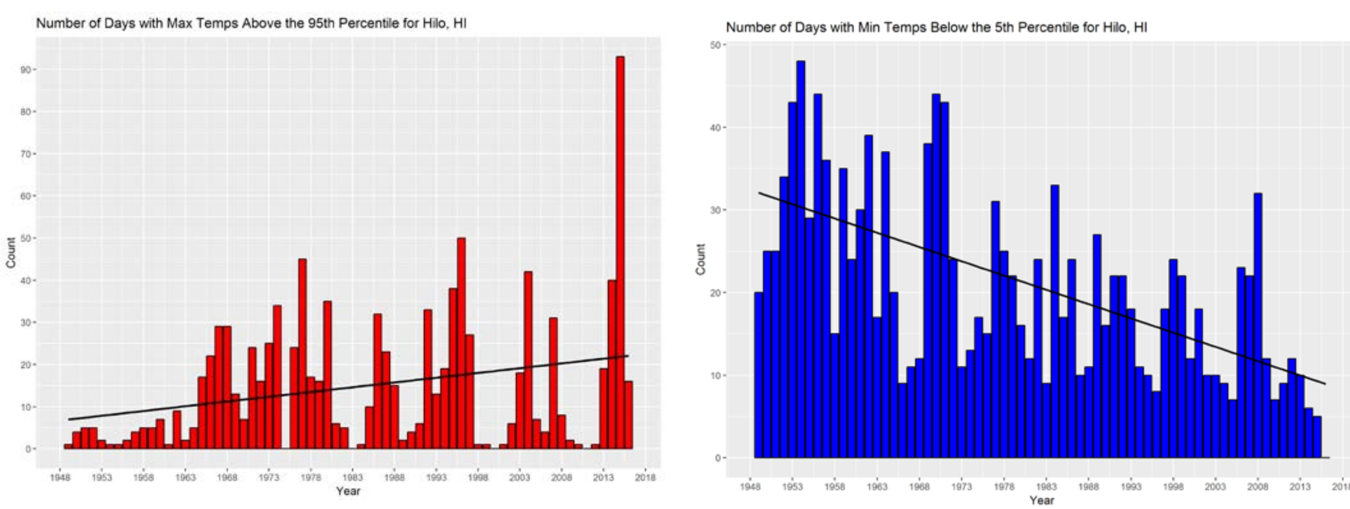
Figure 2.8. Local Surface Temperature Trends for American Samoa. Plot (a) shows the annual average temperature anomaly, with the long-term linear trend indicated by the solid black line. Plot (b) shows the monthly average maximum and minimum temperatures. Original figure created by Michael Kruk, NCEI and Mark Lander, UoG.

- For Yap (2.9e), every year since 2008 has seen 30 or more hot days, despite the long string of zero days between the 1960s and early 2000s. The number of cold nights remains relatively unchanged, near zero, despite the spike in cold nights in the late 1990s, possibly associated with the large El Niño in 1997-1998.
- For Pago Pago (2.9f), the number of hot days has increased from an average of 0–5 days per year in the late 1960s to 25 days on average in 2016 (peak year was 2008 with over 65 hot days). The number of cold nights has decreased from an average of 45 days per year in the late 1960s to an average of less than 5 days per year since 1998, representing a 90% decrease in the last 50 years.

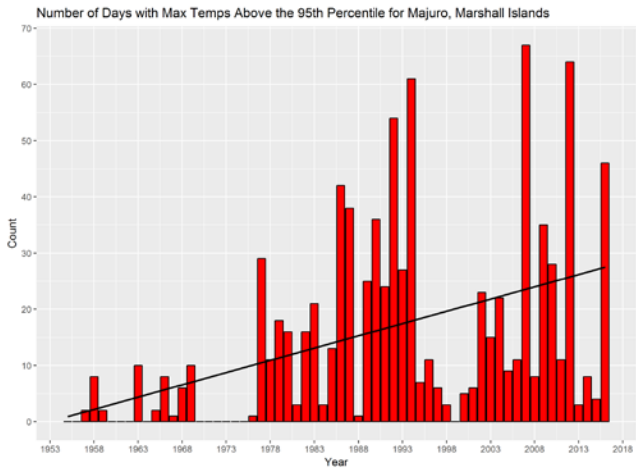
The overall decrease in the occurrence of cold night temperatures appears to be directly correlated with the rise in sea surface temperatures across Oceania (see chapter 6). As warmer ocean waters surround these locations, evaporation and heat from the ocean add to the local moisture content and help sustain elevated nighttime temperatures.

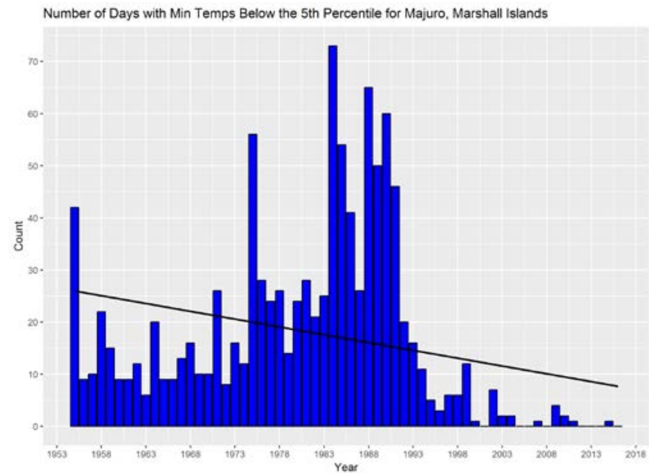


a) Honolulu

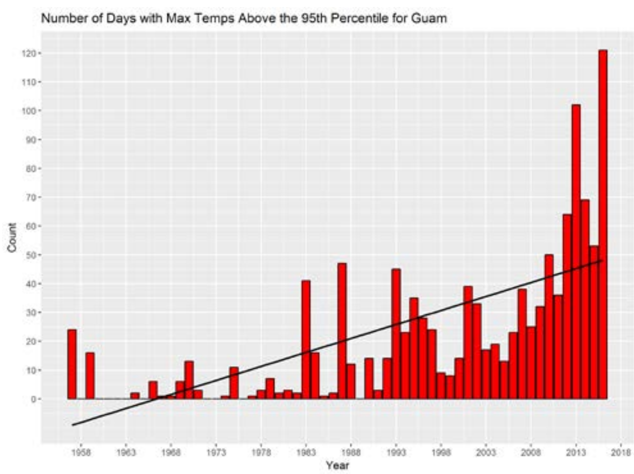


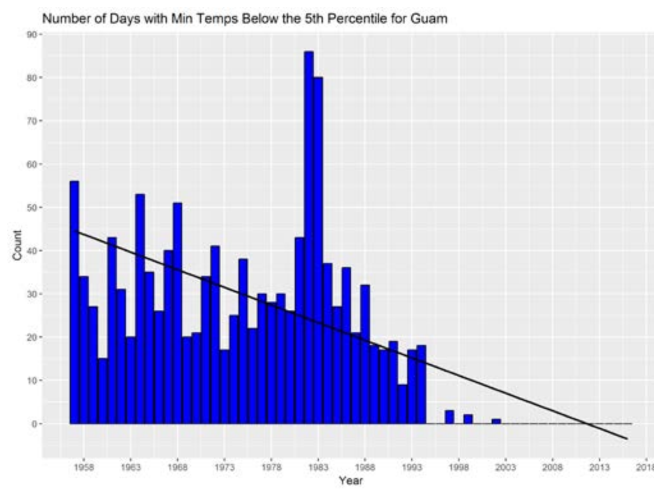
b) Hilo



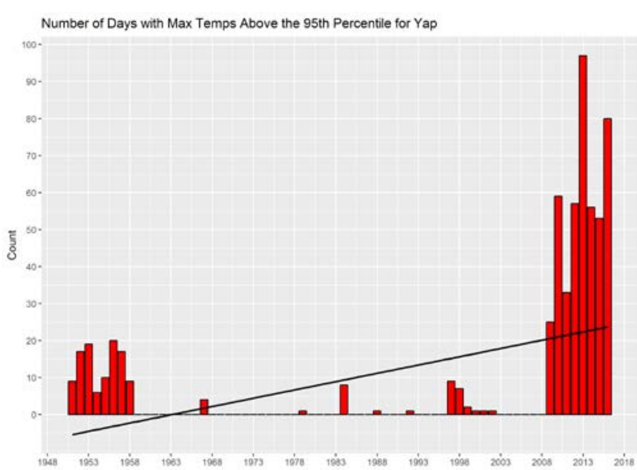


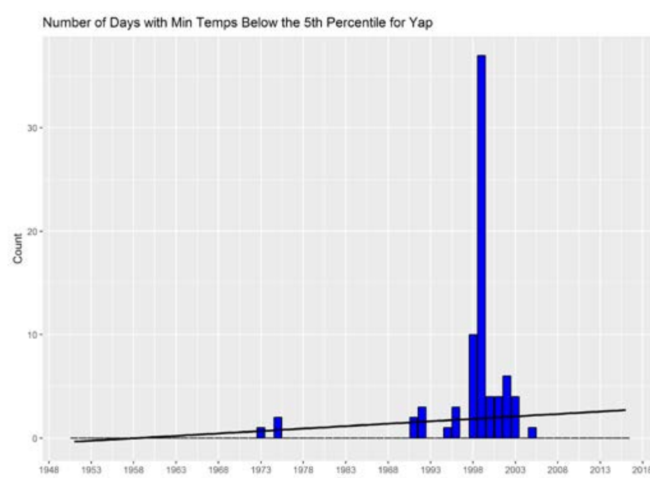
c) Majuro



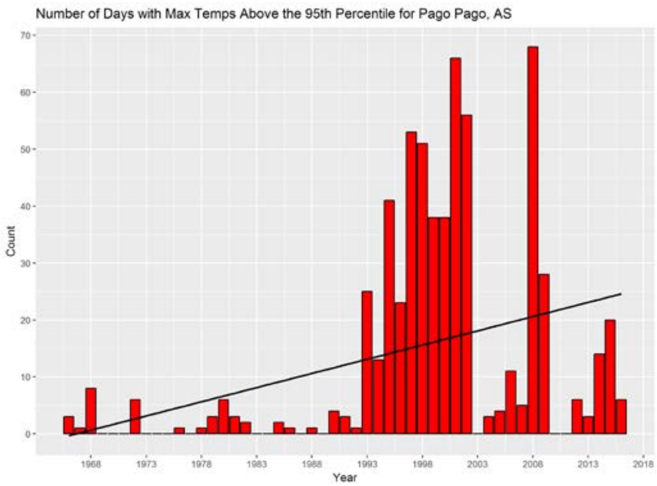


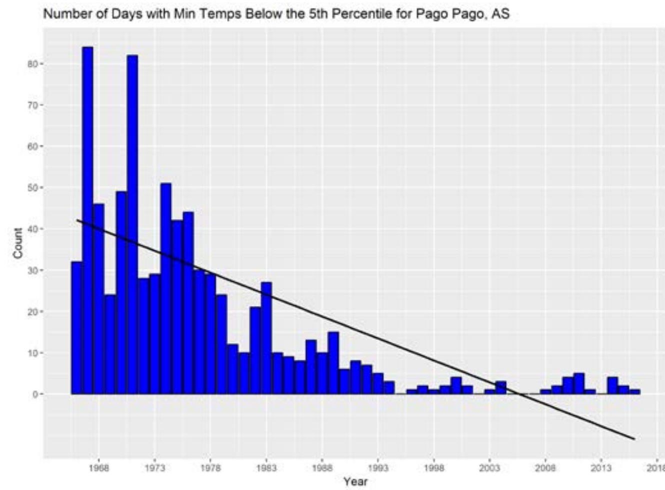
d) Guam





e) Yap





f) Pago Pago

Figure 2.9. Frequency of the number of hot days and cold nights from selected stations in the Pacific. These plots show the number days per year with temperatures above the 95th percentile (left) and below the 5th percentile (right) for: a) Honolulu; b) Hilo; c) Majuro; d) Guam; e) Yap; and f) Pago Pago. Data from GHCN-Daily. Original figures created by Michael Kruk, NCEI.

What does the future hold?

Regional climate model simulations project that, assuming status quo with respect to carbon emissions, surface temperatures will continue to rise across the entire Pacific. By 2055, much of the equatorial Pacific could see 2.0°C (3.6°F) rises above the 1981-2010 average, with at least 1.5°C (2.7°F) rises in the major atolls of RMI, FSM, and Palau[2]. Chapter 11 of the Working Group I Fifth Assessment Report of the Intergovernmental Panel on Climate Change[3] states, "…global mean temperatures averaged in the period 2081–2100 are projected to likely exceed 1.5°C (2.7°F) above the 1850–1900 levels." Of note is that some global climate models produce a global mean temperature change above 2°C (3.6°F) by 2100 above the 1850-1900 levels.

Key Links

State of the Climate https://www.ncdc.noaa.gov/sotc/

NOAA NCEI https://www.ncdc.noaa.gov/cag/time-series/us

NOAA NCEI GHCN ftp://ftp.ncdc.noaa.gov/pub/data/ghcn/daily/

Sources of Information

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2 - Australian Bureau of Meteorology (BoM) and CSIRO, 2011: Climate Change in the Pacific: Scientific Assessment and New Research. Vol. 1: Regional Overview, Vol. 2: Country Reports.

3 - Kirtman, B., S.B. Power, J.A. Adedoyin, G.J. Boer, R. Bojariu, I. Camilloni, F.J. Doblas-Reyes, A.M. Fiore, M. Kimoto, G.A. Meehl, M. Prather, A. Sarr, C. Schär, R. Sutton, G.J. van Oldenborgh, G. Vecchi and H.J. Wang, 2013: "Near-term Climate Change: Projections and Predictability." In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

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3. Rainfall

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Takeaways

- Precipitation patterns are highly regionalized, often with local variations within those regions. Global trends capture the big picture, but the localized trends are usually either different in sign and/or in magnitude.
- Since the late 1970s, trends in global precipitation amounts have varied, with increases across Western Australia, central Africa, and parts of the central and western Pacific.
- In a typical El Niño, dryness and drought are common in the Republic of the Marshall Islands (RMI) and Federated States of Micronesia (FSM). In 2016, much-below-normal precipitation was observed across these areas, associated with the expected evolution of El Niño.
- Average annual rainfall amounts over the last 50 years indicate that western FSM is getting wetter while eastern FSM is trending drier. Hawaii and parts of the Central Pacific are also drying out but rainfall amounts are gradually increasing in the central South Pacific.
- The number of days with extreme rainfall is holding steady over the past 50 years, with only very slight decreases.
- The number of days without measureable rainfall has been relatively steady over the past 50 years, but increasing trends are evident in the Central Pacific region.
- Future projections indicate extreme rainfall events should be on the rise over the next 30–50 years. An increase in atmospheric moisture is projected, which will be wrung out in showers and storms.
- Heavy or extreme rainfall events can increase flood frequency and enhance impacts to crop damage and soil erosion. Conversely, periods of drought have negative impacts on agriculture and can affect the quantity and quality of available freshwater.

Storm approaches a Pacific island. Rainfall is an essential source of freshwater in the Pacific and changes to its frequency and distribution will have significant impacts on its people. Photo courtesy of creative commons.

Why should we care?

Precipitation has wide-ranging impacts on humans and ecosystems, providing fresh drinking water to low-lying atolls, replenishing freshwater lenses, and providing moisture necessary for agriculture. Changes in precipitation 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 can also carry harmful pollutants into nearby water bodies, endangering not only aquatic species, but also humans who depend on those resources for sustenance and their way of life.

Where are we now?

Global

Global precipitation trends have risen across some parts of the world over the past 100 years (Figure 3.1), while other areas have dried out, such as the western United States. Increasing trends are noted across the equatorial areas, especially central Africa and southward to Western Australia. Global precipitation in 2015 was directly affected by the emergence of an El Niño, which lingered into 2016.[1] Below-average precipitation was noted over much of northeastern South America and southern Africa, while above-average precipitation fell across the southeastern United States and southeastern South America.

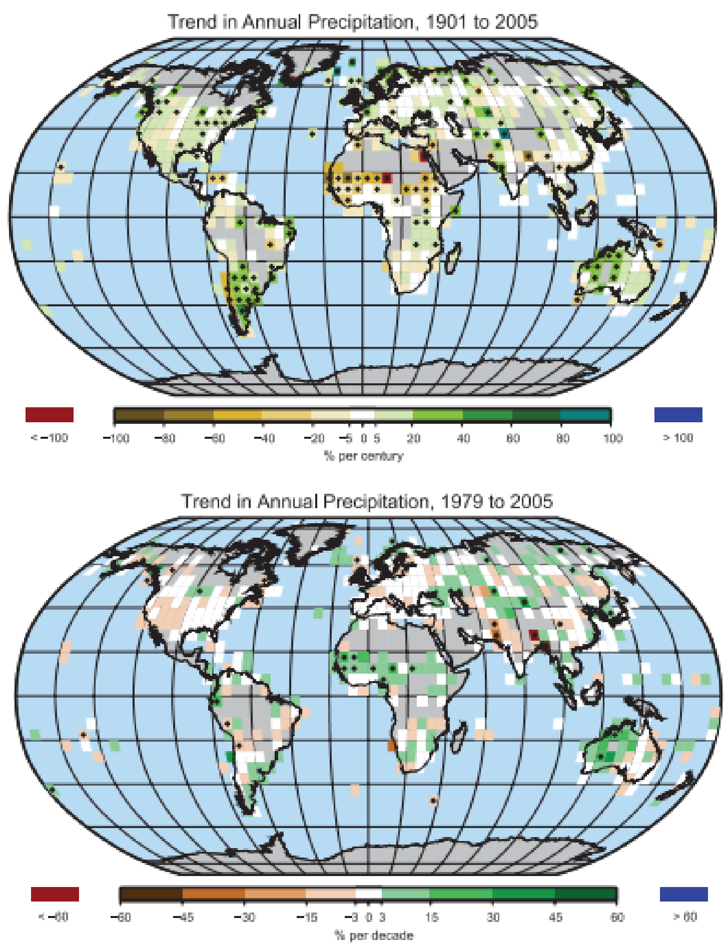


Figure 3.1 Global Precipitation since 1901 and Trends since 1979. Parts of western Australia and central Africa have seen marked rises in precipitation since 1979, with Hawaii and the western United States showing noteworthy decreases. IPCC WG1 http://wg1.ipcc.ch/publications/wg1-ar4/ar4-wg1-chapter3.pdf

Regional

The regional area of Oceania, defined as 40°N–25°S and 120°E–120°W, can be further divided into three distinct subregions: western North Pacific, central Pacific, and southwest Pacific. Each of these subregions have different mechanisms for rainfall production on the larger scale[2], but given the nature

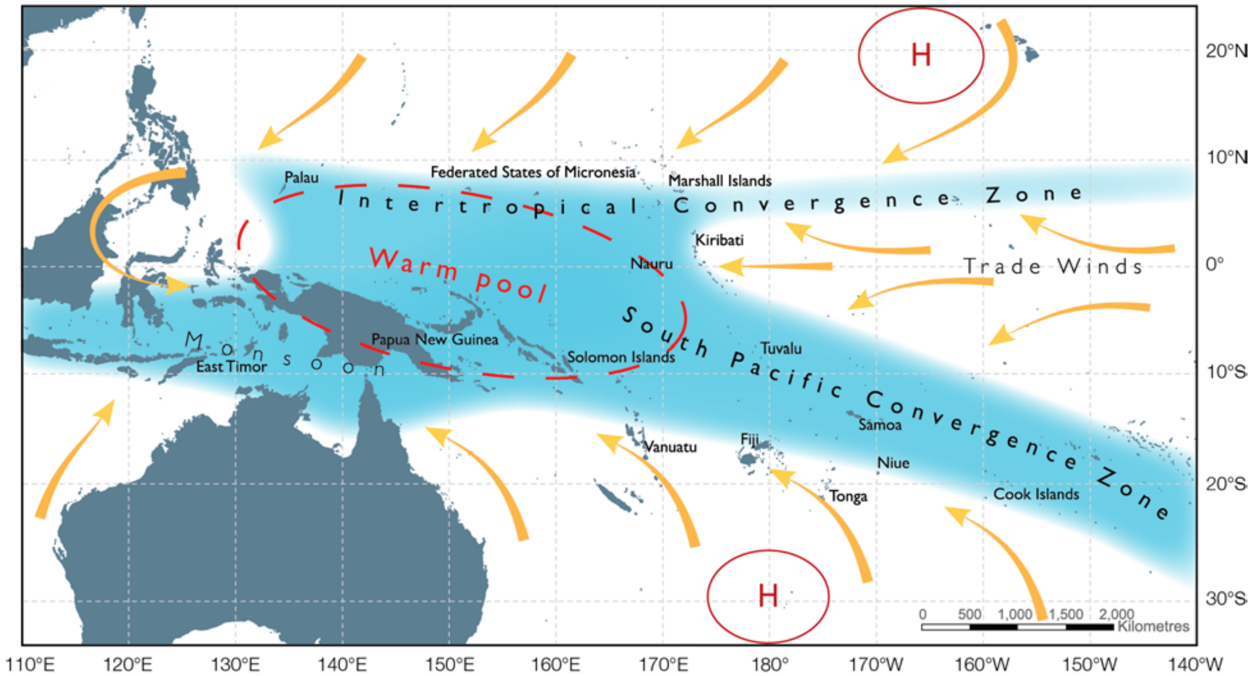


Figure 3.2: Map showing the average positions of the major climate features of the western tropical Pacific region in November to April. The yellow arrows show near surface winds, the blue shading represents the bands of rainfall (convergence zones with relatively low pressure). In this regard, note the terms Intertropical Convergence Zone (ITCZ), South Pacific Convergence Zone (SPCZ), and Monsoon Trough used throughout this section. H represents the typical positions of moving high pressure systems. From Australian Bureau of Meteorology and CSIRO (2014) https://www.pacificclimatechangescience.org/publications/reports/climate-variability-extremes-and-change-in-the-western-tropical-pacific-2014/

of precipitation distribution, there are often localized areas that are influenced by such things as topography and proximity to the large-scale features (Figure 3.2).

Western North Pacific. Defined by the boundaries of 180° to 120°E and 0°N to 40°N, the western North Pacific is well-known for its warm ocean temperatures which fuel tropical cyclones. On average, this region experiences 25-30 tropical cyclones each year, bringing with them very heavy rainfall[3], but often localized near the path of the storm. More widespread rains across this region are attributable to the monsoon season, which runs from June through October. The monsoon is the seasonal reversal of the winds, from easterly to southwesterly, bringing with it copious moisture for rainfall production. The Intertropical Convergence Zone (ITCZ), where the trade winds from the northern Hemisphere collide with trades from the southern Hemisphere near the equator, also plays a factor in this subregion's rainfall as the seasonal drift of this broad area of clouds and rain affects the islands.

Central Pacific. The central Pacific lies between 180° and 140°W and 0°N to 40°N, capturing the state of Hawaii. This region is characterized by a trade wind regime throughout much of the year, replaced only by Kona lows[4] which move across Hawaii from October through April. Tropical cyclones are also found in this region though the seasonal average of 3-5 storms is significantly less than its western counterpart. Rainfall is most abundant and widespread with the passage of the Kona Lows, whereas localized trade wind showers are found along the windward slopes of the mountainous high islands (such as the Big Island of Hawaii).

Southwest Pacific. The southwest Pacific is located south of the equator, from 0°S to 25°S, and from 135°E to 120°W. The territory of American Samoa is located in this subregion. Much like the other subregions, tropical cyclones are also found in the southwest Pacific[5], usually affecting areas from Australia, to Vanuatu, to American Samoa and the Cook Islands. In addition, the South Pacific Convergence Zone (SPCZ[6]), the southern hemispheric companion to the northern ITCZ, lies between the equator and 20°S. This area of converging trade winds brings widespread showers, often heavy localized rains, to American Samoa. Most flooding incidents in American Samoa are a direct result of the SPCZ (outside of landfalling tropical cyclones). Trade wind showers also affect islands in this region, but again, are highly localized and are concentrated on windward slopes of mountainous high islands.

The Pacific regional rainfall anomalies for 2016 are shown in Figure 3.3, with the Exclusive Economic Zones (EEZs) outlined in black. The 2016 anomaly map aligns well with the evolution of El Niño, as evidenced by the dry anomalies (more than 30% below normal) across FSM, southern RMI, and Koror in the Republic of Palau. The northern Hawaiian Islands also experienced a dry 2016, while the passing of several tropical cyclones kept the eastern Hawaiian Islands more than 80% above normal precipitation.

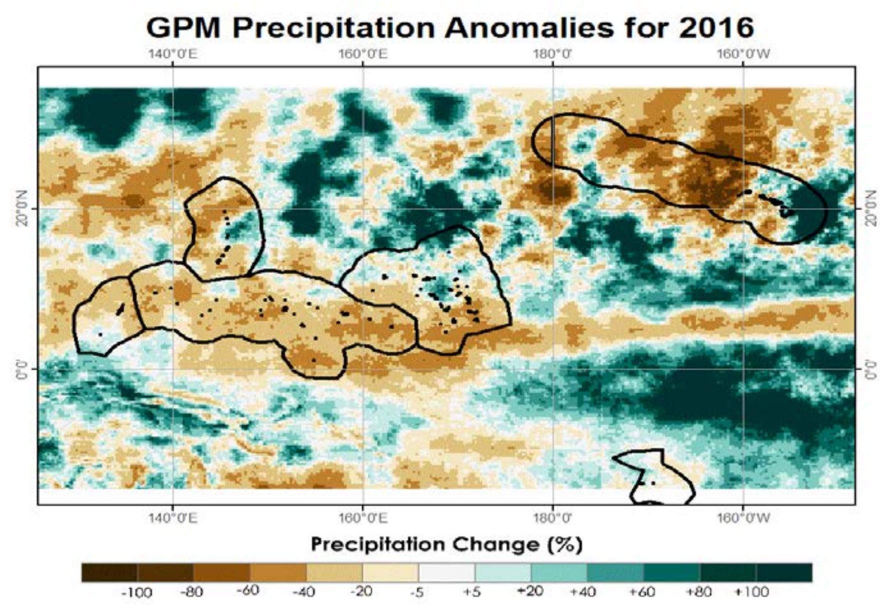


Figure 3.3. Pacific region precipitation anomalies for 2016 based on data from the Global Precipitation Measurement satellite. The brown shading denotes areas that were drier than average whereas green areas were wetter than average. Consistent with El Nino, the wettest areas were near the equator and east of the Dateline; drier areas were commonly found across FSM and the northern Hawaiian Islands. Original figure created by Michael Kruk at NCEI.

Local –Magnitude

The annual rainfall totals are shown for select six locations (Figure 3.4): Honolulu and Hilo in Hawaii, Majuro in RMI, Guam and the Commonwealth of Northern Mariana Islands, Yap in FSM, and Pago Pago in American Samoa. Much like the temperature data issues discussed in Chapter 2, rainfall data are also problematic across the region. While rainfall amounts are regularly observed and recorded on paper at these various sites, the transmission of these data to the National Weather Service and NCEI archives is an ongoing challenge. As a result, there tends to be missing data in the long-term record, which has been accounted for in Figures 3.5 – 3.7. In addition, the quality control measures for the NCEI data archive[7] have a tendency to flag high precipitation amounts as improbable, such as those which are associated with landfalling tropical cyclones, because the nearby neighbors do not exhibit the same rainfall magnitude. However, data from airport stations using the Automated Surface Observing System (ASOS) are routinely transmitted hourly via satellite and are less prone to missing data gaps. Despite the improved reliability of the ASOS data, stations on the islands are subject to land ownership and other siting requirements, which lead to frequent station moves that subsequently affect the reliability of the long-term record.

