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Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II

Hawaiʻi and U.S.-Affiliated Pacific Islands

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Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II

27 Hawaiʻi and U.S.-Affiliated Pacific Islands

Honolulu, Hawaiʻi

Key Message 1

Threats to Water Supplies

Dependable and safe water supplies for Pacific island communities and ecosystems are threatened by rising temperatures, changing rainfall patterns, sea level rise, and increased risk of extreme drought and flooding. Islands are already experiencing saltwater contamination due to sea level rise, which is expected to catastrophically impact food and water security, especially on low-lying atolls. Resilience to future threats relies on active monitoring and management of watersheds and freshwater systems.

Key Message 2

Terrestrial Ecosystems, Ecosystem Services, and Biodiversity

Pacific island ecosystems are notable for the high percentage of species found only in the region, and their biodiversity is both an important cultural resource for island people and a source of economic revenue through tourism. Terrestrial habitats and the goods and services they provide are threatened by rising temperatures, changes in rainfall, increased storminess, and land-use change. These changes promote the spread of invasive species and reduce the ability of habitats to support protected species and sustain human communities. Some species are expected to become extinct and others to decline to the point of requiring protection and costly management.

Key Message 3

Coastal Communities and Systems

The majority of Pacific island communities are confined to a narrow band of land within a few feet of sea level. Sea level rise is now beginning to threaten critical assets such as ecosystems, cultural sites and practices, economies, housing and energy, transportation, and other forms of infrastructure. By 2100, increases of 1–4 feet in global sea level are very likely, with even higher levels than the global average in the U.S.-Affiliated Pacific Islands. This would threaten the food and freshwater supply of Pacific island populations and jeopardize their continued sustainability and resilience. As sea level rise is projected to accelerate strongly after mid-century, adaptation strategies that are implemented sooner can better prepare communities and infrastructure for the most severe impacts.

Key Message 4

Oceans and Marine Resources

Fisheries, coral reefs, and the livelihoods they support are threatened by higher ocean temperatures and ocean acidification. Widespread coral reef bleaching and mortality have been occurring more frequently, and by mid-century these events are projected to occur annually, especially if current trends in emissions continue. Bleaching and acidification will result in loss of reef structure, leading to lower fisheries yields and loss of coastal protection and habitat. Declines in oceanic fishery productivity of up to 15% and 50% of current levels are projected by mid-century and 2100, respectively, under the higher scenario (RCP8.5).

Key Message 5

Indigenous Communities and Knowledge

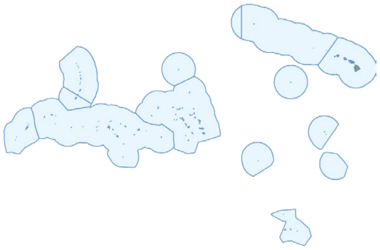
Indigenous peoples of the Pacific are threatened by rising sea levels, diminishing freshwater availability, and shifting ecosystem services. These changes imperil communities' health, well-being, and modern livelihoods, as well as their familial relationships with lands, territories, and resources. Built on observations of climatic changes over time, the transmission and protection of traditional knowledge and practices, especially via the central role played by Indigenous women, are intergenerational, place-based, localized, and vital for ongoing adaptation and survival.

Key Message 6

Cumulative Impacts and Adaptation

Climate change impacts in the Pacific Islands are expected to amplify existing risks and lead to compounding economic, environmental, social, and cultural costs. In some locations, climate change impacts on ecological and social systems are projected to result in severe disruptions to livelihoods that increase the risk of human conflict or compel the need for migration. Early interventions, already occurring in some places across the region, can prevent costly and lengthy rebuilding of communities and livelihoods and minimize displacement and relocation.

Executive Summary



The U.S. Pacific Islands are culturally and environmentally diverse, treasured by the 1.9 million people who call them home. Pacific islands are particularly vulnerable to climate change impacts due to their exposure and isolation, small size, low elevation (in the case of atolls), and concentration of infrastructure and economy along the coasts.

A prevalent cause of year-to-year changes in climate patterns around the globe[1] and in the Pacific Islands region[2] is the El Niño–Southern Oscillation (ENSO). The El Niño and La Niña phases of ENSO can dramatically affect precipitation, air and ocean temperature, sea surface height, storminess, wave size, and trade winds. It is unknown exactly how the timing and intensity of ENSO will continue to change in the coming decades, but recent climate model results suggest a doubling in frequency of both

El Niño and La Niña extremes in this century as compared to the 20th century under scenarios with more warming, including the higher scenario (RCP8.5).[3,4]

On islands, all natural sources of freshwater come from rainfall received within their limited land areas. Severe droughts are common, making water shortage one of the most important climate-related risks in the region.[5] As temperature continues to rise and cloud cover decreases in some areas, evaporation is expected to increase, causing both reduced water supply and higher water demand. Streamflow in Hawaiʻi has declined over approximately the past 100 years, consistent with observed decreases in rainfall.[6]