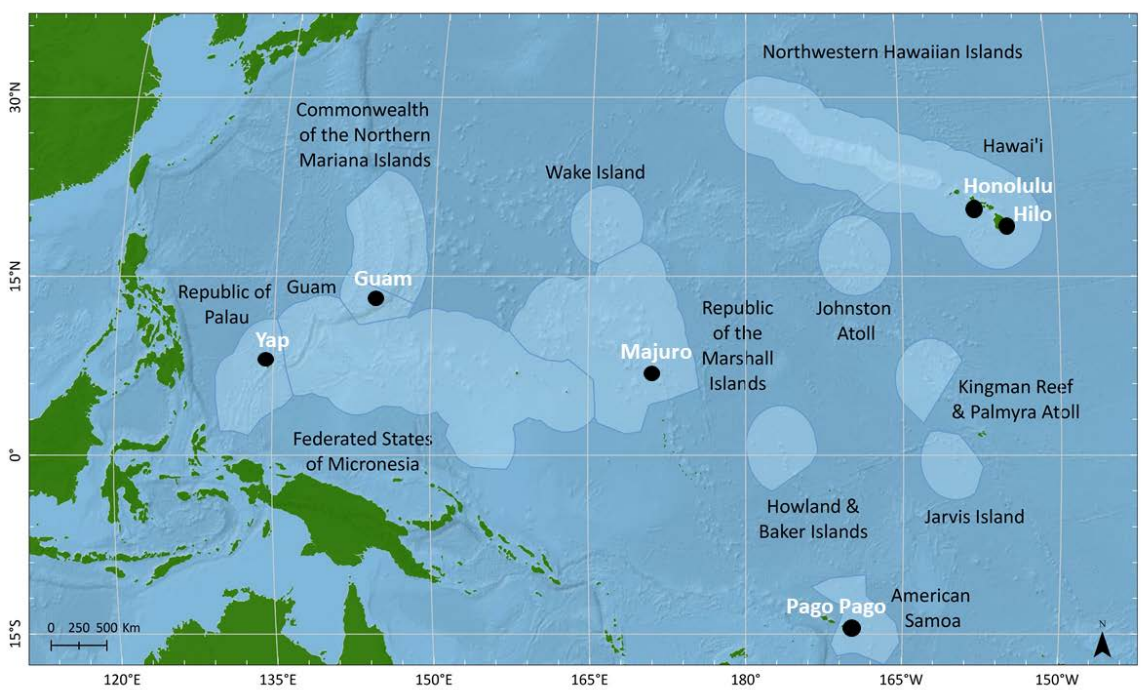


Figure 3.4. Location of selected Pacific region precipitation measurement sites. The distribution of these stations, and quality of their data, offers a holistic regional climate perspective. Original figure created by Michael Kruk at NCEI.

Figures 3.5 a-f show the long-term trend in the average annual rainfall anomaly, based on a 30-year average period from 1981-2010. Brown bars signify years where the anomaly was negative (dry) and green bars denote positive anomalies (wet years).

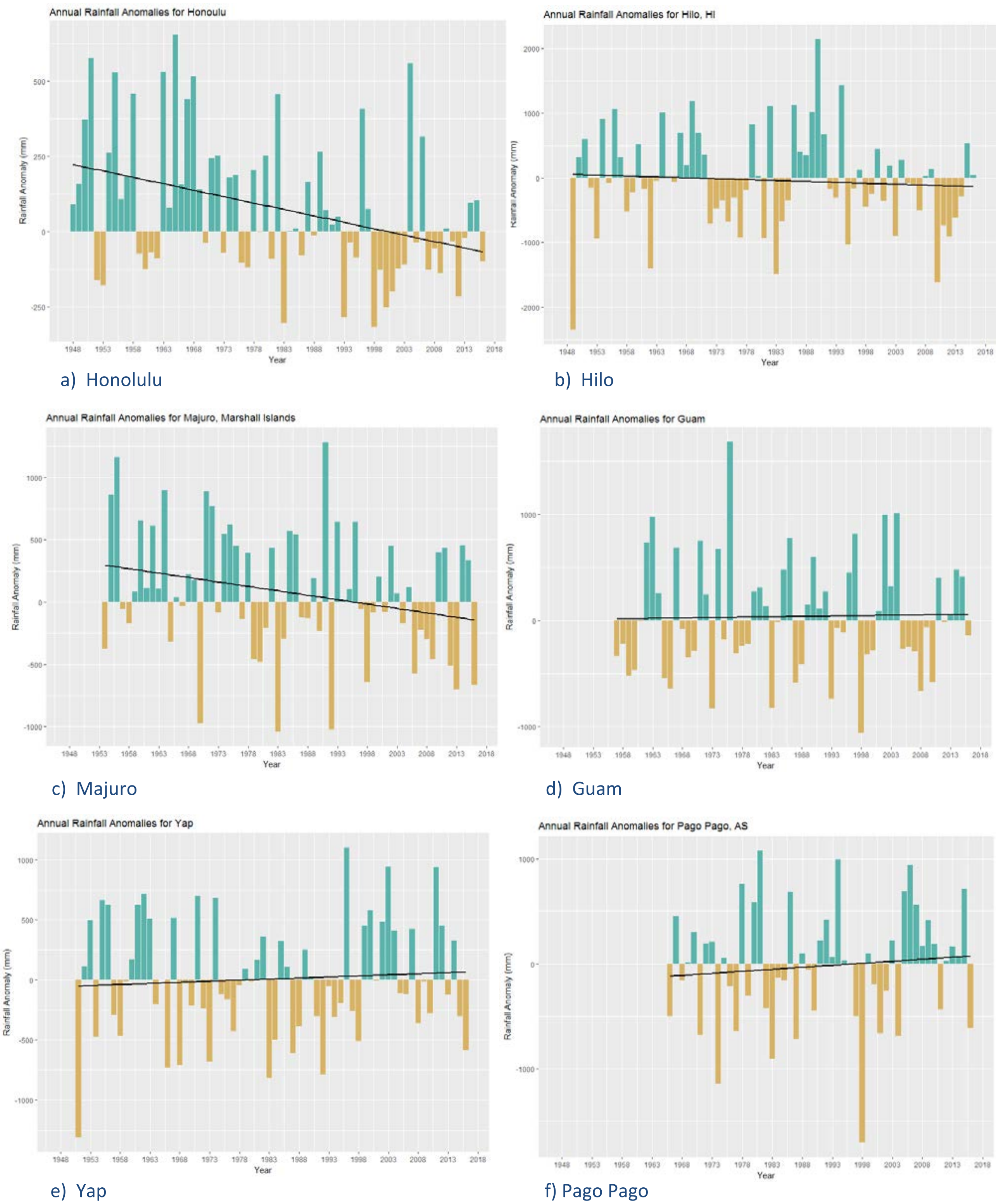


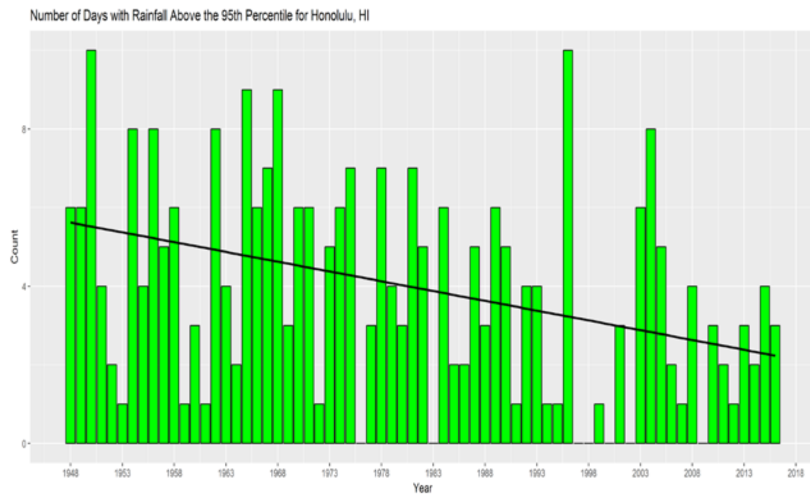
Figure 3.5. Local Annual Rainfall Anomalies and Trends from Select Stations in the Pacific. These plots show the annual rainfall anomaly (in mm) for: a) Honolulu; b) Hilo; c) Majuro; d) Guam; e) Yap; and f) Pago Pago. The long-term linear trend is indicated by the black line. Data from NCEI's Global Historical Climate Network – Daily dataset, original figure created by Michael Kruk at NCEI.

- For Honolulu (Figure 3.5a) since 1948, the trend in annual rainfall totals has been downward, from the wet period of the 1950s and 1960s, to the relatively dry period of the late 1990s and 2000s. Of the last ten years dating back to 2006, only four of them were above normal, and by an average of just 100 mm.
- For Hilo (Figure 3.5b) the long-term trend is only slightly downward, as there are just about as many years below and above average. However, much like Honolulu, the last 10 years have featured drier conditions compared to the 1980s, with 60% of the 2000s decade below normal.
- For Majuro (Figure 3.5c) the steep downward trend in annual average rainfall is punctuated by significant departures in El Niño years (e.g., 1983, 1998, and 2016). El Niño years tend to be very dry, with departures greater than 500 mm below normal.
- For Guam and the Commonwealth of the Northern Marianas (Figure 3.5d) the long-term trend at Andersen Air Force Base is near the long-term normal value. The driest year was 1998 with rainfall departures in excess of 1000 mm below normal. The wettest year was 1976 with over 1250 mm above-normal rainfall.
- For Yap (Figure 3.5e), if not for the very dry year of 1951, the long-term trend might be parallel to the normal value. Here there are roughly the same amount and magnitude of positive and negative departures leading to a near-zero trend.
- For Pago Pago (Figure 3.5f) the driest year of 1998 (with anomalies exceeding 1500 mm below normal) heavily influences the long-term trend. Despite this, the trend is still positive with eight of the last ten years being above normal.

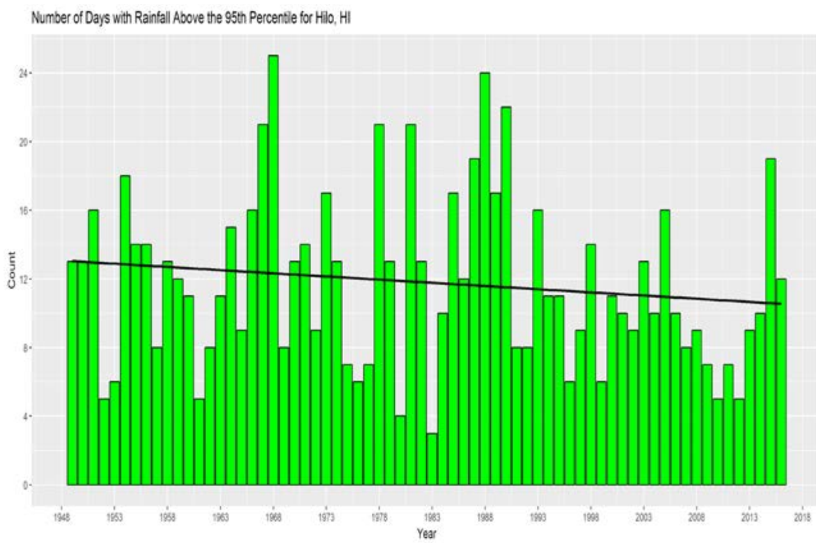
Frequency

Extreme rainfall events are often characterized by daily values exceeding the 95th percentile of the distribution.[8] Exploring the frequency of these events is important for understanding and developing adaptation and mitigation strategies for these islands. For each station location shown in Figure 3.4, the number of days with daily rainfall values exceeding the 95th percentile is shown in Figures 3.6 a–f. By contrast to the extreme precipitation, the number of days with no measurable rainfall is shown in Figures 3.7 a–f, as dry days can negatively impact local agriculture as well as freshwater availability.

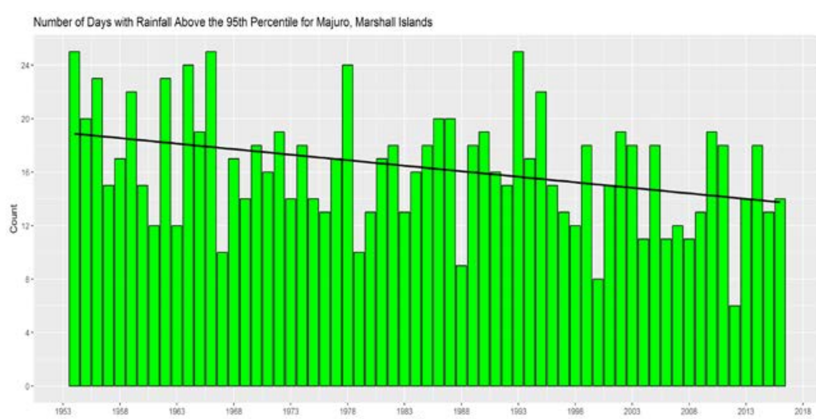
- For Honolulu (Figure 3.6a) there is a distinct downward trend in the number of extreme rainfall days, from about five events per year in 1950 to two events per year in 2016. This is equivalent to a 60% decrease over the last 50 years.
- For Hilo (Figure 3.6b) the long-term trend is only slightly downward since the late 1940s, as this part of the Hawaiian Islands averages 12 rainfall events per year.
- For Majuro (Figure 3.6c) the long-term trend is downward as well, from near 20 events annually in the early 1950s, to 12 events in the last several years, representing a 40% decrease over the last 50 years.
- For Guam and the Commonwealth of the Northern Marianas (Figure 3.6d) the trend in flat over the last 50 years, as the average of 12 events is fairly consistent through that time period.
- For Yap (Figure 3.6e) from 14 events per year in 1950 to 16 events in 2016, representing a 15% increase in the occurrence of extreme rainfall events over the last 50 years.



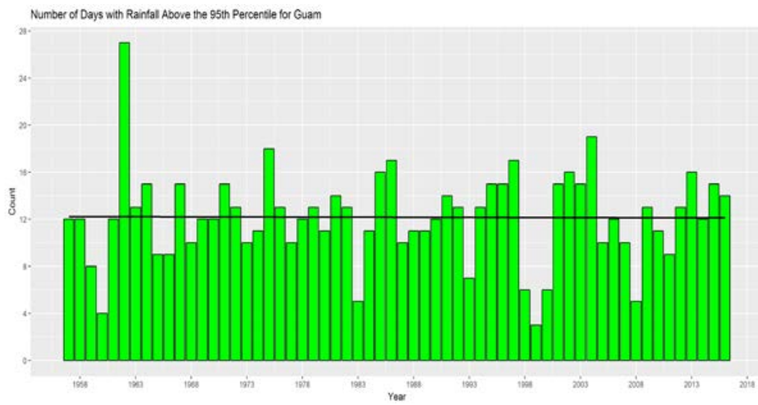
a) Honolulu



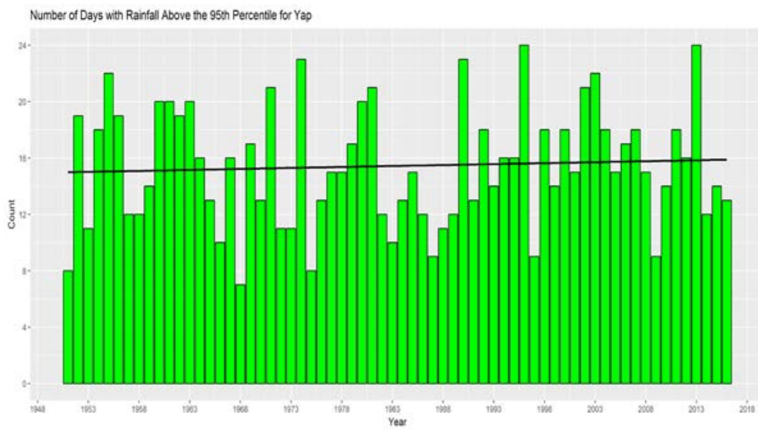
b) Hilo



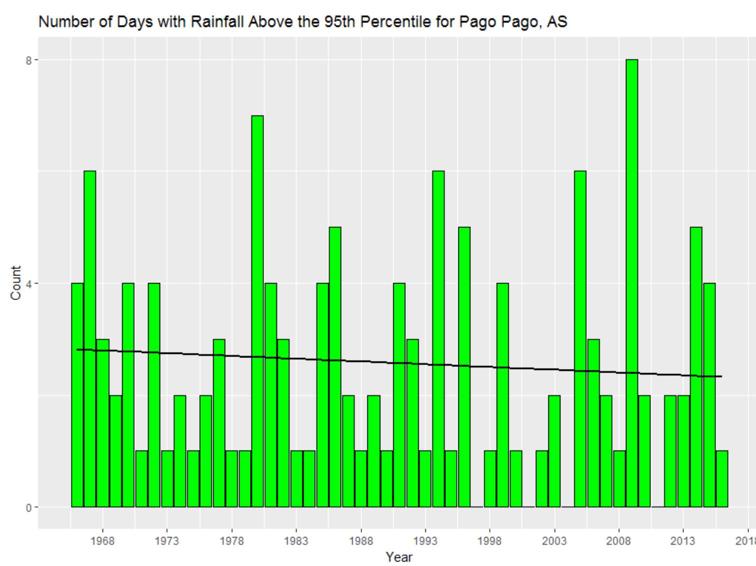
c) Majuro



d) Guam

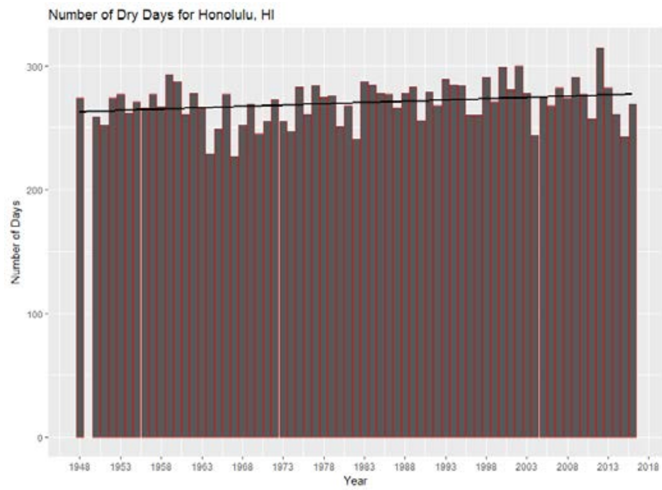


e) Yap

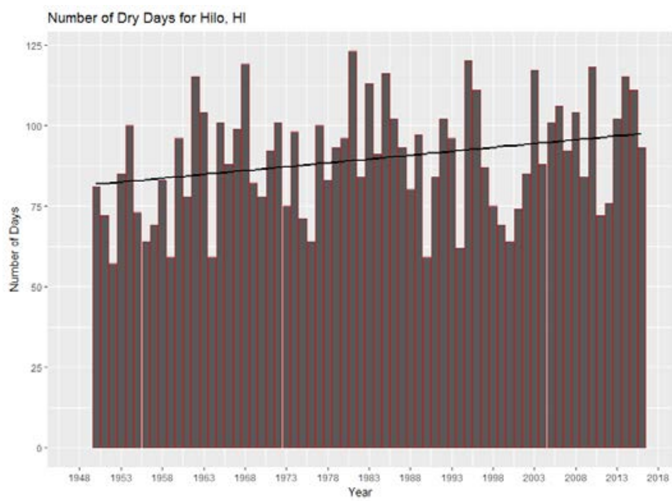


f) Pago Pago

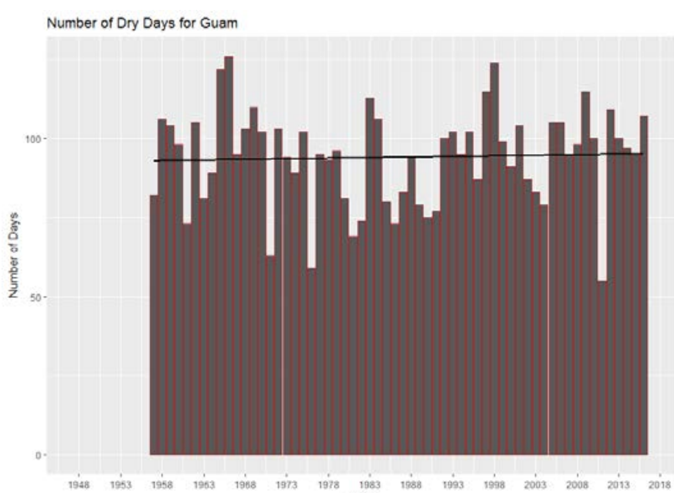
Figure 3.6. Extreme Rainfall Days from Select Rain Gauges in the Pacific. These plots show the number of days with daily rainfall totals exceeding the local climatological 95th percentile of the distribution (i.e., extreme rain days). Data from NCEI's Global Historical Climate Network – Daily dataset. Original figure created by Michael Kruk at NCEI.



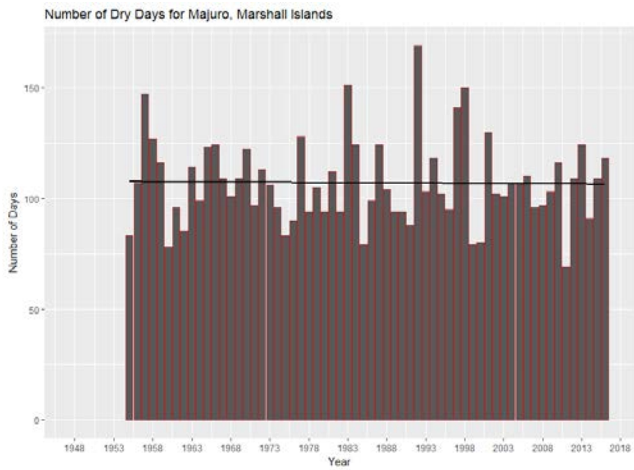
a) Honolulu



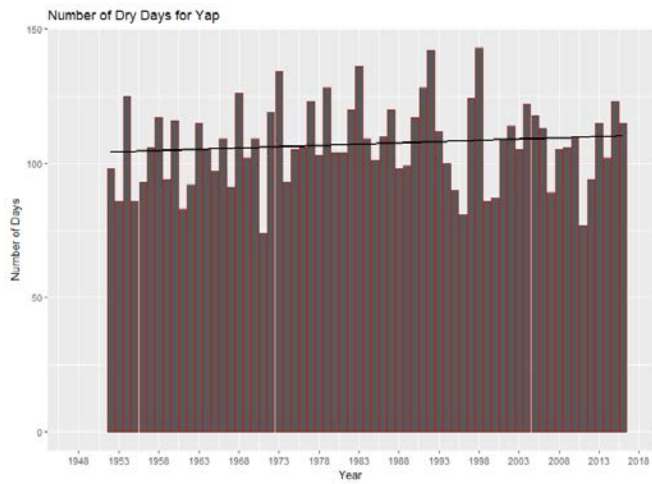
b) Hilo



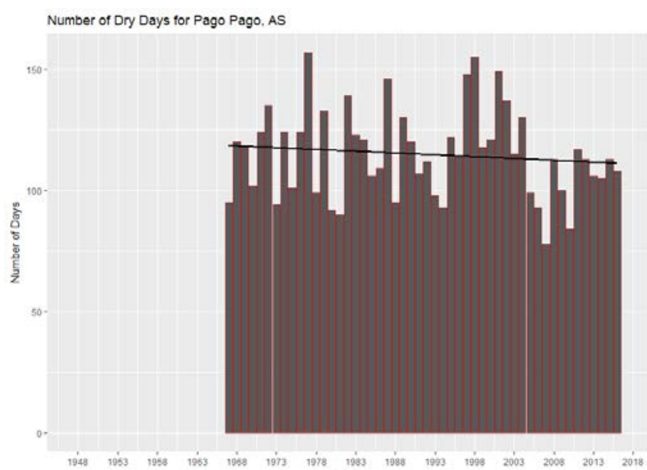
c) Guam



d) Majuro



e) Yap



f) Pago Pago

Figure 3.7. Number of days without rainfall from Select Rain Gauges in the Pacific. These plots show the annual number of days with no measurable rainfall. The number of dry days can adversely affect local subsistence farming and influence the amount of available freshwater for consumption. Data from NCEI's Global Historical Climate Network – Daily dataset, original figure created by Michael Kruk at NCEI.

- For Pago Pago (Figure 3.6f) the long-term average is 10–15 events per year, with many years having over 20–25 extreme rainfall days. The trend is positive over the last 50 years, with an approximate increase of 100% (a near doubling of events).

What does the future hold?

Rainfall trends from climate model projections are strongly linked to changes in the frequency and magnitude of future El Niño/Southern Oscillation (ENSO) events, however, some signals are emerging from the long-range computer model guidance. In particular, an increase in rainfall associated with the ITCZ and the SPCZ are likely.[9] Continued warming of atmospheric temperatures increases the capacity of the atmosphere to hold more water vapor.[10] As such, rainfall rates are projected to be more intense and extreme than is exhibited in the historical record.[11] In the western Pacific, rainfall projections indicate that the wet season will get wetter and the dry season will be drier.[12] Rainfall trends in American Samoa are projected to rise as trade wind showers become heavier and rainfall from the SPCZ increases. Finally, in Hawaii, local downscaled projections indicate that the windward slopes will see enhanced trade wind showers but also a drier wet season.[13] The global consensus also projects that, despite the increase in extreme rain events, there will also be an increase in the number of dry days that will contribute to more, and lengthier, drought events.[14]

Key Links

IPCC https://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch9s9-5-4-2.html

GHCN-Daily https://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/global-historical-climatology-network-ghcn

Climate Change in the Pacific: Scientific Assessment and New Research http://www.pacificclimatechangescience.org/publications/reports/report-climate-change-in-the-pacific-scientific-assessment-and-new-research/

Global Precipitation Measurement (data) https://pmm.nasa.gov/data-access/downloads/gpm

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4. Surface Winds and Tropical Cyclones

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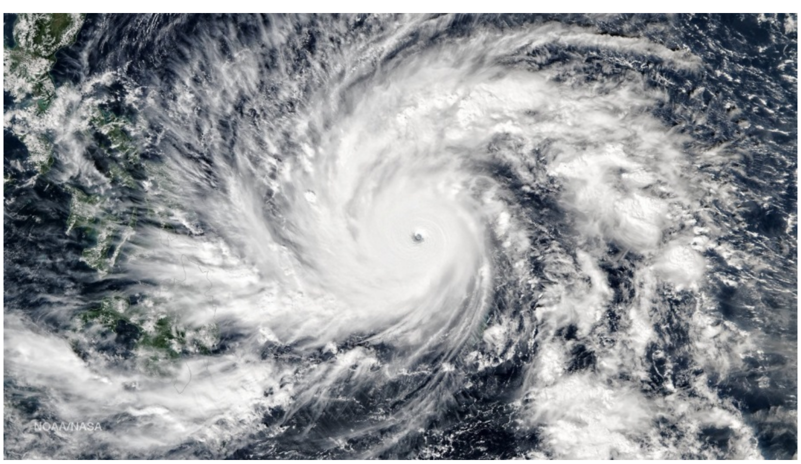
Howard Diamond, NOAA OAR ARL
Mark Lander, UoG WERI

Takeaways

- The frequency of the occurrence of gale-force winds is increasing in the western and south Pacific, but decreasing in the central Pacific.
- Average daily wind speeds are slowly declining in Honolulu and Hilo, while remaining steady across the western and south Pacific sites.
- The global frequency of tropical cyclones (TCs) appears to be showing a slow downward trend since the early 1970s.
- Subregional long-term TC trends are also relatively flat, with the record punctuated by as many active as inactive years.
- Over the last five years, there has been a decrease in TCs west of Mexico, but an increase over the Baja Peninsula.
- Between 2010 and 2015, there has been a decrease in TCs near Vanuatu in the southwestern Pacific and parts of the far northwestern western Pacific, while increasing numbers are noted over the Philippines.
- Future projections are muddled with respect to changes in the broader circulation, thus changes in wind speed are expected to be small in most locations[1].
- Most global climate model simulations indicate that in the future there should be a decrease in the frequency of TCs across the Pacific, but there may also be an increase in the occurrence of major TCs, particularly in the SW Pacific basin.
- The impact to human life and property from a landfalling TC can be devastating, especially for small islands across the Pacific.



Typhoon Hagupit on 5 December 2014. Large hurricanes and typhoons like Hagupit are especially problematic for small islands in the Pacific as their destructive potential overwhelms the local capacity to mitigate and respond. Photo courtesy of NASA Terra MODIS.

Why should we care?

The impact to human life and property from a landfalling TC can be devastating, especially for small islands across the Pacific. Changes to the frequency and/or intensity of TCs can influence local mitigation policies and impacts with respect to, among other things: (1) human infrastructure, (2) human health, and (3) agricultural practices. Severe local flooding and destruction can occur when storm surge from a landfalling TC impacts low-lying and vulnerable islands. Science has not determined the exact relationship between TCs and climate change[2]; nevertheless, the occurrence and intensity of TCs are key measurements of long-term global climate change; and therefore, examining how the anomalies of TCs vary with time is critical to evaluating climate change across the Pacific.

Finally, changes in wind speed and direction also have distinct impacts across the Pacific. Increasing winds, for example, can increase evaporation, thus resulting in greater water demand for agriculture. Decreasing winds under sunny skies can lead to warmer ocean temperatures and potentially enhanced coral bleaching. The social and economic welfare of many tropical countries is linked to the seasonal monsoon cycle, or the annual reversal of the winds, so understanding and documenting these changes is critical to the people's well-being.

Where are we now?

Surface Winds

Regional

The USAPI of the tropical western North Pacific (WNP) are located in a region of the world characterized by large-scale seasonal weather changes associated with the monsoons of the Eastern Hemisphere. For most of the year, the winds are from the east, but during the summer and early autumn, the winds can become west to southwest. The farther to the west, the more persistent the southwest wind. The episodic and highly variable nature of the western North Pacific monsoon needs to be emphasized. The location of the monsoon varies from season to season based on a number of factors, including ongoing tropical cyclones, cloud cover percentage along the equator, and the active state of the monsoon in the northern Indian Ocean[3]. The monsoon replaces the normally easterly trade winds, and during El Niño and La Niña years, the trade winds can break down or speed up respectively.

To visualize the long-term wind vector of the trade winds, NOAA's Climate Prediction Center updates and maintains a regional Trade Wind Index. The Trade Wind Index is defined as the average wind speed and direction in the lowest 1500 m of the atmosphere between 5°N–5°S and 135°E–120°W. Figure 4.1 shows the evolution of the regional Trade Wind Index dating back to 1998. Anomalous westerly winds are shown as a negative standard deviation, and anomalous easterly winds are shown as positive standard deviations. Negative (positive) anomalies are often associated with El Niño (La Niña). Following this, La Niña-like conditions have largely dominated the period, punctuated by El Niño's in 1997–1998, 2002–2003, 2006–2007, 2009–2010, and 2015–2016. The figure also shows that the wind anomaly for the 2015–16 El Niño was the strongest since 1997–98.

Similar to Chapter 3, the same subregions are used in this Chapter (western North Pacific, central Pacific, and South Pacific) as the large-scale atmospheric settings influence the local winds and tropical cyclone

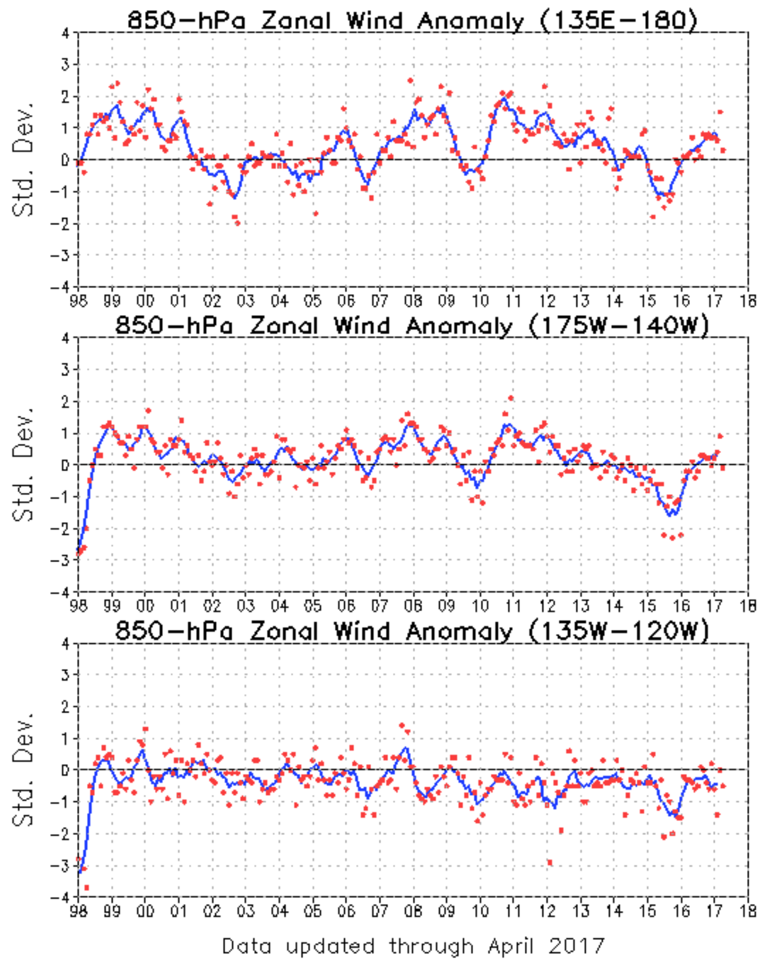
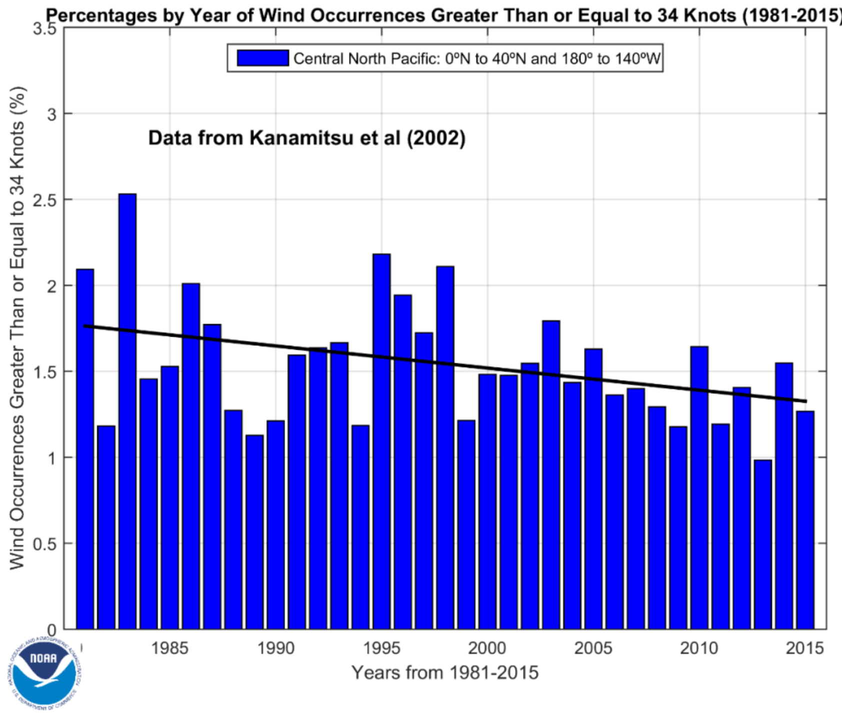


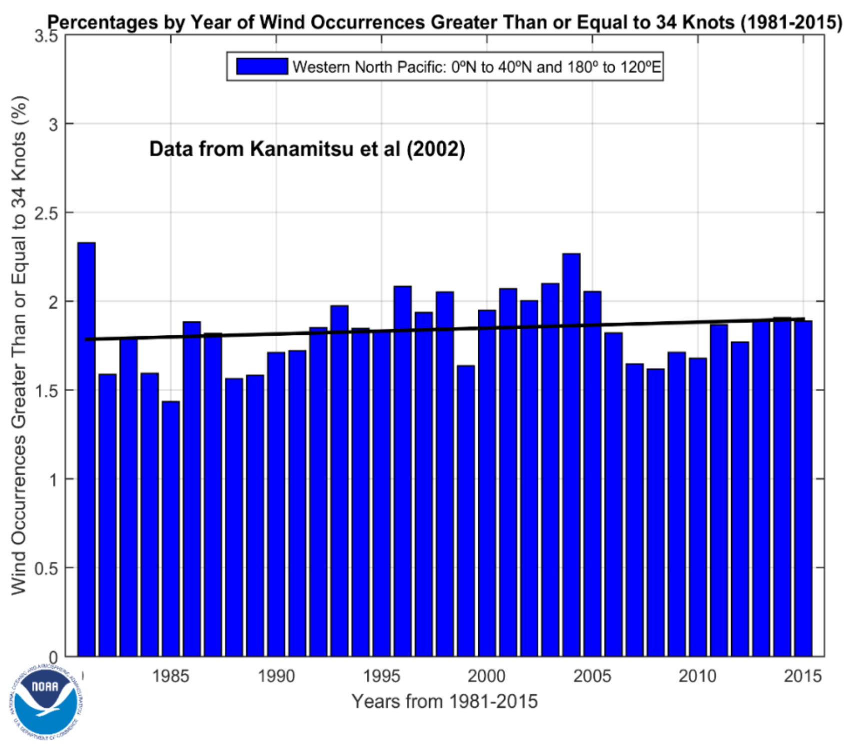
Figure 4.1. Trade Wind Index from NOAA's Climate Prediction Center. This plot shows the standard deviation of the zonal wind anomaly at three different longitudinal sections of the Pacific, starting with the westernmost section (top panel), to the easternmost (bottom panel). Positive standard deviations show stronger easterly trade winds associated with La Niña events (e.g., 2002/2003, 2009/2010) and negative deviations associated with anomalous westerly winds during El Niño events (e.g., 1998/1999, 2015/2016). Source: NOAA CPC http://www.cpc.ncep.noaa.gov/products/CDB/Tropics/figt4.gif

climatology accordingly. The western North Pacific is influenced by trade wind showers, tropical cyclones, and the western Pacific monsoon; the central Pacific has trade wind showers, Kona Lows, and tropical cyclones; the south Pacific is influenced by the South Pacific Convergence Zone (SPCZ), trade wind showers, and tropical cyclones[4].

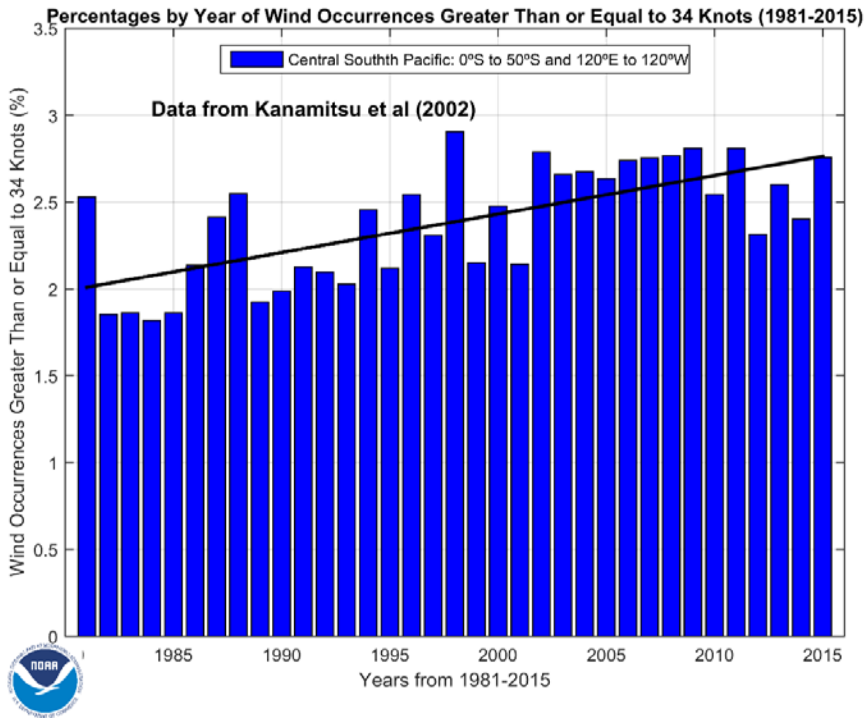
Figures 4.2 a) Central North Pacific, b) Western North Pacific, and c) central South Pacific, show the percentage of wind occurrences greater than or equal to 34 knots since 1980 in the three subregions. The value of 34 knots represents "Gale, fresh gale" on the Beaufort scale, which corresponds to 5-8m wave heights and boating becomes very challenging. Characterizing the percent occurrence of these gale-force winds gives an indication of storminess[5] frequency within each subregion. Indeed, slight increases in the frequency of gale-force winds are noted in both the South and Western Pacific basins, while a downward trend is evident in the Central Pacific.



a) Central North Pacific



b) Western North Pacific



c) central South Pacific

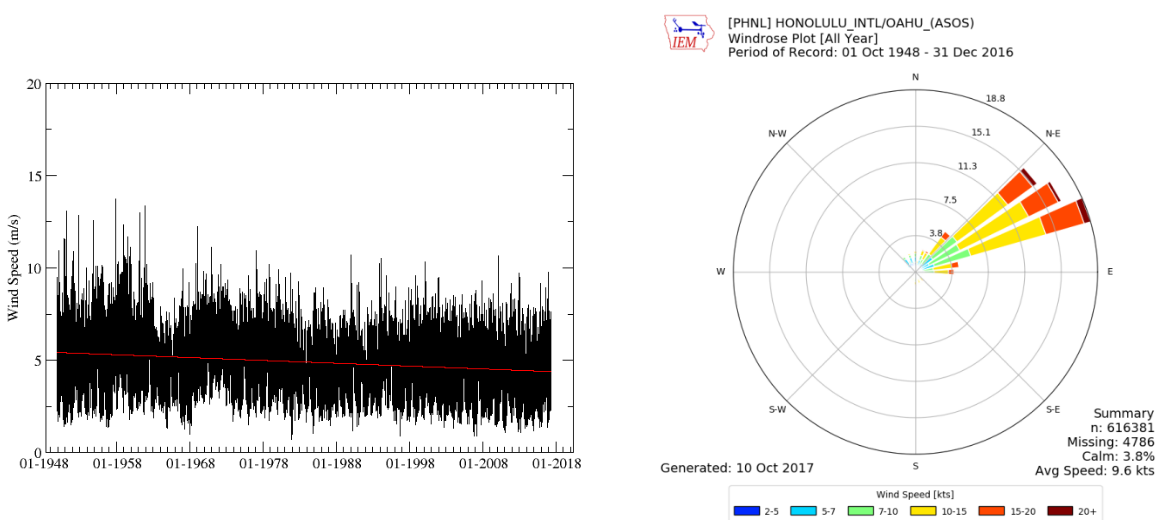
Figure 4.2. Percentages by year of wind occurrences greater than or equal to 34 knots. These plots show the frequency of gale-force winds by annual percentage of exceedance from 1981-2015. Gale-force winds are also responsible for moderate to high waves which can impede boating progress. Data from Kanamitsu et al (2002)[6.] Original figure created by Howard Diamond, NOAA ARL.

Local – Magnitude

Wind speed and direction in the North Pacific are influenced by the subtropical high, which is a semi-permanent feature located in the North Pacific. The flow around that high, in combination with the larger global-scale circulation patterns, results in easterly trade winds across most of all the local sites in the region. Data for each site is made available through the Automated Surface Observing System (ASOS), whose instrumentation is located at airports around the world. For each plot that follows, wind speed and direction data are from the representative airport.

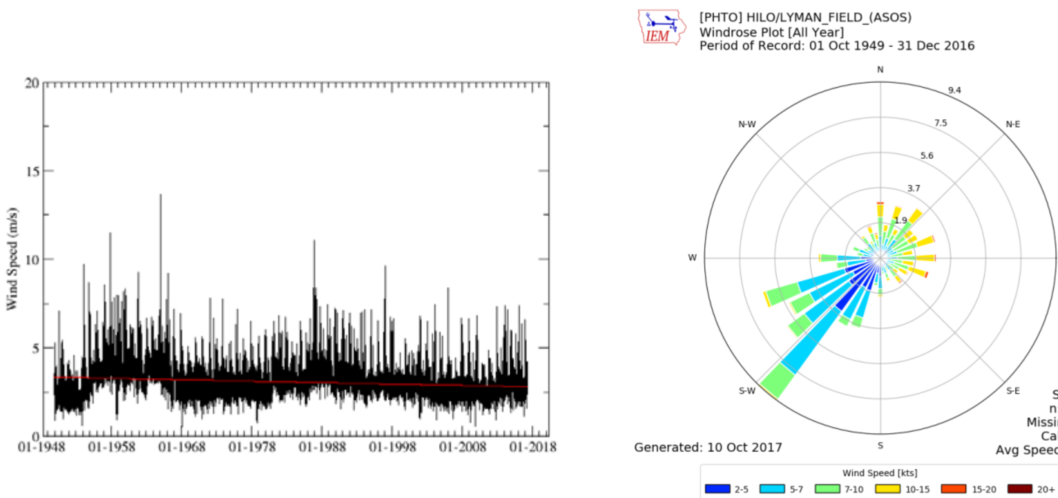
- For Honolulu, Hawaii (Figure 4.3a), 35% of the wind direction is out of the ENE, with another 20% contributing from the NE. Speeds are generally under 10 ms^{-1} (20 kt), with only few instances over 10 ms^{-1}. Since 1948, there has been an approximate 10% reduction in the daily average wind speed.
- For Hilo, Hawaii (Figure 4.3b), wind direction is influenced by local topography, such that predominant direction is some westerly component about 45% of the time but with lower speeds (under 5 ms^{-1}). The other 55% is from an easterly component and breezy, with speeds generally 5-10 ms^{-1}. Wind speed trends are fairly constant, though the peak period between 1950 and 1965 stands out above the rest of the record.

- For Majuro, RMI (Figure 4.3c), the wind direction is from the ENE more than 35% of the year, followed by northeasterly (15%). A majority of the wind speeds are between 5-10 ms^{-1} (10-20 kt) with only rare instances of winds greater than 10 ms^{-1}. Though official wind speed records are based on a period of record that began in 2004, there has been an upward trend since 2004 in the daily average wind speed.
- For Guam (Figure 4.3d), 35% the wind is out of the due east, with only minor variances between ENE and ESE. The average wind speeds are generally under 10 ms^{-1} (20 kt) except in and near typhoons (TCs). Since 1948, the long-term trend in daily average wind speed has remained constant near 4 ms^{-1} (8 kt), though there appears to be fewer high-end events since 2004 (likely coinciding with the general reduction in TC occurrences).
- For Yap (Figure 4.3e), the predominant wind direction is from the ENE (18%), followed by NE (14%), and then easterly (12%). Note that 10% of winds come from the west (though at speeds less than 10 ms^{-1} [20 kt]). Daily average wind speed trends have remained constant since 1948, despite the quiet period of the late 1940s and since 2015.
- For Pago Pago, American Samoa (Figure 4.3f), 25% of the winds are easterly, with another 15% contribution from the ESE. Wind speeds are greater than other locations in the Pacific, with most averaging 5-9 ms^{-1} (10-18 kt) and 5%–10% of the time they are at 9-12 ms^{-1} (18-25 kt). Long-term average wind speeds hover closer to 5 ms^{-1} (10 kt), with only a few notable spikes above that in the climate record since the late 1980s.

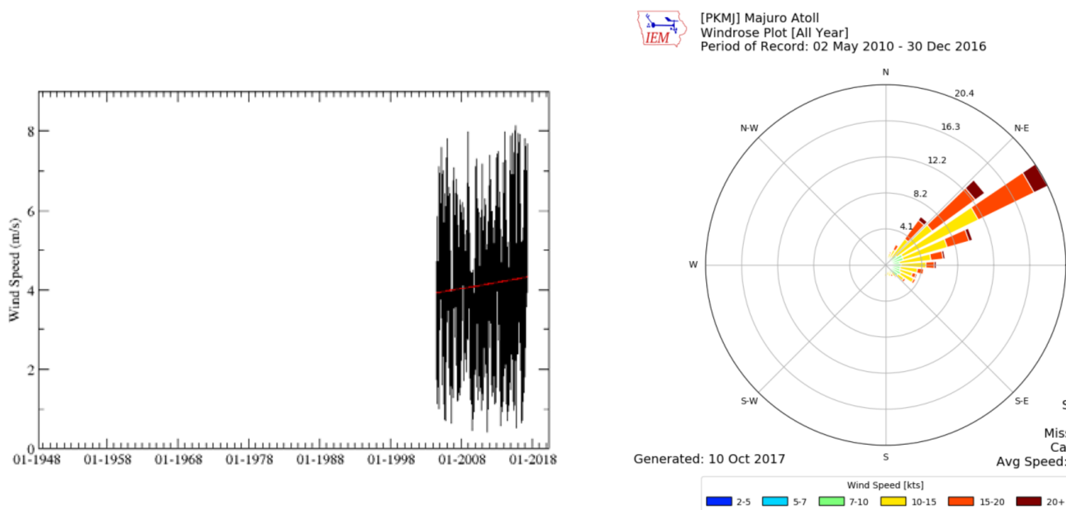


a) Honolulu

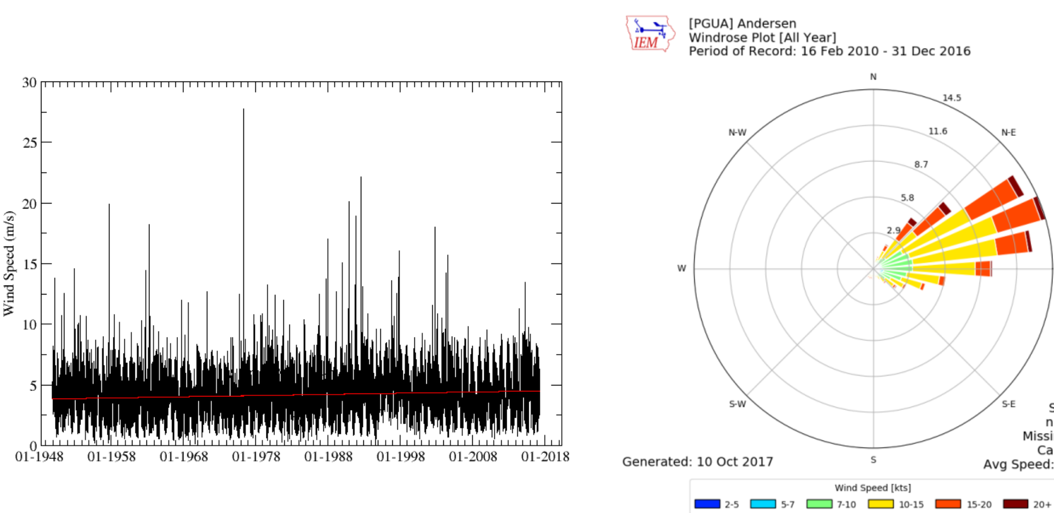
Figure 4.3. Local long-term trends in wind speed. These plots (here and on the following pages) show the annual average wind speed (left panels) and annual distribution of wind speed and direction (right panels) for: a) Honolulu; b) Hilo; c) Majuro; d) Guam; e) Yap; and f) Pago Pago. Red line in the top panels represents the linear trend over the period of record. Data from NCEI Integrated Surface Database. Wind speed plots are originals created by X. Yin at NCEI. The wind rose plots also use the Integrated Surface Database hourly data and are available online at - http://mesonet.agron.iastate.edu/sites/locate.php.



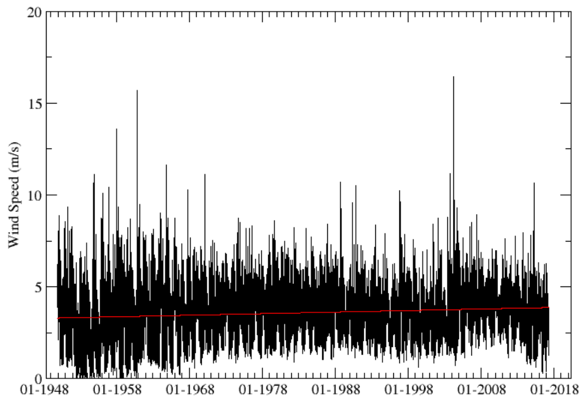
b) Hilo

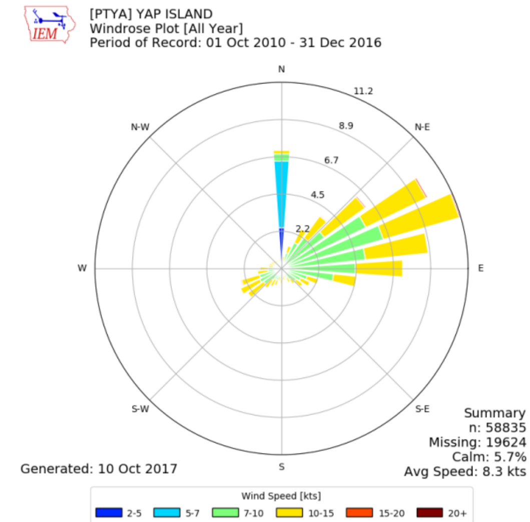


c) Majuro

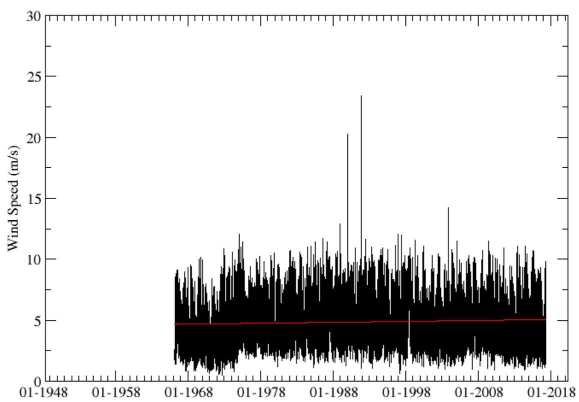


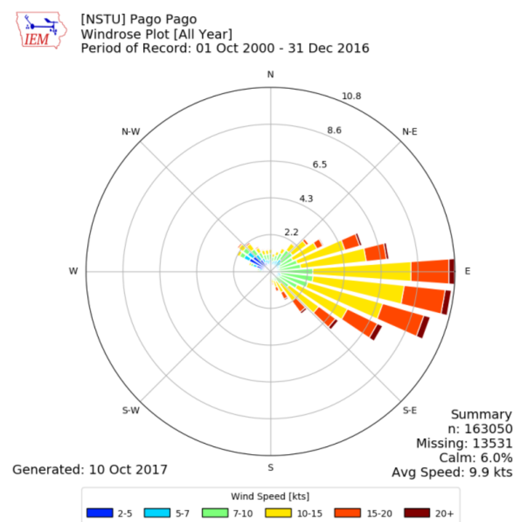
d) Guam





e) Yap





f) Pago Pago

Tropical Cyclones

Global

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 Pacific, Eastern Pacific, and Southwest Pacific for cyclone monitoring and recording-keeping according to the International Best Track Archive for Climate Stewardship (IBTrACS)[7].

Global tropical cyclone (TC) activity since 1970 is shown in Figure 4.4, with the top line showing the number of all hurricanes—storms with winds greater than or equal to 64 kt (75 mph)— and the bottom line indicating only major hurricanes—those storms with intensity greater than or equal to 96 kt (110 mph). Since 1970 the peak year for total number of hurricanes was 1972, with 2016 the busiest since 2005.

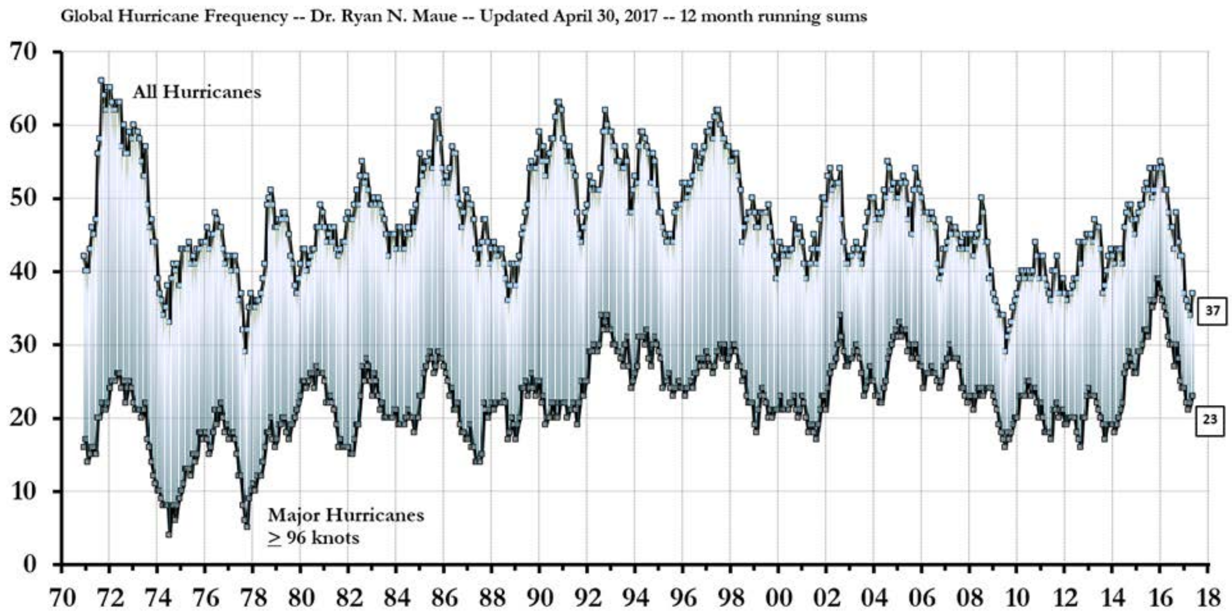


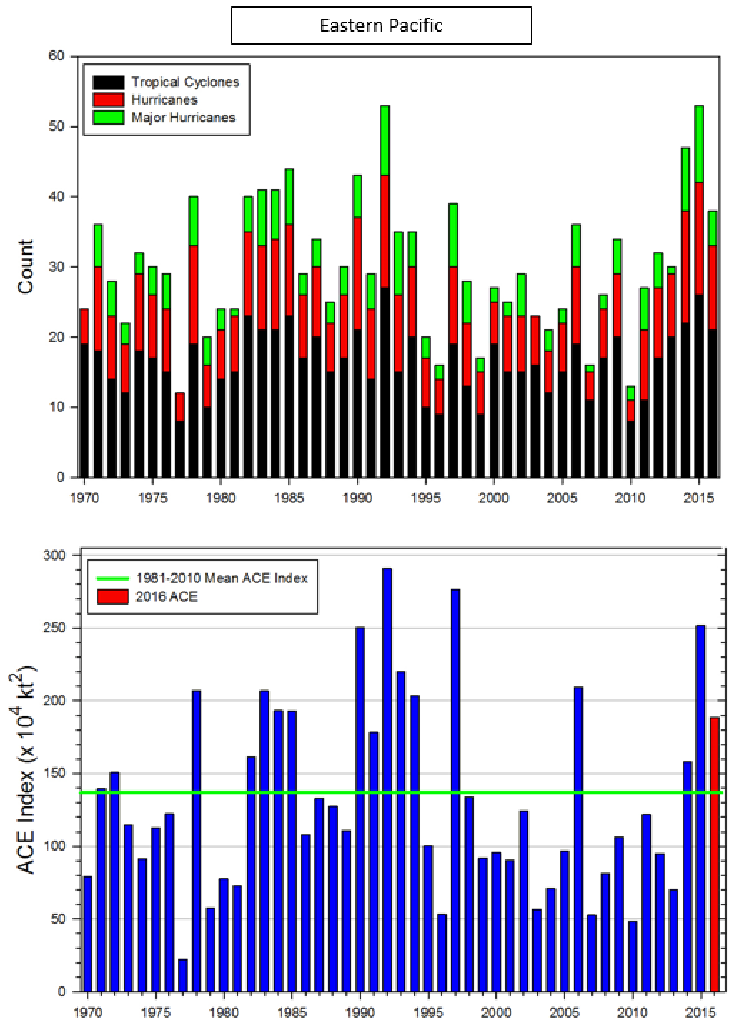
Figure 4.4. Global Hurricane Frequency (all & major) – 12-month running sums[8]. The top time series is the total number of global tropical cyclones that reached at least hurricane-force (maximum lifetime wind speed exceeds 64-kt). The bottom time series is the number of global tropical cyclones that reached major hurricane strength (96-kt+). Available online at http://models.weatherbell.com/tropical.php

Regional

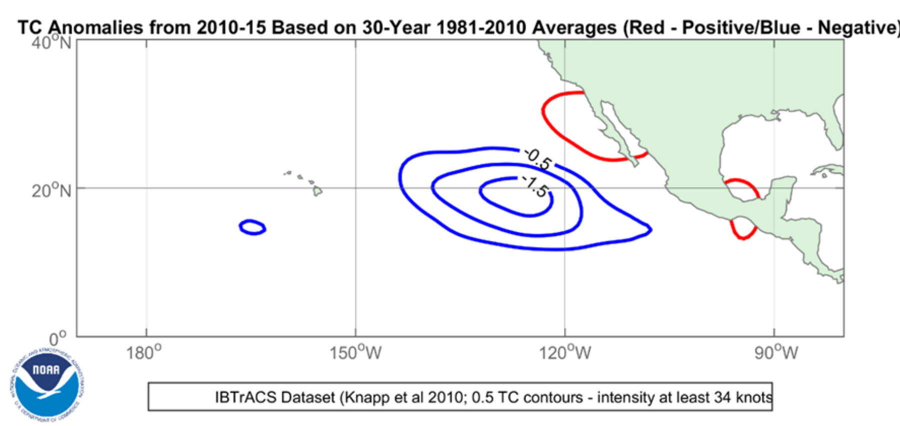
Eastern Pacific (Figures 4.5a,b): Since 1970, trends in the number of named storms, hurricanes, and major hurricanes have remained constant, with nearly an equal number of above- and below- normal season activity. The last three seasons (2014–16) have been more active than the period 1993–2014 (in terms of number of storms), with a similar trend in the total accumulated cyclone energy (ACE), which is a combined measure of the intensity and longevity of a tropical cyclone. The busiest year was 1992, with 28 named storms and a seasonal ACE value just under 300×10^4 kt^2. For the period 1981–2010, the IBTrACS dataset indicates a reduction in TCs near 120°W, west of Mexico, but with a slight increase in occurrences over the Baja Peninsula.

Western Pacific (Figures 4.5c,d): Since 1980, trends in the number of named storms, hurricanes, and major hurricanes 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 below-average ACE values (implying shorter-lived TCs, despite the TC count being near normal). This is also reflected in the regional frequency contour map, which shows a broad area of decreasing activity between 20°–40°N latitude (and an increase near the Philippines).

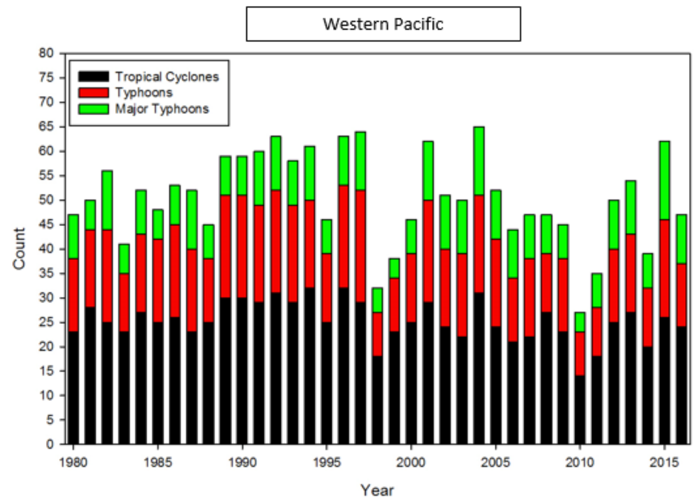
Southwest Pacific (Figures 4.5e,f): 2016 was the busiest year on record since 1998 with 12 TCs and an ACE value that was 100% of normal for the season. Like the other sub-basins, long-term trends do not suggest a notable up or down trend in the frequency or magnitude of storms across the region. The past five years, however, have shown a drop in TC frequency around Vanuatu and the Cook Islands, but an increase along the northern island of New Zealand.

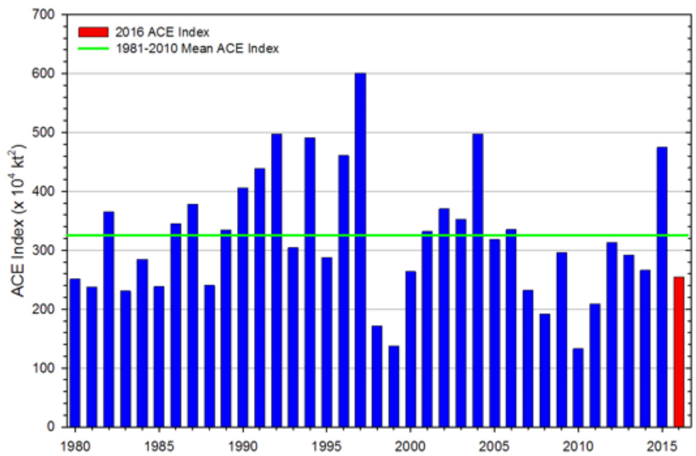


a)

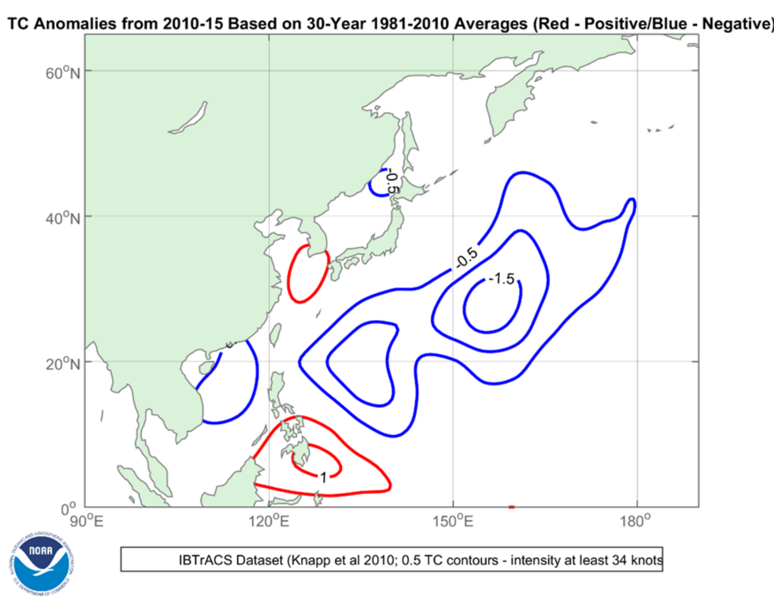


b)

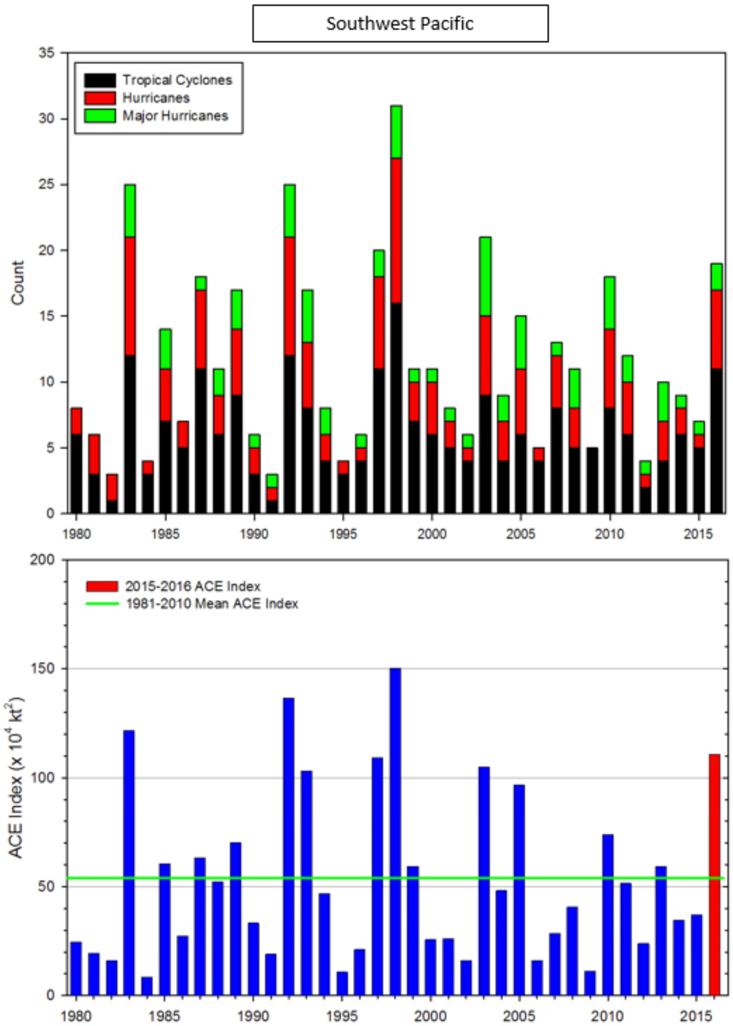

Western Pacific
Tropical Cyclones
Typhoons
Major Typhoons
Count
Year


2016 ACE Index
1981-2010 Mean ACE Index
ACE Index (x 10⁴ kt²)

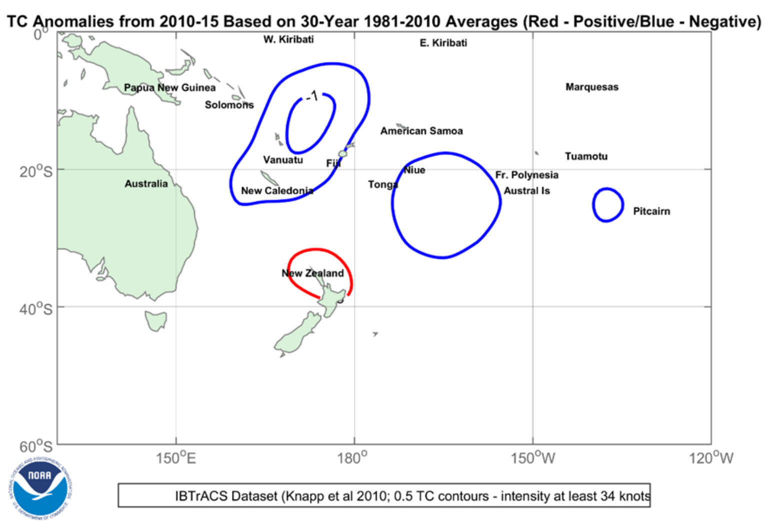
c)


TC Anomalies from 2010-15 Based on 30-Year 1981-2010 Averages (Red - Positive/Blue - Negative)
IBTrACS Dataset (Knapp et al 2010; 0.5 TC contours - intensity at least 34 knots

d)


Southwest Pacific
Tropical Cyclones
Hurricanes
Major Hurricanes
Count
35
30
25
20
15
10
5
0
1980
1985
1990
1995
2000
2005
2010
2015
2015-2016 ACE Index
1981-2010 Mean ACE Index
ACE Index (x 10⁴ kt²)
200
150
100
50
0

e)


TC Anomalies from 2010-15 Based on 30-Year 1981-2010 Averages (Red - Positive/Blue - Negative)
W. Kiribati
E. Kiribati
Papua New Guinea
Solomons
Marquesas
American Samoa
Tuamotu
Vanuatu
Fiji
Niue
Fr. Polynesia
Austral Is
Australia
New Caledonia
Tonga
Pitcairn
New Zealand
-1
0°
20°S
40°S
60°S
150°E
180°
150°W
120°W
NOAA
IBTrACS Dataset (Knapp et al 2010; 0.5 TC contours - intensity at least 34 knots

f)

(preceding pages) **Figure 4.5. Regional Tropical Cyclone Trends and Anomalies.** The bar graphs show tropical cyclone, hurricane, and major hurricane trends from the IBTrACS[7] dataset for the past 25 years. The regional maps are tropical cyclone anomalies, with the blue contours representing areas that had below-average TC activity from 2010–15 as compared to the 30-year long-term normal from 1981–2010; and conversely, the red contours are areas that had above-average TC activity from 2010–15, compared to the 30-year long-term normal from 1981–2010.

What does the future hold?

Any assessment of future changes to the behavior of the wind in the USAPI must take into account changes to the phenomena responsible for local variations. The location of the seasonal monsoon, wind direction, and wind speed are factors influenced by the greater global circulation and the location of the North Pacific high pressure center. Future projections are unclear with respect to changes in the broader circulation. However, long-range climate model simulations suggest decreases in wind speeds for Majuro, Yap, and Guam, with some slight increases projected for American Samoa[9].

In climate model projections, the future is more uncertain for tropical cyclones than other elements. This is largely because certain models simply cannot simulate the environmental conditions needed to produce a cyclone, and TC events are at time scales much shorter than global climate model simulations. In addition, models do not simulate connections between global dynamics and TCs; for example the strong connection between the state of ENSO and the frequency and distribution of tropical cyclones, or the strong connection in between TC frequency and intensity and the phase and intensity of the Madden-Julien Oscillation in the southwest Pacific[10]. Even when considering these factors, however, most simulations indicate that some increase in the mean maximum wind speed is likely with future warming, while models project a decrease in tropical cyclone frequency under a changing climate[11].

Key Links

Pacific Storms Climatology - http://pacificstormsclimatology.org

International Best Track Archive for Climate Stewardship (IBTrACS) – http://www.ncdc.noaa.gov/ibtracs

Iowa State University (wind roses) - http://mesonet.agron.iastate.edu/sites/locate.php

Integrated Surface Database Global Hourly Data (airport data) - https://data.noaa.gov/dataset/integrated-surface-global-hourly-data

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2 - Intergovernmental Panel on Climate Change, 2014: *Climate Change 2013: The Physical Science Basis*. 5th assessment report, T. F. Stocker et al. (Eds.). Cambridge, 1535 pp. [Available online at http://www.climatechange2013.org/.]

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11 - Knutson, T. R., J. L. McBride, J. Chan, K. Emanuel, G. Holland, C. Landsea, I. Held, J. Kossin, A. Srivastava, and M. Sugi, 2010: Tropical cyclones and climate change. *Nature Geoscience*, **3**, 157–163, doi:10.1038/ngeo779.

5. Sea Level

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Takeaways

- Since the early 1990s, global mean sea level (GMSL) has been rising at a rate of about 3.3 mm (0.13 in) per year. This is twice the estimated rate for the 20th century as a whole.
- Sea level has also been rising across the Pacific Islands region. However, regional and local sea level trends may differ significantly from the globally averaged rate over multiyear to multidecadal time scales. For example, local rates of change since the early 1990s are as low as 1.1 mm (0.43 in) per year at the Honolulu tide gauge and as high as 5.4 mm (0.21 in) per year at the Kwajalein tide gauge.
- Natural patterns of variability play an important role in regional and local variation in sea level. Compared to the central Pacific, in the tropical western and South Pacific these interannual and multidecadal changes can be quite large. In Guam, for example, ENSO-related variations in sea level are on the order of 30 cm (12 in).
- These natural patterns of variability can make it difficult to discern a reliable local long-term trend in shorter (less than 50 years long) records. In addition, vertical land motion due to earthquakes or subsidence further impedes the calculation of reliable trends.
- Small increases in the magnitude of sea level have resulted in dramatic increases in the frequency of minor flooding. At the Kwajalein tide gauge for example, high water events that occurred less than once a year, on average, in the 1960s occurred 22 times a year, on average, during the decade staring in 2005. Though with a considerably lower increase, at the Honolulu tide gauge minor flood frequency almost doubled during this same period, going from 6 to 11 times a year on average.
- Models suggest that global warming will raise global sea level significantly over the course of this century. Higher likelihood projections of GMSL call for a rise by 2050 equivalent to roughly double the current rate. By 2100 a rise of 0.5 m (1.6 feet) in GMSL is very likely and a rise greater than 2.0 m (6.6 feet) is plausible. Projections for sea level rise in Hawaii and other tropical Pacific islands call for an additional 20%–30% above the global mean.
- Increasing mean water levels means an increased potential for coastal flooding and erosion, as high waves ride the rising seas and threaten built and natural environments on all islands in the Pacific region.

On 3 March 2014, high tides combined with high waves causing the sea to sweep across portions of Majuro Atoll, in the Republic of the Marshall Islands (RMI), forcing almost 1000 residents to leave their homes. Coastal flooding takes many forms, ranging from major flooding associated with strong winds, high seas, and heavy rains during storms to minor flooding that occurs when exceptionally high tides combine with high waves and other oceanic and atmospheric phenomena on storm-free days. There is growing recognition that the frequency of such minor coastal flooding events will increase dramatically with rising sea levels.[1,2,3]

Source Karl Fellenius

Why should we care?

Sea level is an important indicator of climate change and variability. 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 which can have significant economic, social, and environmental costs.

Where are we now?

Global Sea Level

Global mean sea level (GMSL) has risen by about 20 cm (8 in) over the past 100 years (Figure 5.1). As of December 2016, the rate of GMSL rise measured by satellite altimeters since 1993 is 3.28 mm (0.129 in) per year (Figure 5.2). This recent rate reflects roughly a doubling of the rate that was observed over the 20th century based on tide-gauge reconstructions.[4,5,6] This rise in GMSL can be attributed to an increase in the volume of water in the ocean due primarily to global warming. Heating of the ocean subsurface causes the water to become less dense and expand, whereas melting of glaciers and ice sheets transfer water mass from the land to the ocean. Changes in storage of water on land (e.g. lakes and reservoirs) can also affect sea level.

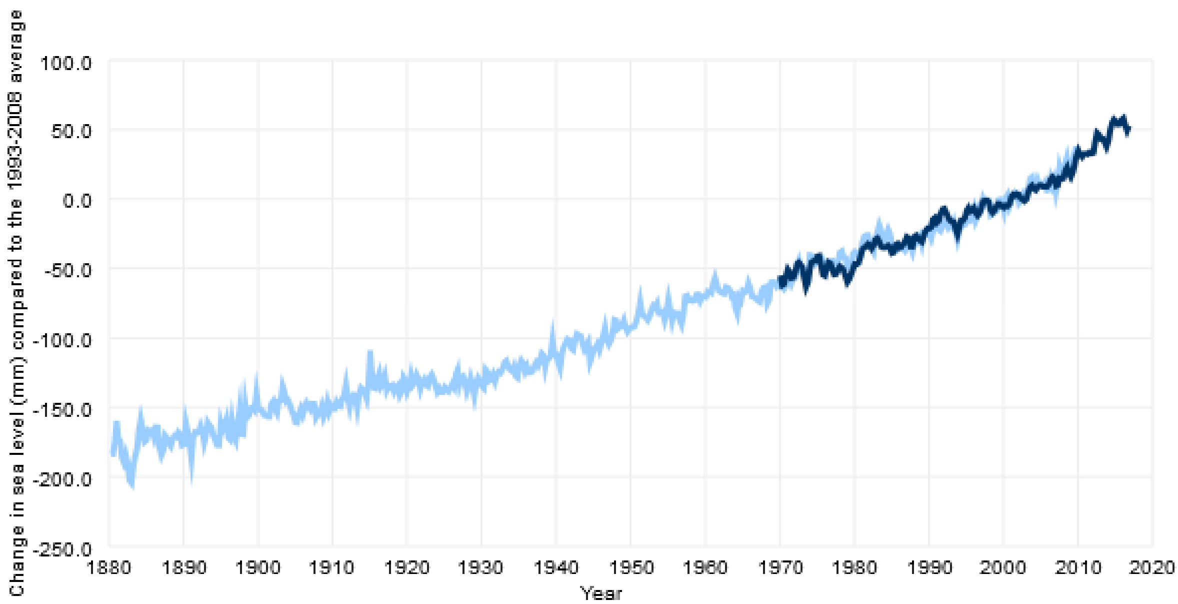


Figure 5.1 Global Mean Sea Level (GMSL) since 1880. The light blue line shows seasonal (3-month) sea level estimates from Church and White (2011).[5]. The darker line is produced by the University of Hawaii Sea Level Center (UHSLC) using UHSLC Fast Delivery sea level data. From Lindsey, R. (2016) *Climate Change: Global Sea Level:* https://www.climate.gov/news-features/understanding-climate/climate-change-global-sea-level

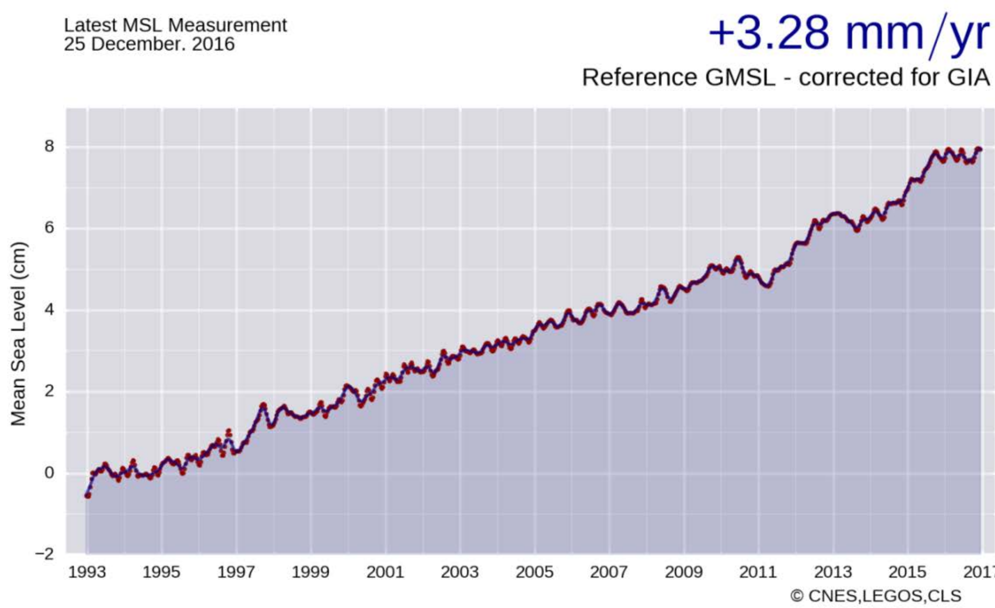
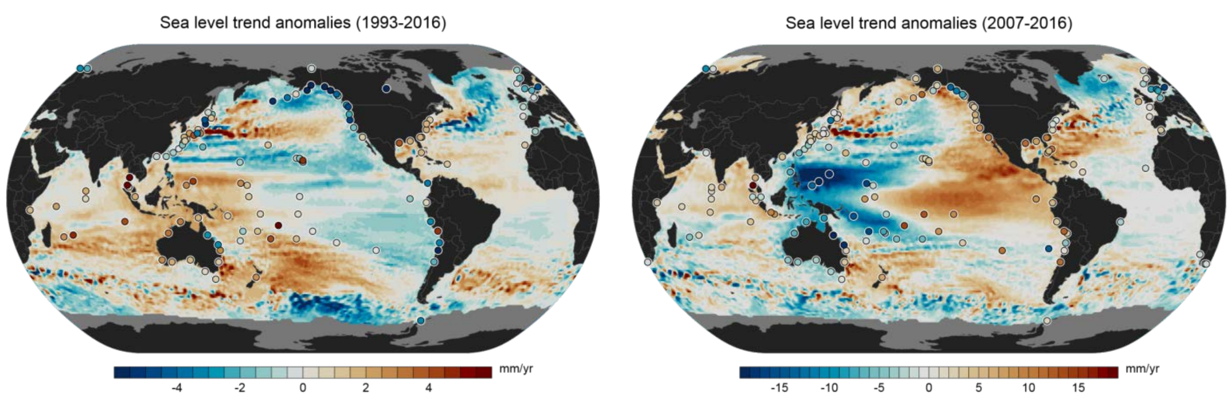


Figure 5.2. Global Mean Sea Level (GMSL) since 1993. The reference mean sea level since January 1993 is calculated after removing the annual and semi-annual signals. A 2-month filter is applied to the red points, while a 6-month filter is used on the blue curve. By applying the postglacial rebound correction (−0.3 mm [0.012 in] per year), the rise in mean sea level has thus been estimated as **3.28 mm (0.129 in) per year** (mean slope of the plotted data). Analyzing the uncertainty of each altimetry correction made for calculating the GMSL, as well as a comparison with tide gauges gives an error in the GMSL slope of approximately **0.5 mm (0.020) per year** with a 90% confidence interval. From:
http://www.aviso.altimetry.fr/en/data/products/ocean-indicators-products/mean-sea-level.html.

Regional Sea Level

Regional sea level (RSL) trends may differ significantly from the globally averaged rate over multiyear to multidecadal time scales.[6,7,8,9,10,11] Several factors contribute to RSL trends. Changes in ocean circulation associated with natural patterns of climate variability such as the El Niño–Southern Oscillation (ENSO) on interannual time scales[12,13,14,15] and the Pacific decadal oscillation (PDO) on decadal to multidecadal time scales[16,17,18,19] are particularly relevant to the Pacific Islands region. Large west-to-east differences in rates of sea level rise across the Pacific Basin are associated with these natural patterns of climate variability (Figures 5.3a and b). RSL trends across much of the tropical western and South Pacific since the start of the satellite record (~1993) are on the order of twice the global rate and close to or less than the global rate along much of the eastern Pacific (Figure 5.3a). When looking at just the last 10 years, this pattern is reversed (Figure 5.3b). RSL trends across much of the eastern Pacific are on the order of twice the global rate and rates along much of the tropical western and South Pacific on the order of two to three times lower than the global rate. This basin-wide reversal in RSL rates appears to be indicative of a PDO-phase switch and an associated change in prevailing trade wind forcings over the last couple of years. [10,11,20]



a) b)

Figure 5.3. Regional Sea Level Trends from Satellite Altimetry and Tide Gauges. The maps show sea level trends from satellite altimetry (colored contours) and tide gauges (circles) since (a) the beginning of the satellite record in 1993 and over the last 20 years and (b) over the last 10 years. The GMSL trend (3.28 mm [0.129 in] per year) has been removed. Local and regional trends can be as much as 5 times, more or less, than the global rate depending on location and time period. Satellite data is from Aviso (delayed-mode supplemented with near-real-time). Tide gauge data is from the from the UHSLC Fast-Delivery database, http://uhslc.soest.hawaii.edu/

Gravitational changes associated with glacial and ice sheet adjustment(GIA) and vertical land motion (VLM) in the form of uplift or subsidence may also be important factors affecting RSL. Thus, the rate of change in GMSL may not be indicative of the rate of change in sea level observed at a particular location.

Local Sea Level—Magnitude

Local variations in the rate of sea level change are evident in the series of NOAA CO-OPS plots of monthly mean sea level in select tide gauges from across the Pacific (Figure 5.4; Figure 5.5).

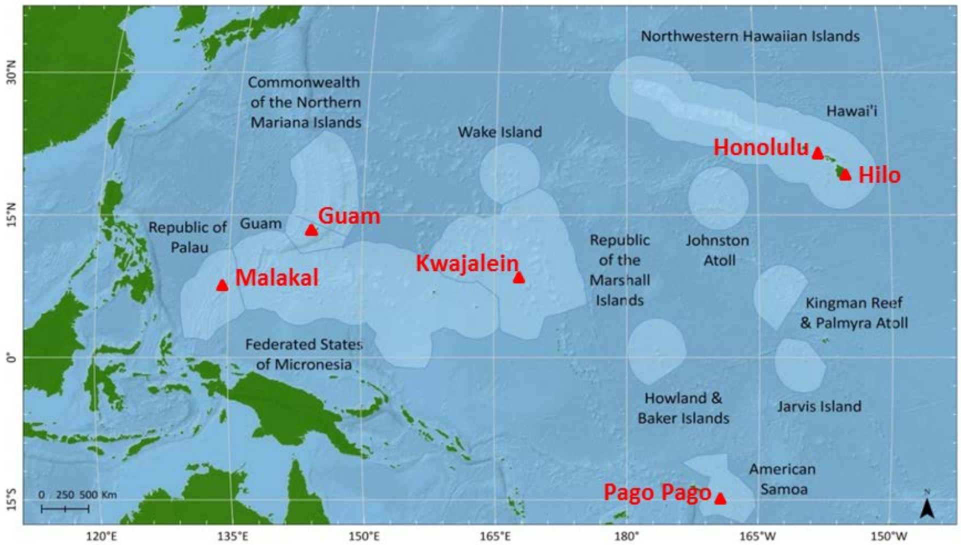


Figure 5.4. Map of Tide Gauges in the Pacific Islands. The map shows the locations of tide gauges referred to in this document. Shading indicates each island's Exclusive Economic Zone (EEZ).

- For Honolulu (Figure 5.5a), the mean sea level trend is 1.41 mm (0.055 in) per year with a 95% confidence interval of ±0.21 mm (0.008 in) per year based on monthly mean sea level data from 1905 to 2015. This equivalent to a change of 14.0 cm (0.46 feet) in 100 years.
- For Hilo (Figure 5.5b), the mean sea level trend is 2.95 mm (0.116 in) per year with a 95% confidence interval of ±0.31 mm (0.0258 in) per year based on monthly mean sea level data from 1927 to 2015. This is equivalent to a change of 29.6 cm (0.97 feet) in 100 years.
- For Kwajalein (Figure 5.5c), the mean sea level trend is 2.20 mm (0.087 in) per year with a 95% confidence interval of ±0.82 mm (0.0322 in) per year based on monthly mean sea level data from 1946 to 2015. This is equivalent to a change of 21.9 cm (0.72 feet) in 100 years.
- For Guam (Figure 5.5d), the mean sea level trend is 4.55 mm (0.18 in) per year with a 95% confidence interval of ±4.68 mm (0.18 in) per year based on monthly mean sea level data from 1993 to 2015. This equivalent to a change of 45.4 cm (1.49 feet) in 100 years. The trend for 1948-1993, prior to the 1993 earthquake is negative, at -0.84 ± 1.78 mm per year.
- For Pago Pago (Figure 5.5e), the mean sea level trend based only on data before the 2009 earthquake is 2.21 mm (0.087 in) per year with a 95% confidence interval of ± 0.81 mm (0.0319 in) per year based on monthly mean sea level data from 1948 to 2009. This is equivalent to a change of 21.9 cm (0.72 feet) in 100 years.

Note the break caused by earthquakes in three of the tide gauge records (Figures 5.5b, d, and e). Among other considerations like record length and start/end dates, disruptions such as these can make it difficult to discern a reliable long-term trend. Compared to the GMSL rise measured by satellite altimeters since 1993 of 3.28 mm per year, when adjustments are made to these records to account for vertical land motion the rates calculated from 1993 to 2016 for the above tide gauges are*:

- for Honolulu, 1.10 mm (0.043 in) per year;
- for Hilo, 1.78 mm (0.070 in) per year;

- for Kwajalein, 5.44 mm (0.214 in) per year;
- for Guam, 3.41 mm (0.134 in) per year; and
- for Pago Pago, 3.95 mm (0.156 in) per year.

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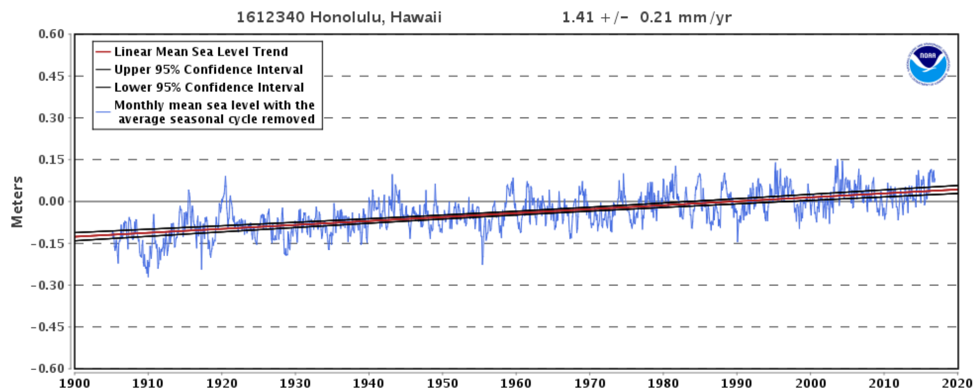
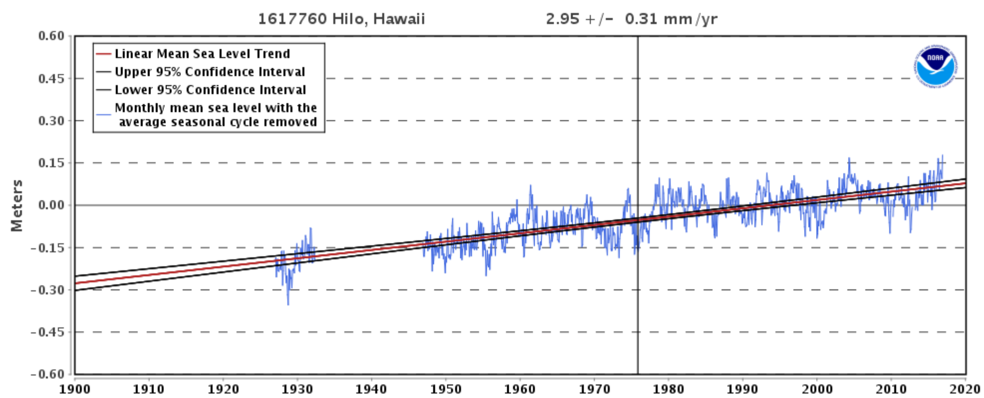
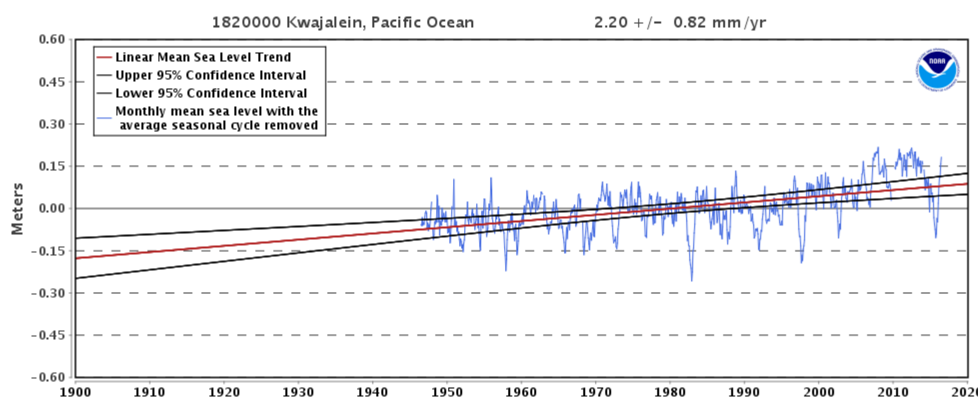
* *For Guam a 6.6 cm offset was calculated for the pre- versus post-earthquake periods.*
For Pago Pago an 11.8 cm offset was calculated for the pre- versus post-earthquake periods.



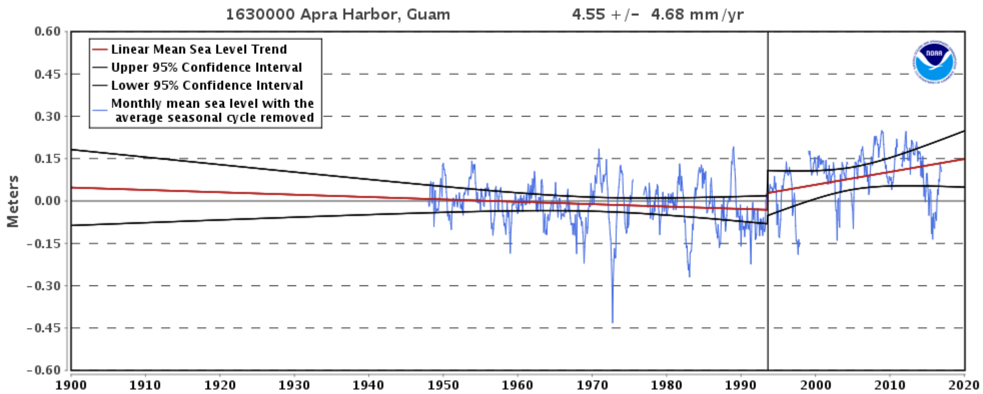
a) Honolulu



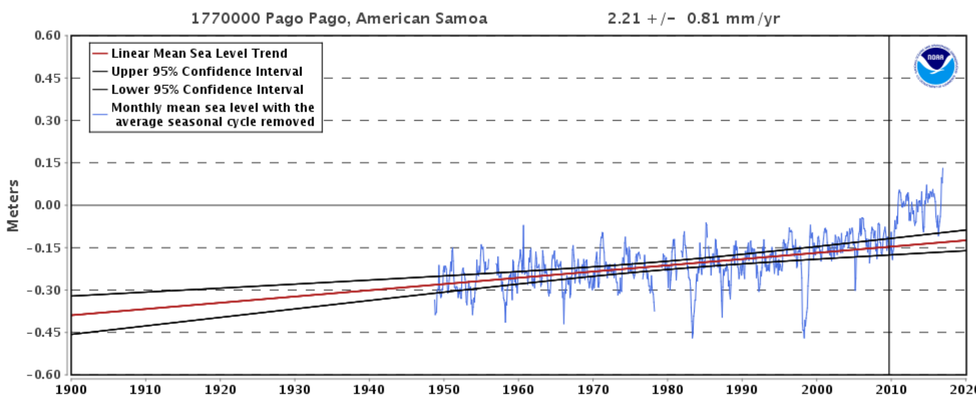
b) Hilo



c) Kwajalein



d) Guam



e) Pago Pago

Figure 5.5. Local Sea Level Trends from Selected Tide Gauges in the Pacific. These plots show the monthly mean sea level without the regular seasonal fluctuations due to coastal ocean temperatures, salinities, winds, atmospheric pressures, and ocean currents for: a) Honolulu; b) Hilo; c) Kwajalein; d) Guam; and e) Pago Pago. The long-term linear trend is also shown, including its 95% confidence interval. The plotted values are relative to the most recent Mean Sea Level datum established by NOAA CO-OPS. If present, solid vertical lines indicate times of any major earthquakes in the vicinity of the station.
From: https://tidesandcurrents.noaa.gov/sltrends/sltrends.html

Like GMSL, local mean sea level has risen at all locations, albeit not uniformly in space or time. Like regional variations in mean sea level, interannual and multidecadal variations apparent in the local tide gauge records can be linked to natural patterns of climate variability noted above. These changes can be quite large in the tropical western and South Pacific. In Guam, for example ENSO-related variations in sea level are on the order of 30 cm.[21] This is roughly equivalent to 50 years of GMSL rise (at the current rate), and these changes can last for months. Locations like Honolulu and Hilo, in the center of the Pacific, are less sensitive to these forcings.

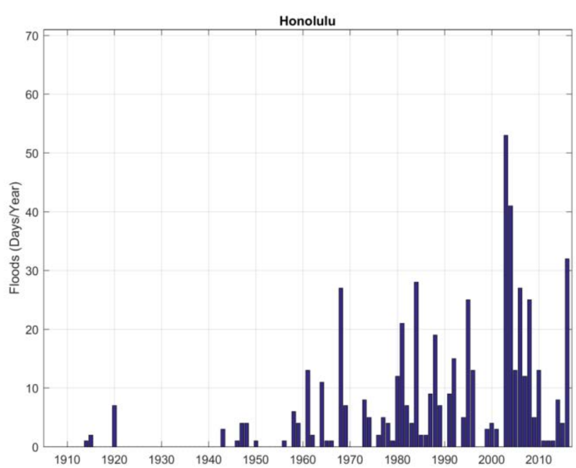
Local Sea Level—Frequency

Small changes in the absolute magnitude of sea level rise can manifest as big changes in terms of minor flood frequency.[2,3,22,23,24,25] Minor floods occur when tides are exceptionally high, due to their combination with high waves and/or other oceanic and atmospheric phenomena. Though their impacts are less than major floods that occur during big storms, when viewed cumulatively, the impacts associated with minor flooding can be considerable.[26]

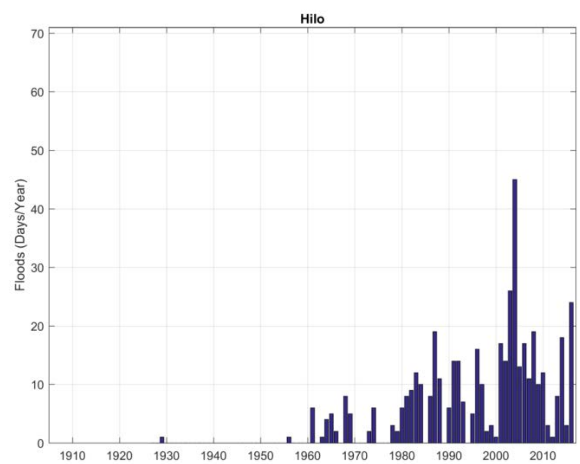
The number of 'minor' flood days per year for select tide gauges from across the Pacific is shown in Figure 5.6. A minor flood day is defined as a day in which the elevation of the sea at the tide gauge exceeded the elevation associated with the 0.5 (twice a) year return interval of a given station based on extreme value analysis. In response to sea level rise the frequency of minor flooding has increased. Since the 1960's compared to the decade starting in 2005, the change has been

- in Honolulu (Figure 5.6a), from 6 days per year, on average, to 11 per year;
- in Hilo (Figure 5.6b), from 3 days per year, on average, to 11 per year;
- in Kwajalein (Figure 5.6c), from just less than 1 day per year, on average, to 22 days per year;
- in Guam (Figure 5.6d), from 2 days per year, on average, to 21 per year; and
- in Pago Pago (Figure 5.6f), from just less than 1 day per year, on average, to 15 per year.

Matching trends in mean sea level, flood frequency has risen at all locations. Unlike mean sea level, in most cases these changes are dramatic, ranging from a 71% increase at Honolulu to a 2638% increase at Kwajalein in the frequency of minor flood days per year. Links between variations in flood frequency and natural patterns of climate variability are also discernable in the tide gauge records.

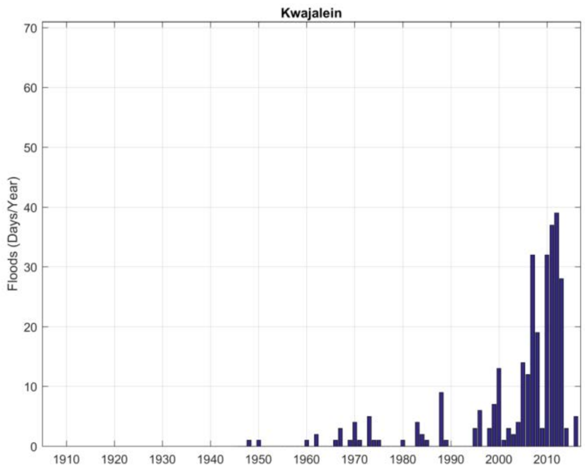


a)

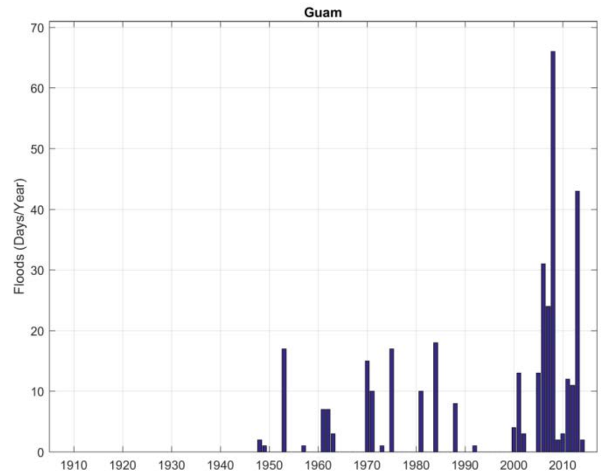


b)

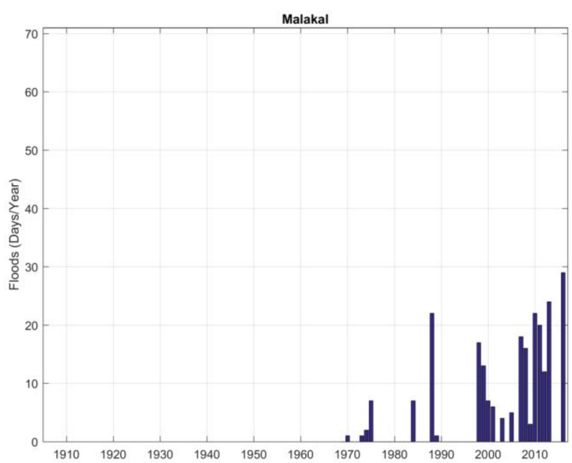
Figure 5.6. Minor Flood Frequency from Selected Tide Gauges in the Pacific. These plots show the number of 'minor' flood days per year for: (a) Honolulu; (b) Hilo; (c) Kwajalein; (d) Guam; (e) Malakal; and (f) Pago Pago. A minor flood day is defined as a day in which the elevation of the sea at the tide gauge exceeded the elevation associated with the 0.5 year return interval of a given station based on extreme value analysis. Data was de-trended prior to GEV analysis and results set relative to the 2005 datum. Tsunamis were not removed. Guam (d) includes a correction of 6.6 cm from 1993 to present. Pago Pago (f) includes a correction of 11.8 cm from 2010 to present.



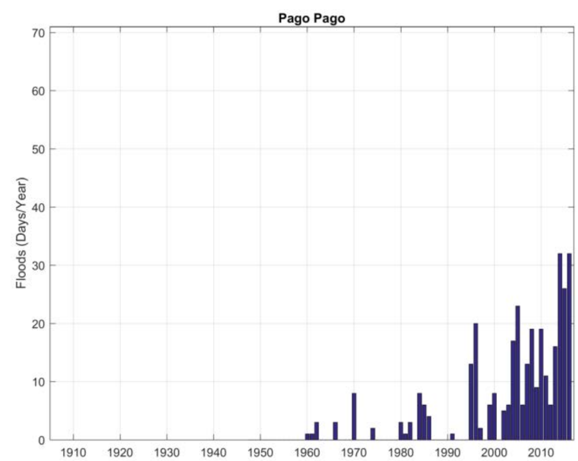
c)



d)



e)



f)

What does the future hold?

Considering all regional concentration pathway scenarios (RCPs), GMSL rise by 2050 is projected to range from 0.16 to 0.63 m (6.3 to 24.8 in).[11,27] Considering only Intermediate (higher likelihood) Scenarios, this range narrows to a 0.24–0.44 m (9.4–17.3 in) projected rise in GMSL by 2050. By 2100, under the highest "business as usual" RCP (RCP 8.5), 0.3 m (11.8 in) of GMSL rise is virtually certain (>99% probability), a GMSL rise 0.5 m (19.7 in) is very likely (>90% probability) and, when projections that take into account the result of recent observational and modeling of the potential for rapid ice melt in Greenland and Antarctica are considered, a GMSL rise greater than 2.0 m (78.7 in) is plausible[11]. Future mean sea level rise estimates are somewhat higher in Hawaii and other Pacific islands, where due to regional effects RSL is projected to be on the order of 20%–30% above the global mean. Also, projections call for natural patterns of variability to be more frequent and more extreme.[28,29,30,31]

Key Links

NOAA COOPS https://tidesandcurrents.noaa.gov/sltrends/sltrends.html

NASA https://sealevel.nasa.gov/understanding-sea-level/key-indicators/global-mean-sea-level

UHSLC http://uhslc.soest.hawaii.edu/

CU Sea Level Research Group http://sealevel.colorado.edu/

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6. Sea Surface Temperature

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Takeaways

- Globally averaged sea surface temperature (SST) increased by about 1.0°C (1.8°F) over the past 100 years. Half of this rise has occurred since the early 1990s.
- In 2016, aided by the second strongest El Niño on record (1997–98 being the strongest), the annually averaged temperature for ocean surfaces around the world reached a record of 0.75°C (1.35°F) higher than the 20th century average, and the warmest in the 137-year-long record.
- Regionally averaged SST trends follow the globally averaged trend. The absolute magnitude of the regional trends, however, are somewhat higher than the globally averaged trend—on the order of 1.20°C (2.16°F) above the global average over the past 100 years in all regions.
- Within a region changes in SST vary in space as well as time. Over the last 5 years most of the tropical Pacific and in particular areas along the equator have seen temperatures warmer than average over the last 30 years.
- Analysis of the Degree Heating Week (DHW), a measure of accumulated coral bleaching heat stress that can be used to quantify the impacts of changing ocean temperature on coral, indicates that anomalous warming harmful to coral is covering a larger area, occurring more often, lasting longer, and reaching higher intensity. Over the past 25 years, the number of days per year with a DHW value reaching at least 1°C-week has increased dramatically at many Pacific reef regions; for instance, at the eastern Federated States of Micronesia the number has increased from a maximum of 14 during the first 10 years of the record to frequently more than 20 days during the last 10 years of the record, and for American Samoa and Samoa from 8 days to frequently more than 50 days.
- Extended periods of coral bleaching heat stress were not usually observed in the tropical Pacific until 1998, and then only over an area limited mostly to Micronesia. In some locations, such as the Marshall Islands and the Main Hawaiian Islands, extended periods of bleaching heat stress did not first occur until 2014 and 2015, respectively, as part of the 2014–17 global scale bleaching event that was the longest ever recorded.
- Models suggest that global warming will raise SST significantly over the course of this century. Depending on the emissions scenario, SST increases by 2100 are predicted to range from 1.6°C to 4.3°C (2.9°F to 7.7° F) relative to pre-industrial levels (1850–1900). Warming through the next two decades is fairly consistent across emissions scenarios because it is mostly determined by historical (recent) emissions levels. The SST projections diverge around 2035 based on the different emissions scenarios in the coming years and decades.
- An increase in the frequency and duration of SSTs above the increasing background SST means an elevated potential for coral bleaching leading to coral death. Models predict that ocean warming will cause annual coral bleaching for some areas, like the central equatorial Pacific Ocean, as early as 2030 and almost all reefs by 2050. This will not only devastate local coral reef ecosystems but will also have profound impacts on ocean ecosystems more broadly. Ultimately it will threaten the communities and economies that depend on a healthy ocean.

Source R. Vevers, XL Catlin Seaview Survey ©

The prolonged high temperatures that bleached corals in American Samoa were part of a 2014–17 global coral bleaching event that was the longest, most extensive, and in many locations the worst ever recorded. When corals are stressed beyond their tolerance levels by changes in ambient environmental conditions such as temperature, light, or nutrients, they expel the symbiotic algae living in their tissues, causing the reefs to turn white. Coral reefs are ecologically and economically important marine ecosystems and are a key indicator of the impacts of ocean warming on the marine environment.

Why should we care?

Sea surface temperature (SST) is a key climate indicator. Changes in the temperature of the water at the ocean surface are 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, such as El Niño–Southern Oscillation (ENSO) and the Pacific decadal oscillation (PDO).[1,2,3,4,5] SST is also an indicator of the state of marine ecosystems, as variations in ocean (surface and subsurface) temperature can influence species distribution, growth, and life span, alter their migration and breeding patterns, and threaten sensitive ecosystems such as coral reefs.[6,7,8]

Where are we now?

Global

Globally averaged SST has risen by about 1°C (1.80°F) over the past 100 years, 0.75°C (1.35°F) over the last 50 years, and 0.50°C (0.90°F) since the early 1990s (Figure 6.1). SST rose at an average rate of 0.07°C (0.13°F) per decade from 1901 through 2015, and has been consistently higher during the past three decades than at any other time since reliable observations began in 1880.[7] The rise in SST values can be attributed to the increase in the concentration of CO_2 and other greenhouse gases in the atmosphere.[9]

In 2016, the annually averaged temperature for ocean surfaces around the world was 0.75°C higher than the 20th century average and was the warmest year on record. The 2016 value edged out the previous record set in 2015 by 0.02°C (0.04°F), which had bested the 2014 temperature by a record increase of 0.10°C (0.18°F).[10] A near-record strong El Niño in the Pacific Ocean during 2015–16 led to some of the highest monthly global ocean temperatures on record, with January, February, March, April, June, July, and August of 2016 all ranking among the 12 warmest of all corresponding months in the 137-year record.[10] The El Niño dissipated in the boreal spring of 2016 and was replaced by weak La Niña conditions near the end of 2016. Despite that, global ocean temperatures remained high, with the December temperature 0.61°C (1.10°F) above the 20th century average. Record warmth for the year was particularly notable across parts of the southern and western Pacific.

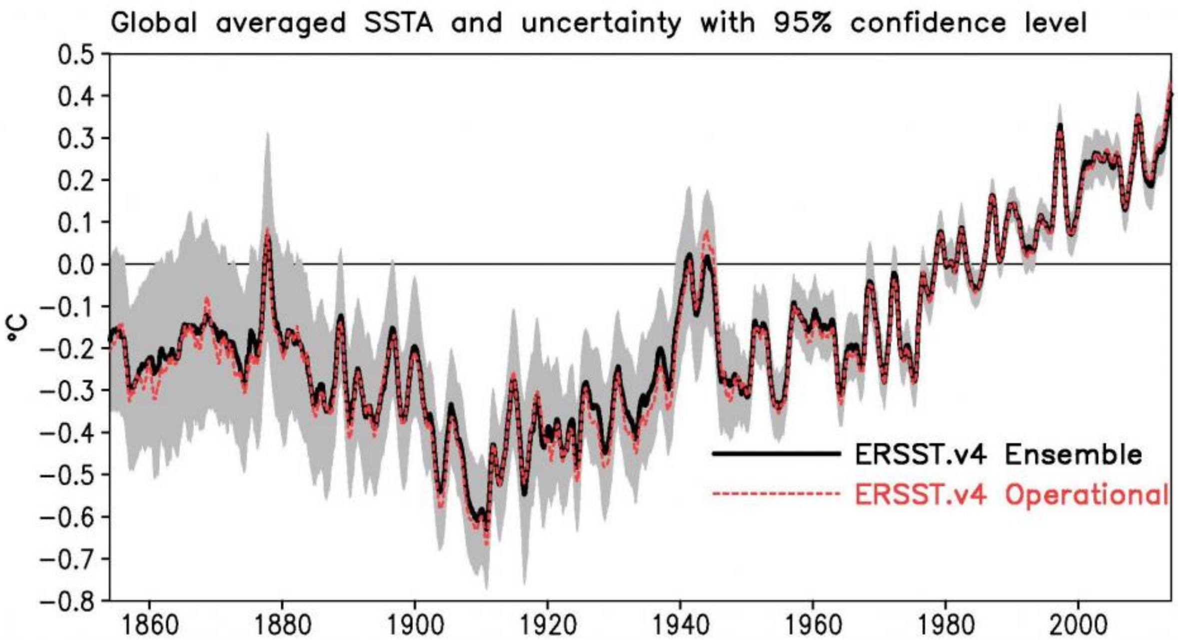
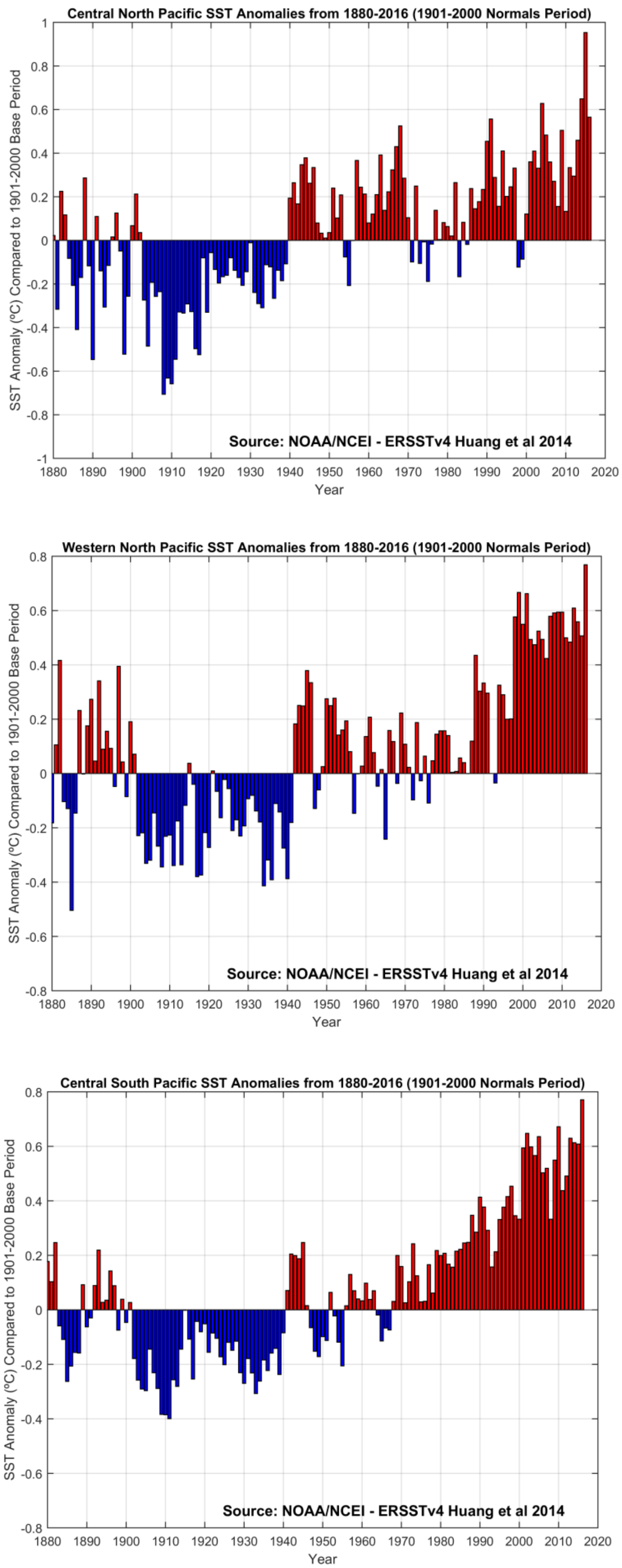


Figure 6.1 Global-average Sea Surface Temperature Anomaly since 1854. Globally averaged SST anomalies of ERSST v4 ensemble average (black line) and operational production (dashed red line). The shaded region represents the 95% confidence interval due to total quantified uncertainty in ERSST v4. The analysis is based on the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) Release 2.5. The anomalies are computed with respect to a 1971–2000 climatology. From Huang, Boyin & National Center for Atmospheric Research Staff (Eds). Last modified 06 Jan 2017. "The Climate Data Guide: SST data: NOAA Extended Reconstruction SSTs, Version 4"; *https://climatedataguide.ucar.edu/climate-data/sst-data-noaa-extended-reconstruction-ssts-version-4*.

Regional

Regionally averaged SST trends in the Pacific clearly indicate warming through the past century, consistent with the global trend (Figure 6.2). However the magnitude of Pacific regional trends is higher than the globally averaged trend (of 0.07°C per decade). Variations between regions over time are also apparent in Figure 6.2. For example, the central North Pacific shows an oscillating pattern of SST variation, particularly evident since the 1940s, in conjunction with the overall increasing SST trend. These marked interannual-to-decadal variations correspond closely to those associated with the ENSO cycle (see ONI side bar). In contrast, the central South Pacific exhibits a smoother interannual-to-decadal variability with lower magnitude, but within an extended period of higher-than-average and relatively rapidly increasing SST since the late 1960s.



SST anomalies within the three Pacific regions during the most recent years highlight the spatial consistency of the warming (Figure 6.3). SST anomalies over the period 2010–15 are higher (red) than the 30-year (1982–2011) average across almost all of three regions. Notably warmed areas were seen in: northeast Pacific along the U.S. West coast and across the equator (upper); northwest Pacific along the equator and northern portions of the North Pacific east of Japan and south of Korea (middle); and southwest Pacific along the equator and across southern portions of the south Pacific, around 40°S (lower). The only exceptions, where recent SSTs are below average (blue), are small patches of ocean in the north west Pacific on either side of Japan and a patch of ocean in the southern Pacific (around 50°S, 160°W) near Antarctica.

Figure 6.2 Average Sea Surface Temperature Anomaly since 1854 for sub-regions in the Pacific: (upper) Central North Pacific; (middle) Western North Pacific; and (lower) Central South Pacific (as defined below in Figure 6.3). *The anomaly is shown in ^{o}C compared to the normal over the 1901–2000 base period, with blue bars indicating a negative and red bars a positive anomaly. Note the patterns as well as trends in the records.*

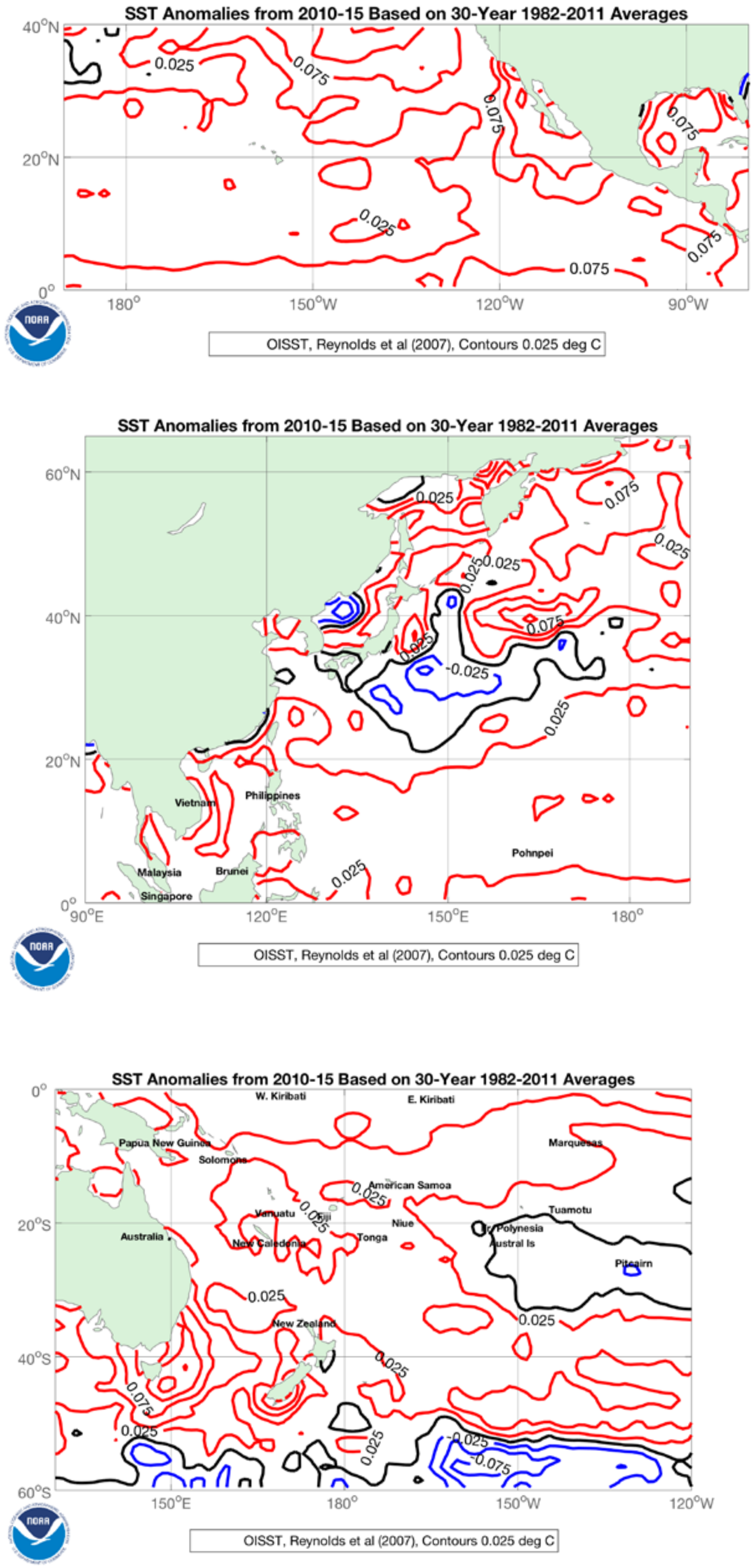


Figure 6.3. SSTs anomalies over the period 2010–15 as compared to the 30-year (1982–2011) average for different regions in the Pacific: (upper) north east Pacific; (middle) north west Pacific; (lower) south west Pacific. *Contours indicate 0.025°C, with red contours being positive SST anomalies and blue being negative; black contours are no anomaly.*

Local – Accumulated Heat Stress

The NOAA Coral Reef Watch (CRW) monitors coral bleaching heat stress in near real-time and assesses heat stress history based on satellite-derived SST to identify areas potentially at risk for coral bleaching.[11,12] Coral Bleaching HotSpot and Degree Heating Week (DHW), two key CRW products, monitor the instantaneous and accumulated heat stress conducive to coral bleaching, respectively. Using a temperature dataset that spans 1982–2016[13], HotSpot and DHW were used to assess the long-term change in the bleaching heat stress in seven select geographic regions in the Pacific Ocean: main Hawaiian Islands, Marshall Islands, eastern Micronesia, western Micronesia, Northern Marianas Islands, Guam, American Samoa and Samoa, hereafter the Samoas (Figure 6.4).

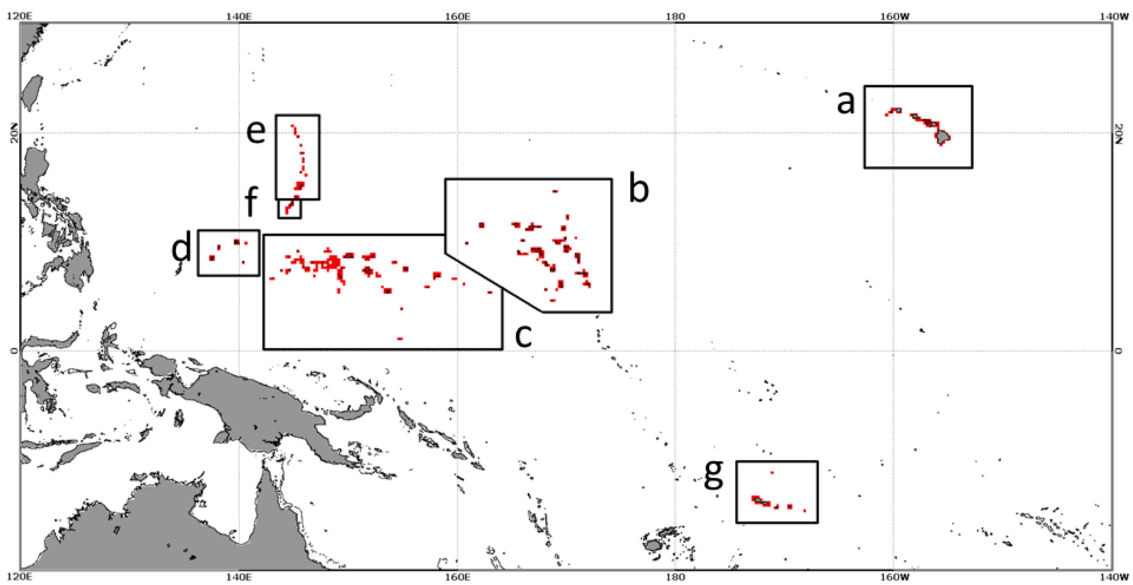
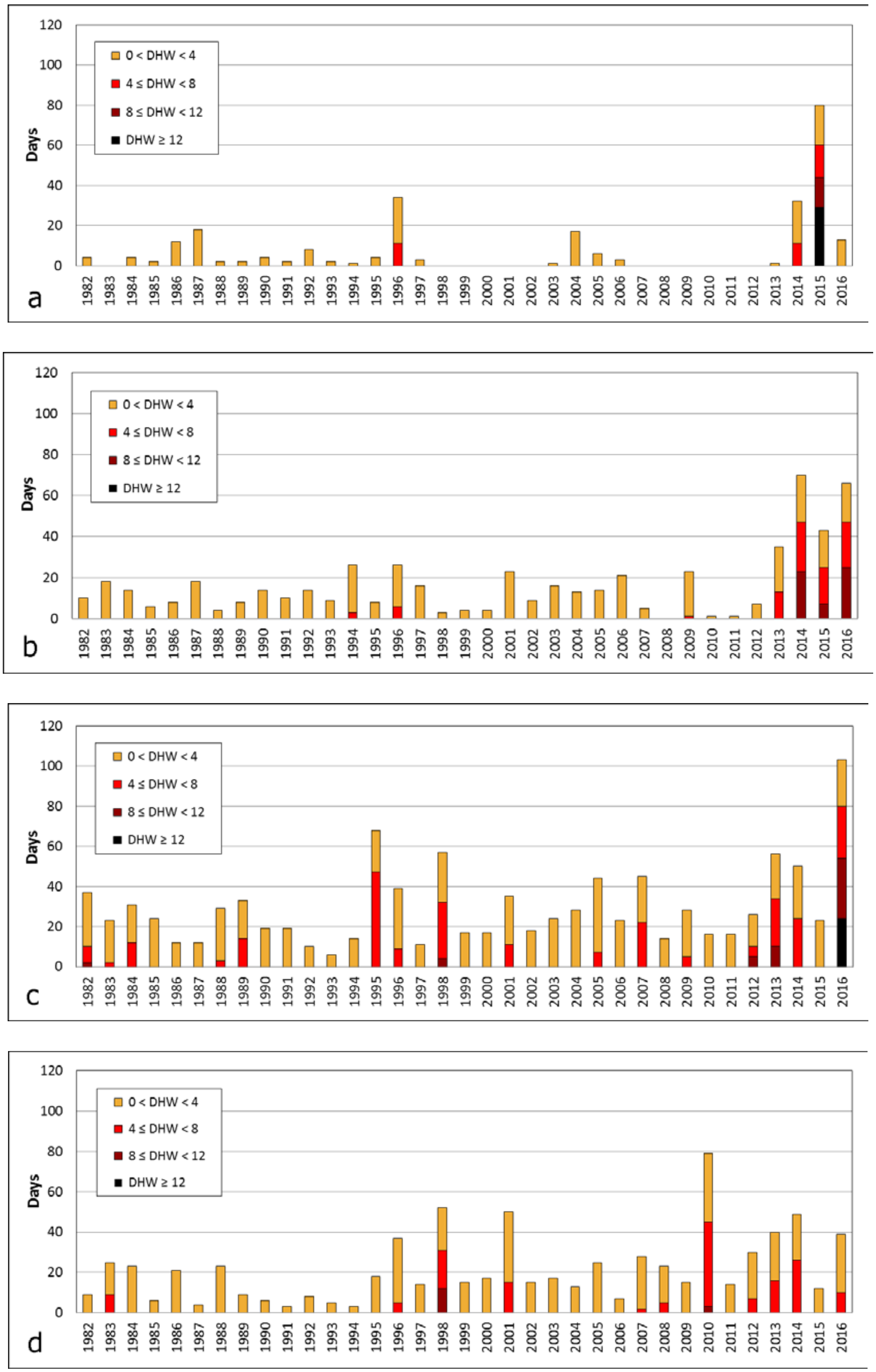


Figure 6.4. Seven coral reef regions in the Pacific Ocean where long-term change in the bleaching heat stress was assessed in this study: (a) main Hawaiian Islands; (b) Marshall Islands; (c) eastern Micronesia; (d) western Micronesia; (e) Northern Mariana Islands; (f) Guam; and (g) American Samoa and Samoa.

Bleaching heat stress is classified into four categories by CRW for each day based on the relationship between the values of HotSpot and DHW and on the observed severity of bleaching from past studies[11]: Warning, Alert Level 1, low Alert Level 2, and high Alert Level 2. Bleaching is expected for all these categories but at various severities. In each region, long-term change in exposure to heat stress was examined by counting the number of days each year for each category for a given reef-containing grid cell. Using the highest counts among all the reef grid cells in each region, the time series of exposure days indicates the intensity and duration of stress (Figure 6.5). The spatial extent of heat stress in each region is shown using the percentage of the grid cells with reefs in each category (Figure 6.6).

A clear pattern is revealed on reefs across the Pacific Ocean since 1982: both the intensity of heat stress and number of days exposed have increased in all seven regions. The trends, however, are not uniform


a
b
c
d
Days
0 < DHW < 4
4 ≤ DHW < 8
8 ≤ DHW < 12
DHW ≥ 12
0
20
40
60
80
100
120
1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016

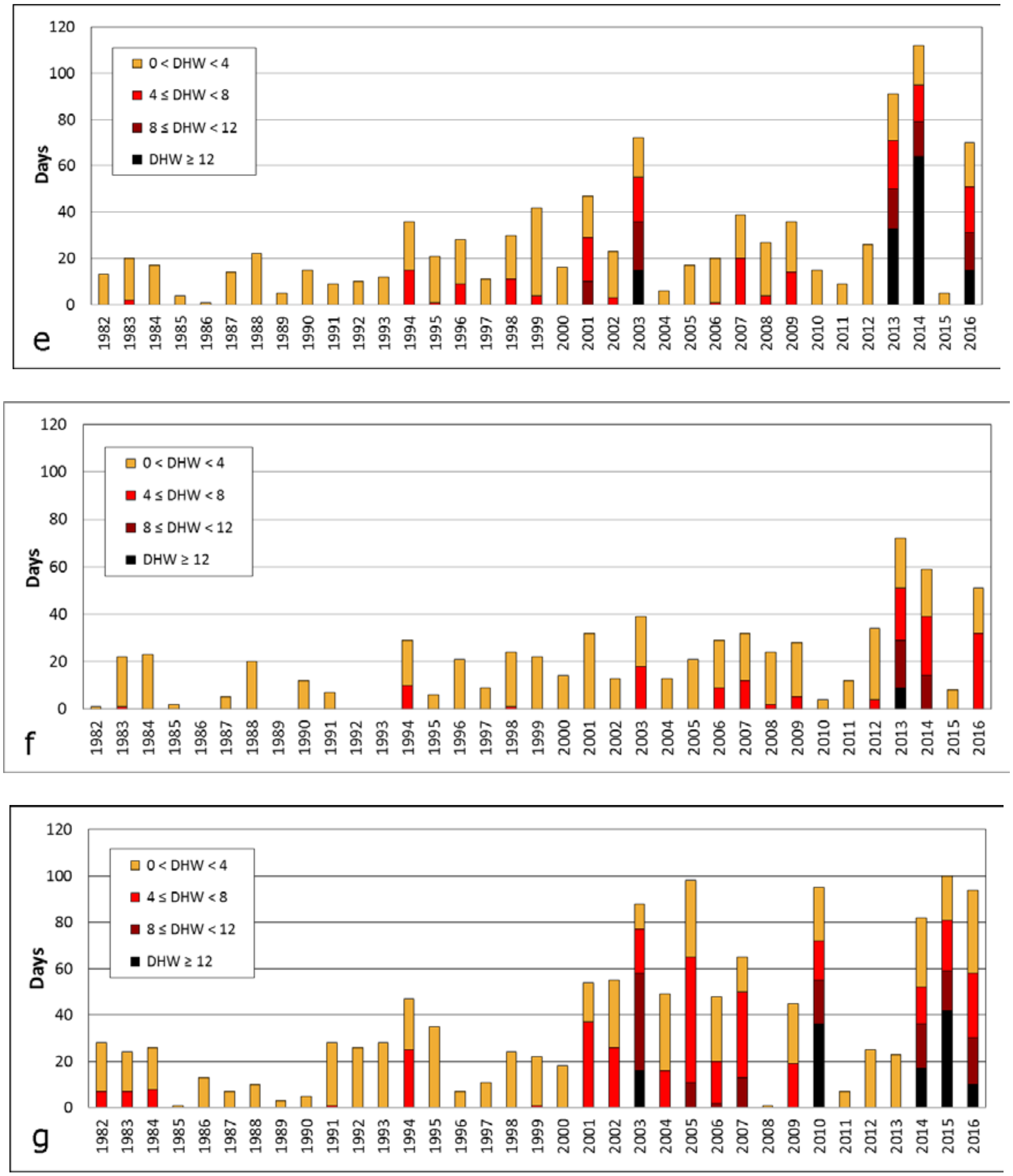


Figure 6.5. Days exposed to coral bleaching heat stress for seven reef regions in the Pacific: (a) main Hawaiian Islands; (b) Marshall Islands; (c) eastern Micronesia; (d) western Micronesia; (e) Northern Mariana Islands; (f) Guam, and (g) Samoas, showing number of days that reef data grids in the corresponding reef regions were exposed to categorized levels of heat stress: ***Warning*** *- bleaching is underway but usually not visible, 0 < DHW < 4°C-weeks;* ***Alert Level 1 -*** *ecologically significant bleaching is likely, 4 ≤ DHW < 8°C-weeks;* ***Alert Level 2*** *- widespread bleaching with significant mortality is likely,* ***Low****: 8 ≤ DHW < 12°C-weeks,* ***High:*** *DHW ≥ 12°C-weeks.*

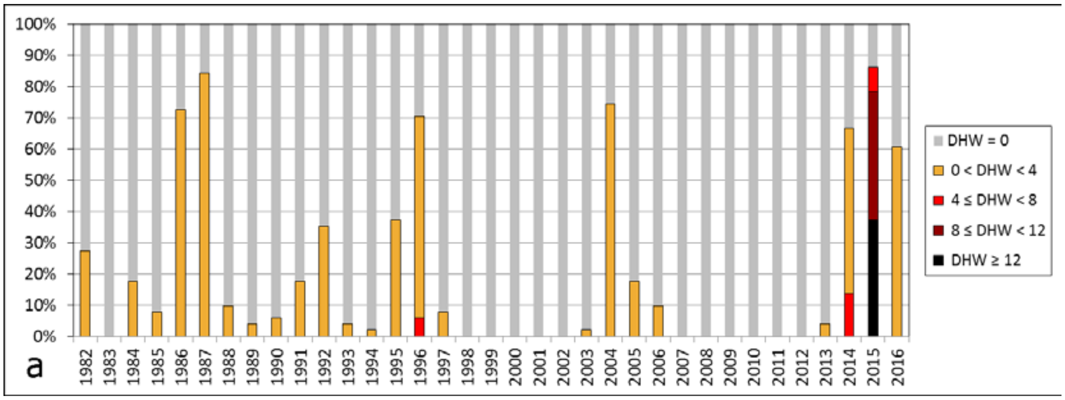
among them. Changes are apparent when we compare the number of days with accumulated heat stress present (i.e., DHW > 0°C-weeks) from the earliest (1982–91) and most-recent (2007–16) decades in the record:

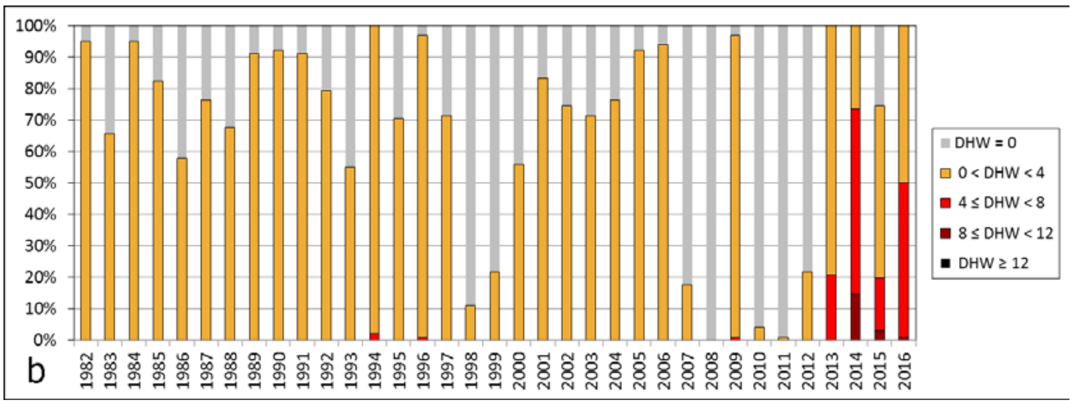
- main Hawaiian Islands (Figure 6.5a): Stress increased from 5 days per year in the earliest decade to 13 days per year in the most-recent decade, a 152% increase over the last 25 years.
- Marshall Islands (Figure 6.5b): From 11 to 25 days per year, a 128% increase.
- eastern Micronesia (Figure 6.5c): From 24 to 38 days per year, a 58% increase.
- western Micronesia (Figure 6.5d): From 13 to 33 days per year, a 155% increase.
- Northern Marianas Islands (Figure 6.5e): From 12 to 43 days per year, a 258% increase.
- Guam (Figure 6.5f): From 9 to 32 days per year, a 252% increase.
- Samoas (Figure 6.5g): From 15 to 54 days per year, a 270% increase.

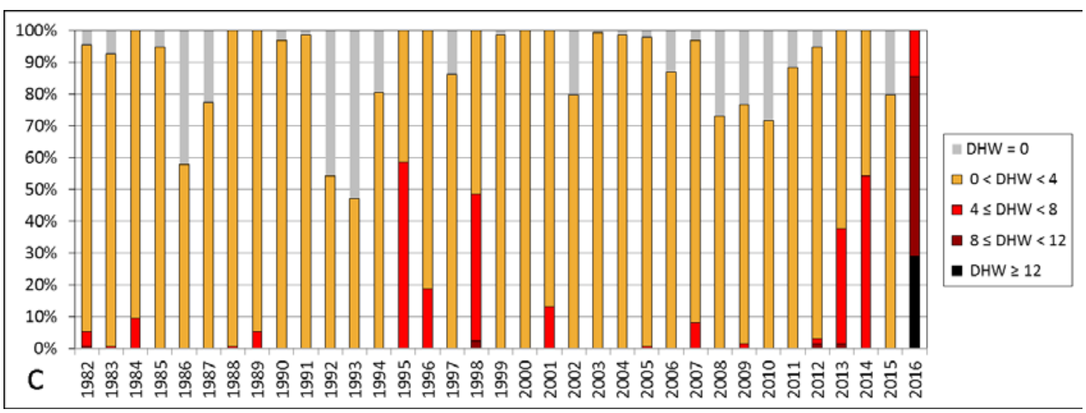
All of these regions, except for the western Federated States of Micronesia, were exposed to severe stress during the 2014–17 global bleaching event.[14] Many of these regions had not seen intense heat stress during the earlier years of the 1982–2016 assessment period. This may indicate a shift in the regime of coral bleaching heat stress starting with the 2014–17 global bleaching event. An exception to this broad pattern is a much earlier shift around 2001 in the vicinity of the Samoas, the only of the regions analyzed that is in the Southern Hemisphere. However, ongoing monitoring for the future years is critical to validate this potential shift and further inform the situation.

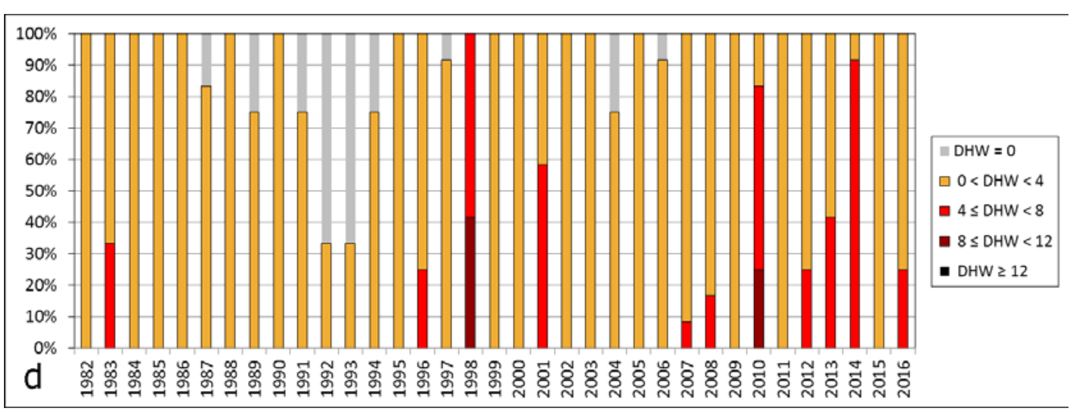
The 2014–17 event caused more reefs to be exposed to heat stress linked to bleaching than any previous global bleaching event, including in the seven Pacific regions considered here. However, both the history of exposure extent within the regions and the extent during the recent global event varied across the seven regions (Figure 6.6), which are addressed individually.

- Main Hawaiian Islands (44 grids): The year 2015 saw unprecedented exposure to prolonged heat stress, reaching Alert Level 2 and causing an unprecedented widespread severe bleaching event observed in the region. Beside 2015, there were only two years, 1996 and 2014, with only Alert Level 1 present at 25 km or larger scales. Alert Level 1 or 2 reached only a very small portion (<15% at most) of the reefs, except for 2015 when >85% of reef grids reached these high levels.
- Marshall Islands (102 grids): Heat stress at Alert Level 1 or 2 hit this region four years in a row from 2013–16, reaching Alert Level 2 in the last three of those years. Two of these years, 2014 and 2016, saw at least 50% of reef grids affected. Alert Level 1 appeared only three times earlier—in 1994, 1996, and 2009—but with only up to six days in exposure and in fewer than 2% of the grids.
- Eastern Micronesia (138 grids): This region has been exposed frequently to Alert Level 1, and occasionally to Alert Level 2, during the entire time period, including 1982 (during a possibly global bleaching event) and 1998 (during the first recorded global bleaching event). Only in 2016, did long-lasting high heat stress spread over the entire region, with 100% of grids exposed to Alert Levels 1 and 2, and 85% of those to Alert Level 2.
- Western Micronesia (12 grids): While Alert Level 1 was regularly apparent during the second half of the 1982–2016 time period, Alert Level 2 was not seen during the 2014–17 global bleaching event. Alert Level 2 was present only in two years: for up to 12 days in 1998 (during the first global bleaching event) and for three days in 2010 (during the second global bleaching event).


a
DHW = 0
0 < DHW < 4
4 ≤ DHW < 8
8 ≤ DHW < 12
DHW ≥ 12


b
DHW = 0
0 < DHW < 4
4 ≤ DHW < 8
8 ≤ DHW < 12
DHW ≥ 12


c
DHW = 0
0 < DHW < 4
4 ≤ DHW < 8
8 ≤ DHW < 12
DHW ≥ 12


d
DHW = 0
0 < DHW < 4
4 ≤ DHW < 8
8 ≤ DHW < 12
DHW ≥ 12

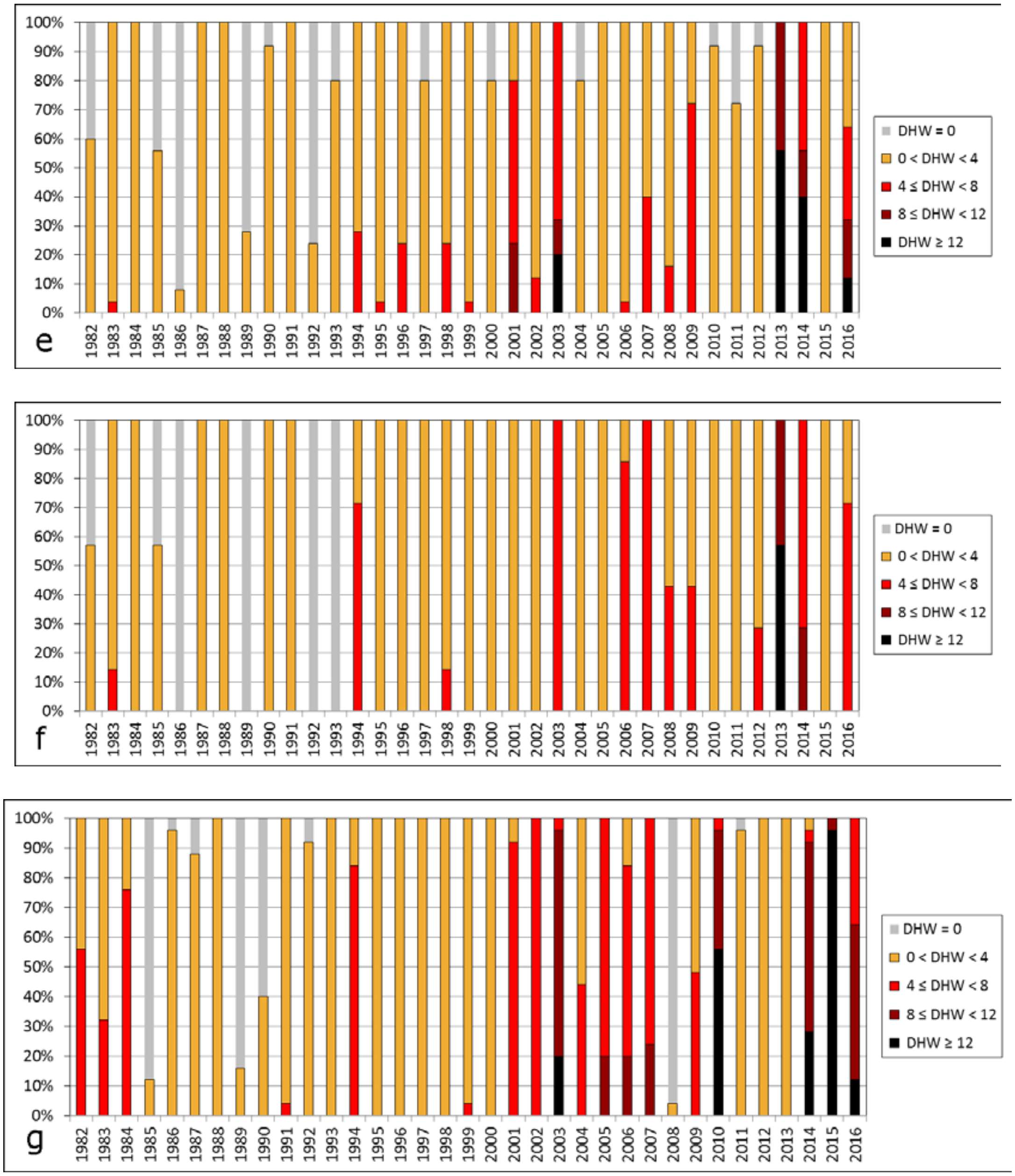


Figure 6.6. Extent of reef area exposed to coral heat stress for seven Pacific reef regions: (a) main Hawaiian Islands (44 grids); (b) Marshall Islands (102); (c) eastern Micronesia (138); (d) western Micronesia (12); (e) Northern Mariana Islands (25); (f) Guam (7); and (g) Samoas (25), showing the percentage of reef grids exposed to five heat stress categories: No Accumulated Stress (DHW = 0°C-weeks); Warning (0 < DHW < 4°C-weeks); Alert Level 1 (4 ≤ DHW < 8°C-weeks); Low Alert Level 2 (8 ≤ DHW < 12°C-weeks); and High Alert Level 2 (DHW ≥ 12°C-weeks).

Only during the three global bleaching events were more than 80% of reef grids exposed to Alert Levels 1 and 2, including 100% of reef grids in 1998.

- Northern Mariana Islands (25 grids): This region saw increasing duration of heat stress exposure and intensity of accumulated heat stress over the time period. Extreme stress days (high Alert

Level 2; DHW ≥ 12°-weeks) appeared in four years, all since 2003, and with three of them in the last four years. The region was repeatedly exposed by high levels of heat stress during the third global bleaching event. Among these four years, 100% of the reef grids were exposed to Alert Levels 1 or 2 in 2003, 2013, and 2014.

- Guam (7 grids): At the southern end of the Mariana archipelago, heat stress was less intense compared with its northern neighbor. However, increases in exposure duration and accumulated heat stress are also clearly shown in the region. The region was essentially free from severe bleaching stress during the first half of the assessment period. Since 2000, Alert Level 1 events occurred with some regularity, with Alert Level 2 apparent in 2013 and 2014. The entire region (100% of reef grids) was exposed to Alert Level 1 or higher in 2003, 2007, 2013, and 2014; 100% of reef grids were exposed to Alert Level 2 in 2013.
- The Samoas (25 grids): This region was repeatedly exposed to intense heat stress during the second half the 1985–2016, and especially during the third global bleaching event. In contrast, the region was mostly free from long-lasting severe bleaching stress during the first half of the assessment period. A shift in the regime of bleaching heat stress seems to occur around 2001. Whereas no years prior to 2000 recorded heat stress at Alert Level 1 or higher for 90% of reef grids, nine of the most-recent 16 years had >90% of the reef grids exposed to Alert Levels 1 or 2 (and seven of those years had 100% exposure).

What does the future hold?

SST is projected to continue to increase through the 21st century under all emissions scenarios.[9] Before 2035 the projected increase of SST is fairly consistent across the scenarios; beyond 2035 the projected warming diverges depending on the scenario employed, resulting in projected warming above pre-industrial levels of 1.6°–4.3°C (2.9°–7.7°F) by 2100.[9] With respect to coral reefs, devastating impacts due to increased SST are projected to occur between the 2030s and 2050s as bleaching level stress is reached annually under all emissions scenarios.[9,15] Locations where the onset of annual severe bleaching is anticipated to occur early in this time range include the central equatorial Pacific Ocean; locations where the onset of annual severe bleaching is anticipated to occur late in this time range include the South Pacific.[16,17] Global projections are for severe degradation and potential loss of corals from most global locations by 2050 under the current warming trajectory.[9]

Key Links

NOAA Extended Reconstructed SST (ERSST), V4 https://www.ncdc.noaa.gov/data-access/marineocean-data/extended-reconstructed-sea-surface-temperature-ersst-v4,

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

IUCN http://www.eenews.net/assets/2016/09/07/document_pm_01.pdf

El Niño & La Niña (El Niño-Southern Oscillation) https://www.climate.gov/enso

The Oceanic Niño Index (ONI)

El Niño and La Niña are the warm and cool phases of a recurring climate pattern across the tropical Pacific—the El Niño–Southern Oscillation, or "ENSO" for short. The pattern can shift back and forth irregularly every two to seven years, and each phase triggers predictable disruptions of temperature, precipitation, and winds. These changes disrupt the large-scale air movements in the tropics, triggering a cascade of global side effects.[18] The ENSO state is characterized by a five consecutive 3-month running mean of sea surface temperature (SST) anomalies in the Niño 3.4 region (Figure 6.7). This measure is known as the Oceanic Niño Index (ONI), and is recognized as the preeminent descriptor of climate variability within the Pacific. When the ONI is +0.5 or higher, El Niño conditions are present indicating the east–central tropical Pacific is much warmer than usual. La Niña conditions exist when the ONI is −0.5 or lower, indicating the region is cooler than usual (Figure 6.8).[18,19]

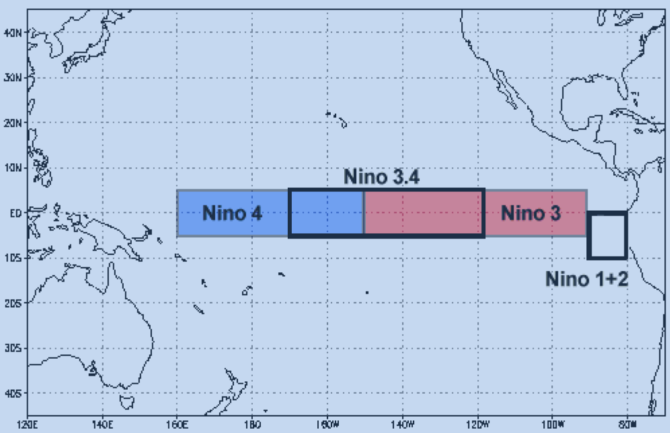
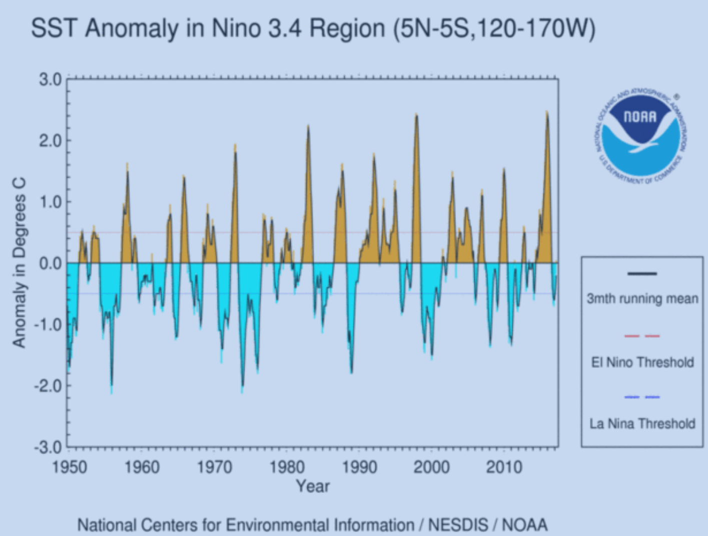


Figure 6.7. Location of the Niño regions for measuring SST in the eastern and central tropical Pacific Ocean. The Niño 3.4 region spans from 120˚ to 170˚W longitude. This region provides a good measure of important changes in SST and SST gradients that result in changes in the pattern of deep tropical convection and atmospheric circulation. From NOAA NCEI Equatorial Pacific Sea Surface Temperatures From NOAA NCEI Equatorial Pacific Sea Surface Temperatures .

From https://www.ncdc.noaa.gov/teleconnections/enso/indicators/sst.php

Figure 6.8. Period of Record Time Series for SST Anomaly in the Nino 3.4 Region. This plot shows the three-month running mean of SST anomaly (°C) calculated using the Extended Reconstructed Sea Surface Temperature version 4 (ERSST.v4).[20] The horizontal red and black lines show the ±0.5°C anomaly, denoting the El Niño and La Niña thresholds, respectively.
From https://www.ncdc.noaa.gov/teleconnections/enso/indicators/sst.php



During 2014-16 the globe experienced an exceptionally strong El Niño. The El Nino technically started in December of 2014, concluding in June of 2016 for a total of 19 consecutive months with the Oceanic Nino Index above 0.5. At its peak in 2015-16, the strength of the El Niño was comparable in strength to the very strong 1982-83 and 1997-98 El Niño events.[17] Impacts were widespread across the Pacific, including record numbers of Tropical Cyclones, extended drought, dramatic changes in sea level, extensive coral bleaching, and changes in the distribution of commercial fish species.

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18 - NOAA Climate.gov https://www.climate.gov/enso

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7. Ocean Acidification

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Takeaways

- Globally, the carbonite mineral aragonite saturation state (Ω_{arag}; a proxy for ocean acidity) has decreased at a rate of −0.03 per decade over the last 200+ years.
- More recent rates of change in aragonite saturation state on the order of −0.13 per decade are reported for the Pacific Ocean.
- Nearly 30 years of oceanic pH measurements, based on data collected from Station ALOHA, Hawaii, show a roughly 8.7% increase in acidity over this time.
- Ocean acidification is projected to increase through the 21st century. By 2050, all existing coral reefs would be exposed to regional waters with Ω_{arag} less than 3.5 under RCP8.5.
- Increasing ocean acidification reduces the ability of marine organisms to build shells and other hard structures. This adversely impacts coral reefs and threatens marine ecosystems more broadly.

Source T. Clemente/ UH SOEST

Scientists at the University of Hawaiʻi at Mānoa working on the Hawaii Ocean Time-series (HOT) program have been making regular cruises to collect observations at Station ALOHA (A Long-Term Oligotrophic Habitat Assessment) located north of Oahu, Hawaii. Increasing ocean acidification makes it more difficult for corals and plankton to produce calcium carbonate, the primary mineral that makes up their hard skeletons and shells. Monitoring pH on a continuous basis provides a foundation for documenting, understanding, and, ultimately, predicting the effects of ocean acidification. See http://hahana.soest.hawaii.edu/hot/#

Why should we care?

Ocean pH is an important indicator of the chemistry of the ocean. As the amount of CO_2 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 (i.e., the ocean pH has decreased). Increasing ocean acidity makes it harder for corals and plankton to form calcium carbonate, the main mineral that makes up their hard skeletons and shells. This adversely impacts coral reefs and threatens other marine ecosystems including pelagic fisheries.[1,2,3]

Where are we now?

Global

The aragonite saturation state (Ω_{arag}) describes the amount of aragonite—a type of calcium carbonate—dissolved in seawater that is available for use by coral to form skeletons.[2,3] Ocean surface waters are considered optimal for maintaining coral accretion where Ω_{arag} is greater than 4.0; an Ω_{arag} less than 3.0 is considered extremely marginal.[4]

Globally, aragonite saturation state has seen a steady decrease over the past century (Figure 7.1).[2,5,6] Modelling of global historical aragonite saturation state suggests that during the period ca. 1780 to 2006, when the CO_2 concentration increased from 280 ppm to 380 ppm, the average Ω_{arag} surrounding reefs decreased from 4.1 to 3.4 (Figure 7.2).[2,6] Over this period, Ω_{arag} was a declining at a rate of −0.03 per decade. Rates of decrease in Ω_{arag} across the Pacific over recent decades are on the order −0.13 per decade, or −3.4%, which is higher than the long-term trend.[2,7]

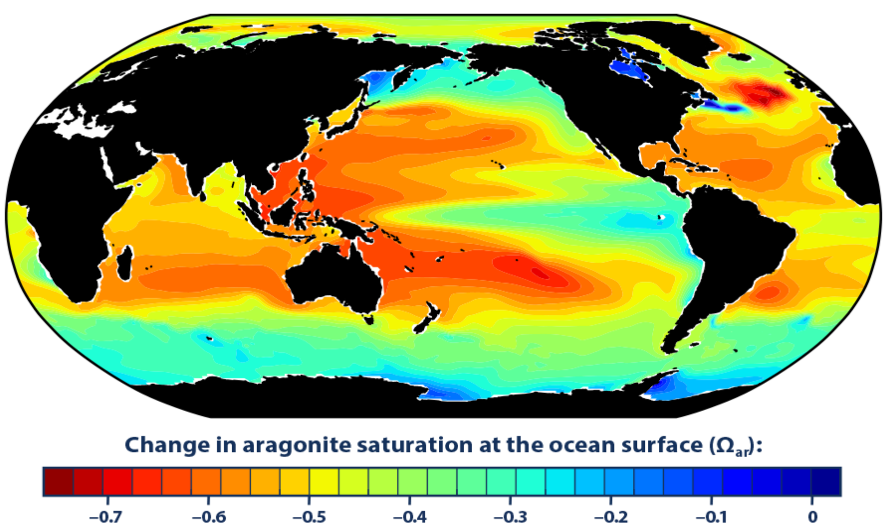

Figure 7.1. Changes in aragonite saturation of the world's oceans surface waters between the 1880s and the most recent decade (2006–15).[3] This map shows changes in ocean acidity in terms of the aragonite saturation state. Aragonite is a form of calcium carbonate that many marine animals use to build their skeletons and shells. The lower the saturation level (the higher the acidity), the more difficult it is for organisms (like corals and shellfish) to build and maintain their skeletons and shells. A negative change represents a decrease in saturation state; https://www.epa.gov/climate-indicators/climate-change-indicators-ocean-acidity.

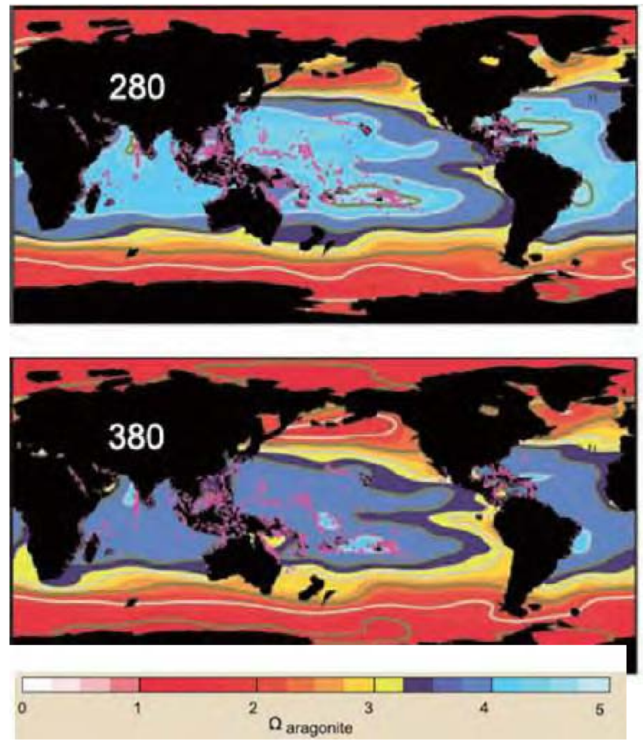

Figure 7.2. Historical aragonite saturation state of the world's oceans surface waters. Modelled surface aragonite saturation state for the global ocean for atmospheric concentrations of CO_2 at 280 ppm (top) and 380 ppm (bottom).[From 2 after 3] When atmospheric CO_2 was 280 ppm (ca. 1780), waters surrounding over 98% of global coral reefs had Ω_{arag} above 3.5. By the time CO_2 concentration reached 380 ppm (in 2006), only 38% of global coral reefs had Ω_{arag} above 3.5.[6] Ω_{arag} less than 3.5 is considered to be marginal for maintaining coral accretion.[3]

Regional

Since October 1988, scientists working on the Hawaii 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 ALOHA (A Long-Term Oligotrophic Habitat Assessment) located 100 km north of Oahu, Hawaii. 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 25+ year time series at Station ALOHA represents the best available documentation of the significant downward trend in oceanic pH since data collection began in 1988 (Figure 7.3). Over the nearly 30 years spanned by this time series, oceanic pH has shown a significant linear decrease of 0.036 pH units, or roughly an 8.7% increase in acidity. 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.

What does the future hold?

Ocean acidification is projected to increase through the 21st century, as both pH and Ω_{arag} continue to decrease over time.[2,3] Under RCP8.5, atmospheric CO_2 concentration is projected to reach 550 ppm around 2050.[8,9] At this level all existing coral reefs would be exposed to regional waters with Ω_{arag} less than 3.5.[5] Projections under RCP2.6 indicate atmospheric CO_2 concentration will peak at 440 ppm around 2050.[8,9] Even at this level, all existing coral reefs would be exposed to regional waters with Ω_{arag} less than 3.75, and many would be exposed to Ω_{arag} less than 3.25.[5,8,9] Tropical oceans are expected to experience the greatest absolute decrease in Ω_{arag}. These are the same areas projected to experience the highest levels of thermal stress[2] (see also previous section), which could exacerbate the effects of increasing acidity.

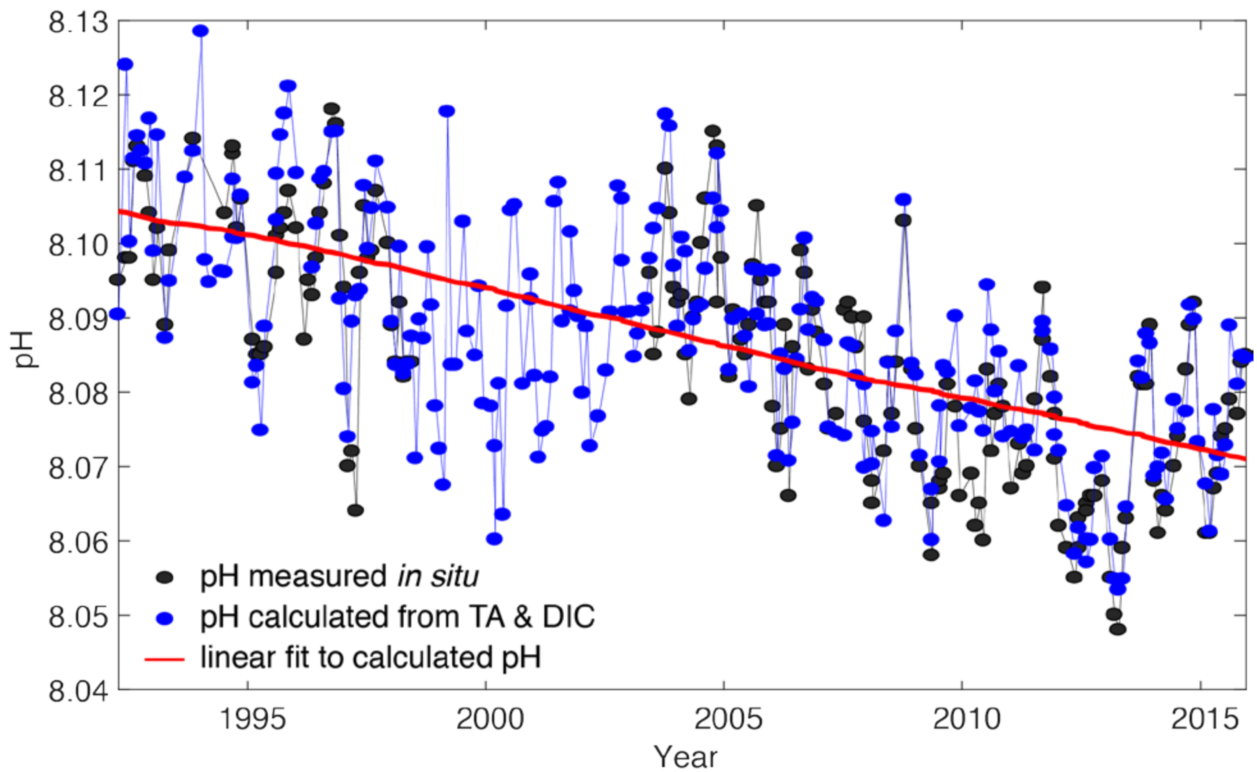

Figure 7.3. Measured and calculated trends in surface (0–10 meter) pH at Station ALOHA, collected by the Hawai'i Ocean Time-series (HOT). The black lines and circles represent directly measured pH from 5-meter depth. The blue lines and circles represent pH calculated from total alkalinity (TA) and dissolved inorganic carbon (DIC). The linear fit to calculated pH is shown in red. Lower pH indicates higher acidity.

Key Links

IUCN http://www.eenews.net/assets/2016/09/07/document_pm_01.pdf

NOAA OA Program http://oceanacidification.noaa.gov/Home.aspx

IOOS OA Data Explprer http://www.ipacoa.org/

IOOS OA Program https://ioos.noaa.gov/project/ocean-acidification/

PacIOOS OA Project http://www.pacioos.hawaii.edu/projects/acid/

UH Station Aloha http://hahana.soest.hawaii.edu/hot/hot_jgofs.html

EPA https://www.epa.gov/climate-indicators/climate-change-indicators-ocean-acidity

Sources of Information

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8. Ocean Chlorophyll Concentration

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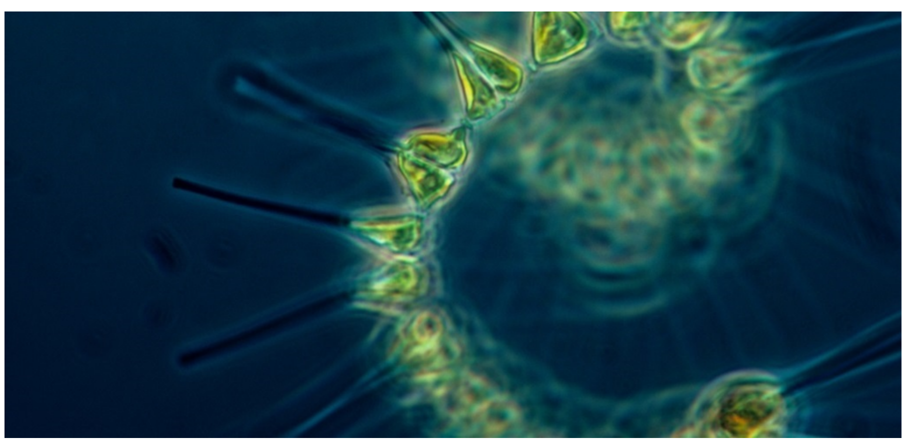
Takeaways

- Chlorophyll-*a* concentrations in the surface ocean are an indicator of phytoplankton abundance and biological production. Phytoplankton is the foundational food source for a wide range of sea creatures. Changes in phytoplankton abundance, both too little and too much, have the potential to negatively impact fisheries, aquaculture, and human health.
- In all major mid-ocean subtropical gyres, warming of surface waters is occurring and is accompanied by expansion of "oligotrophic" waters (areas with low biological productivity/low chlorophyll-*a* concentration). During the 9-year period 1998–2006, oligotrophic waters within the North Pacific subtropical gyre grew by 2.2% per year.
- The transition zone chlorophyll front (TZCF) roughly marks the northern boundary of the North Pacific subtropical gyre and is used as a migration and foraging corridor by both commercially-valuable and protected species. In the first quarter of 2016 the TZCF was farther south than average conditions west of 150°W and farther north than average east of 135°W.
- Regional images show varying patterns of changes in chlorophyll-*a* concentration between 2011–15 and the long-term average (2003–15). Differences generally were larger at higher latitudes.
- Ocean models and other observations show warming and increased vertical stratification occurring in all oceans, thus continued expansion of nutrient poor (oligotrophic) regions within the gyres is predicted. As these oligotrophic regions expand, fish abundance in newly oligotrophic waters is projected to decline as much as 50%–75% over the 21st century.

Source: NOAA



Caption: Phytoplankton is the base of aquatic food webs. Microscopic phytoplankton floating in the upper layers of the ocean use the sun's energy to photosynthesize carbohydrates. These carbohydrates can be eaten for energy, and these plants—mostly diatoms and algae—are the foundation of the majority of the ocean's biological community. Chlorophyll-*a* concentrations in the surface ocean are an indicator of phytoplankton abundance and biological production. From http://www.noaa.gov/resource-collections/aquatic-food-webs

Why should we care?

Satellite remotely-sensed ocean color is used to determine chlorophyll-*a* concentration in the surface ocean. These data can be used as proxies for phytoplankton abundance and biological production at the base of the ocean food chain. Phytoplankton is the foundational food source for a wide range of sea creatures including fish, whales, shrimp, snails, and jellyfish. A decrease in phytoplankton abundance associated with too few nutrients in the seawater has the potential to negatively impact fish abundance and catch. When too many nutrients are available, phytoplankton may grow out of control and form harmful algal blooms (HABs). These blooms can produce extremely toxic compounds that have harmful effects on fish, shellfish, mammals, birds, and even people. Changes in phytoplankton abundance have been linked to both natural climate variability and anthropogenic climate change.

Where are we now?

Chlorophyll-*a* concentration is higher near the coasts and at higher latitudes. The central regions of mid-ocean subtropical gyres are characterized by low levels of phytoplankton production. The Hawaiian Islands sit in the middle of the North Pacific subtropical gyre. Studies using remote-sensing data of surface chlorophyll document an expansion of the most nutrient poor or “oligotrophic” waters in all major mid-ocean subtropical gyres in concert with rising sea surface temperatures (Figure 8.1).[1,2] Biological oceanographers define these oligotrophic regions—essentially open ocean deserts—as waters with chlorophyll concentrations of 0.07 milligrams per cubic meter of water or less. Warming of the gyres, whether induced by natural processes or human activities, strengthens vertical stratification of these open-ocean regions, reducing the likelihood that nutrient-rich deep waters will be transported into the surface layer where photosynthetic activity occurs. The expected result is lower rates of primary production in these waters, with cascading effects through higher levels of the food chain. This phenomenon appears, to varying degrees, in subtropical gyres of both the Northern and Southern Hemispheres. During the 9-year period 1998–2006, oligotrophic waters within subtropical gyres of the North and South Pacific and the North and South Atlantic expanded.[2] In the North Pacific subtropical gyre, the oligotrophic region grew by 2.2% per year, and expansion of low-chlorophyll surface waters was particularly evident in a wide band of the central Pacific east and west of the Hawaiian Archipelago.

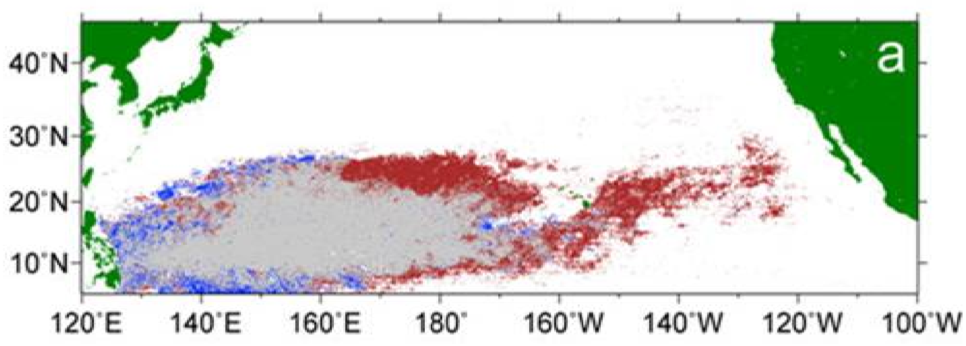


Figure 8.1. Oligotrophic areas in the North Pacific subtropical gyre. Most areas that were oligotrophic (i.e., had low levels of chlorophyll) in 1998/99 also were oligotrophic in 2005/06 (gray region). A few areas were oligotrophic in 1998/98 but not in 2005/06 (blue region). And many areas not oligotrophic in 1998/99 had become so by 2005/06 (red region).

The transition zone chlorophyll front (TZCF), identified by the 0.2 mg chl-*a* m^{-3} isopleth (the level of approximately the same amount of chlorophyll-*a*), roughly marks the northern boundary of the North Pacific subtropical gyre. The TZCF is used as a migration and foraging corridor by both commercially-valuable and protected ocean species. The front shifts meridianally (north-south) with the seasons and its position is impacted by the phase of El Niño–Southern Oscillation (ESNO). The front also exhibits significant interannual migration, as shown on Figure 8.2. Long-term northward displacement of the frontal zone may also occur in response to anthropogenic climate change.

In the first quarter of 2016, the TZCF was farther south than average conditions west of 150°W and farther north than average east of 135°W. This may be due to El Niño conditions as well as other factors. Northward displacement of the frontal zone can increase the distance fishing vessels must travel to set their gear. This can, in turn, increase operational expenses and potentially the price of seafood for consumers.

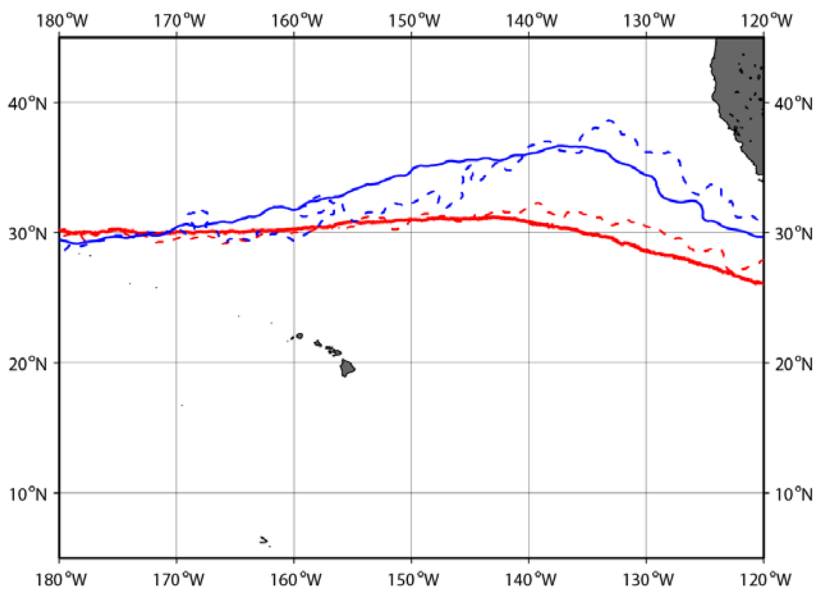


Figure 8.2 North Pacific subtropical front and transition zone chlorophyll front. The climatological (solid) and 2016 (dashed) position of the transition zone chlorophyll front (blue) and Pacific subtropcial tront (red) are shown for the first quarter of the year (January–March). The climatological period for the TZCF is 2003–15. *NOAA OceanWatch ocean color data;* http://oceanwatch.pifsc.noaa.gov/

The maps in Figure 8.3 show anomalies in chlorophyll-*a* concentration in three regions of the Pacific Ocean over the period 2011–15, compared to the climatology over 2003–15. Blue (red) areas indicate where chl-*a* concentrations were lower (higher) in 2011–15 compared to the long-term average.

In the northwest Pacific, differences in chl-*a* concentrations were low except in the Sea of Japan and the East China Sea; changes were more pronounced at higher latitudes. The range of differences in chl-*a* concentrations around the Hawaiian Islands was very low, with generally higher concentrations nearer the islands and lower concentrations farther away. In the South Pacific, chl-*a* concentrations were slightly higher in 2011–15 compared to the long-term average, except around New Zealand where they were considerably lower.

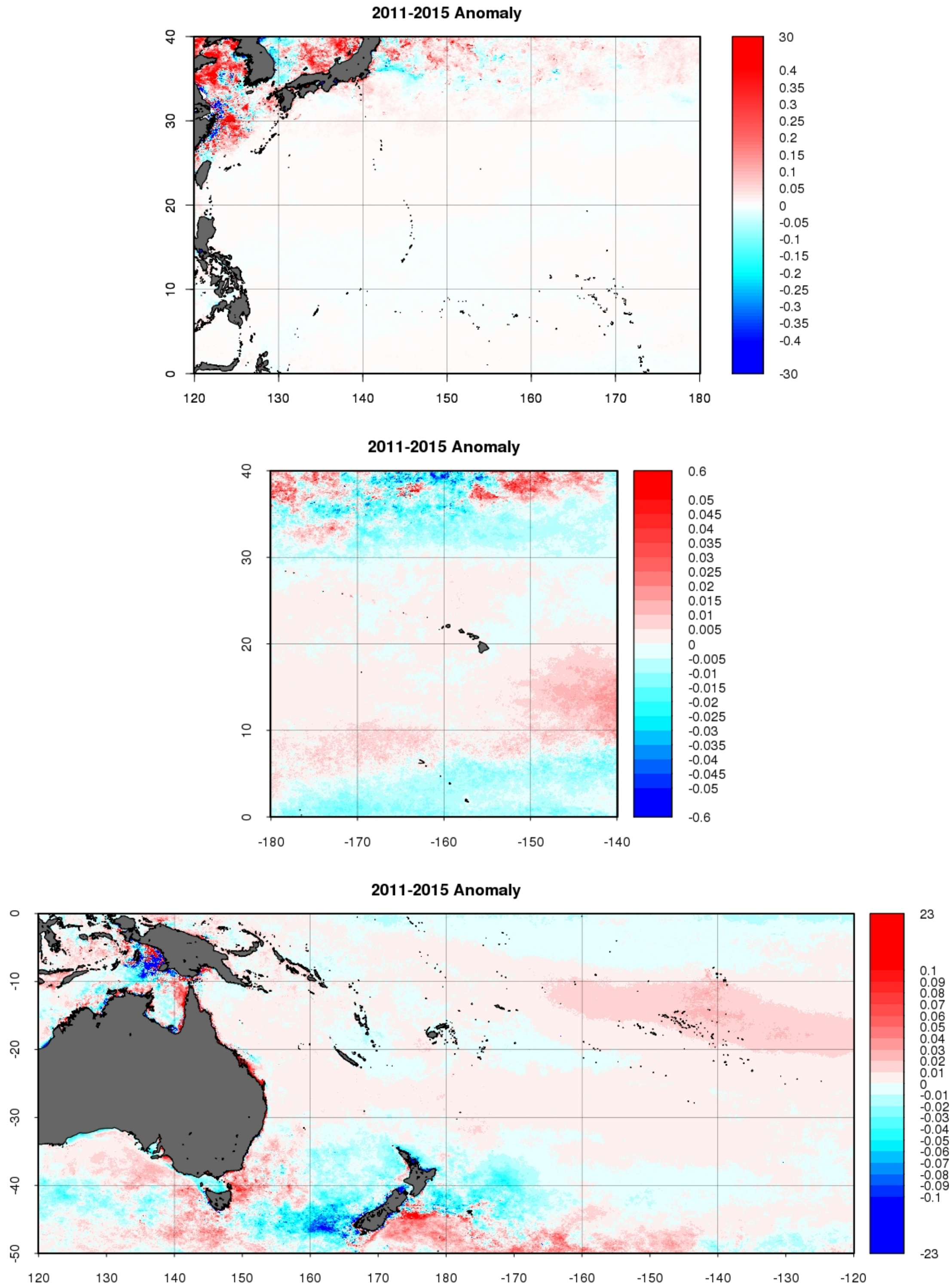


Figure 8.3 Anomalies in chlorophyll-*a* concentrations in three regions of the Pacific Ocean over the period 2011–15, compared to the climatology over the period 2003–15. Blue (red) areas indicate where chl-*a* concentrations were lower (higher) in 2011–15 compared to the long-term average. *NOAA OceanWatch ocean color data;* http://oceanwatch.pifsc.noaa.gov/

Since October 1988, scientists working on the Hawaii 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 ALOHA (A Long-Term Oligotrophic Habitat Assessment) located 100 km north of Oahu, Hawaii. The chlorophyll-*a* concentration at Station Aloha does not show a distinct trend over the nearly 30 years spanned by this period of record, though it does show a decrease starting around 2013 (Figure 8.4).

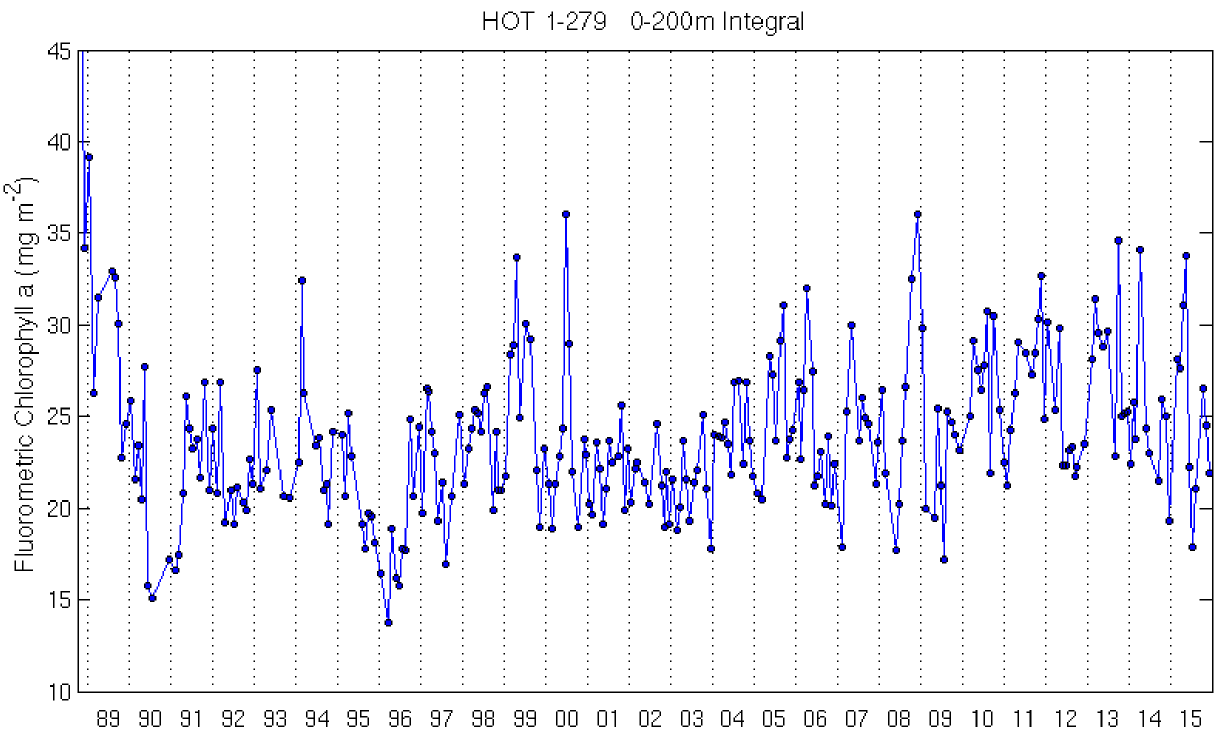


Figure 8.4 Chlorophyll concentration measured at Station Aloha, collected by the Hawai'i Ocean Time-series (HOT). *HOT data;* http://hahana.soest.hawaii.edu/hot/trends/trends.html

What does the future hold?

The expansion of oligotrophic surface waters in the subtropical gyres appears to be directly linked to increasing temperatures. Ocean models and other observations show warming and increased vertical stratification occurring in all oceans, thus continued expansion of oligotrophic regions within the gyres is predicted.[2] Expansion of oligotrophic gyres is likely to impact the entire food web. For example, ecosystem modeling projects that newly oligotrophic waters in the North Pacific may see a 50%–75% decline in fish abundance over the 21st century.[3]

Key Links

NOAA Pacific Islands Fisheries Science Center
https://www.pifsc.noaa.gov/media/news/polovinaetal_Feb08.php

UH Station Aloha http://hahana.soest.hawaii.edu/hot/hot_jgofs.html

IUCN http://www.eenews.net/assets/2016/09/07/document_pm_01.pdf

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