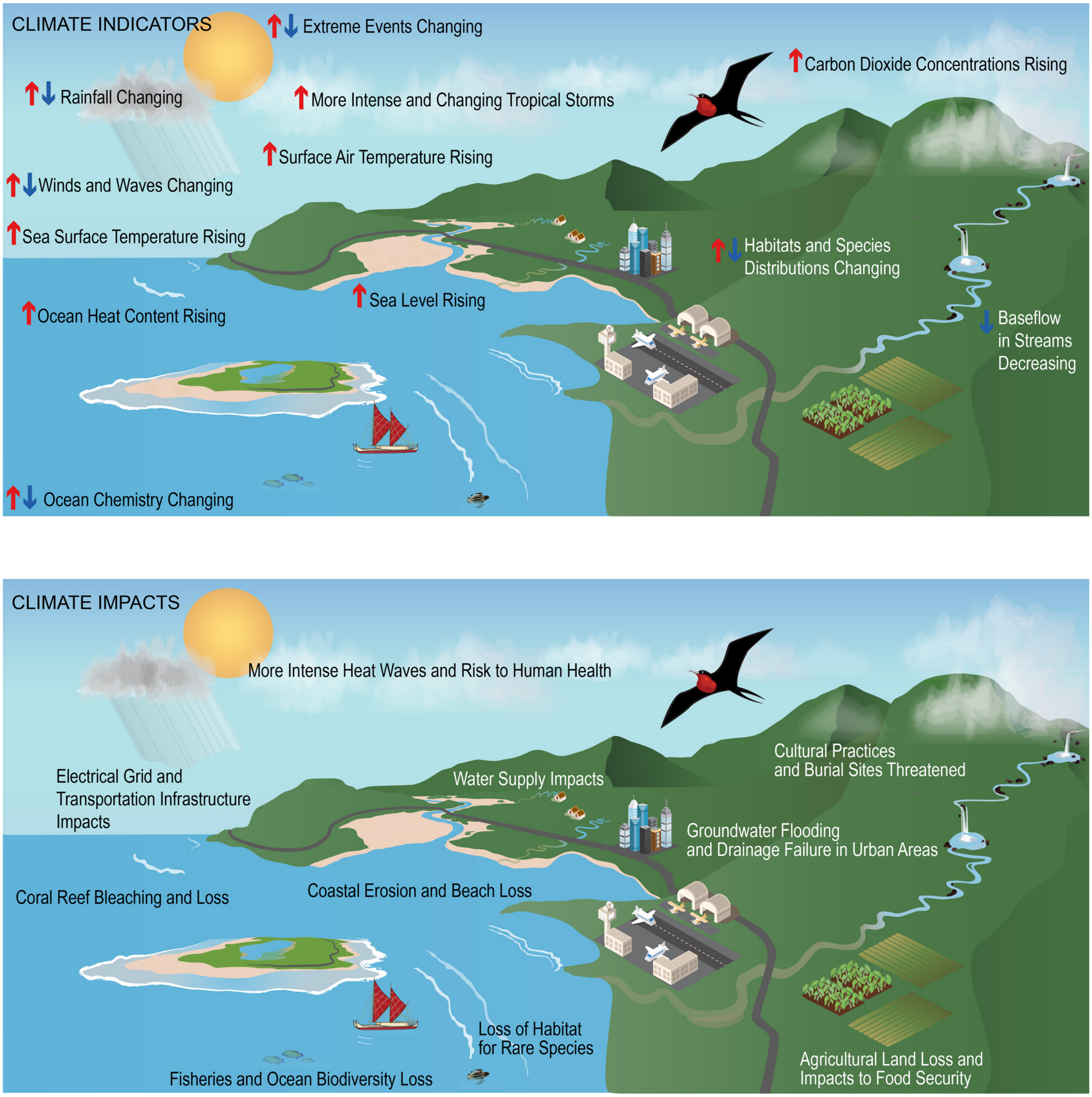
The impacts of sea level rise in the Pacific include coastal erosion,[7,8] episodic flooding,[9,10] permanent inundation,[11] heightened exposure to marine hazards,[12] and saltwater intrusion to surface water and groundwater systems.[13,14] Sea level rise will disproportionately affect the tropical Pacific[15] and potentially exceed the global average.[16,17]

Invasive species, landscape change, habitat alteration, and reduced resilience have resulted in extinctions and diminished ecosystem function. Inundation of atolls in the coming decades is projected to impact existing on-island ecosystems.[18] Wildlife that relies on coastal habitats will likely also be severely impacted. In Hawaiʻi, coral reefs contribute an estimated $477 million to the local economy every year.[19] Under projected warming of approximately 0.5°F per decade, all nearshore coral reefs in the Hawaiʻi and Pacific Islands region will experience annual bleaching before 2050. An ecosystem-based approach to international management of open ocean fisheries in the Pacific that incorporates climate-informed catch limits is expected to produce more realistic future harvest levels and enhance ecosystem resilience.[20]

Indigenous communities of the Pacific derive their sense of identity from the islands. Emerging issues for Indigenous communities of the Pacific include the resilience of marine-managed areas and climate-induced human migration from their traditional lands. The rich body of traditional knowledge is place-based and localized[21] and is useful in adaptation planning because it builds on intergenerational sharing of observations.[22] Documenting the kinds of governance structures or decision-making hierarchies created for management of these lands and waters is also important as a learning tool that can be shared with other island communities.

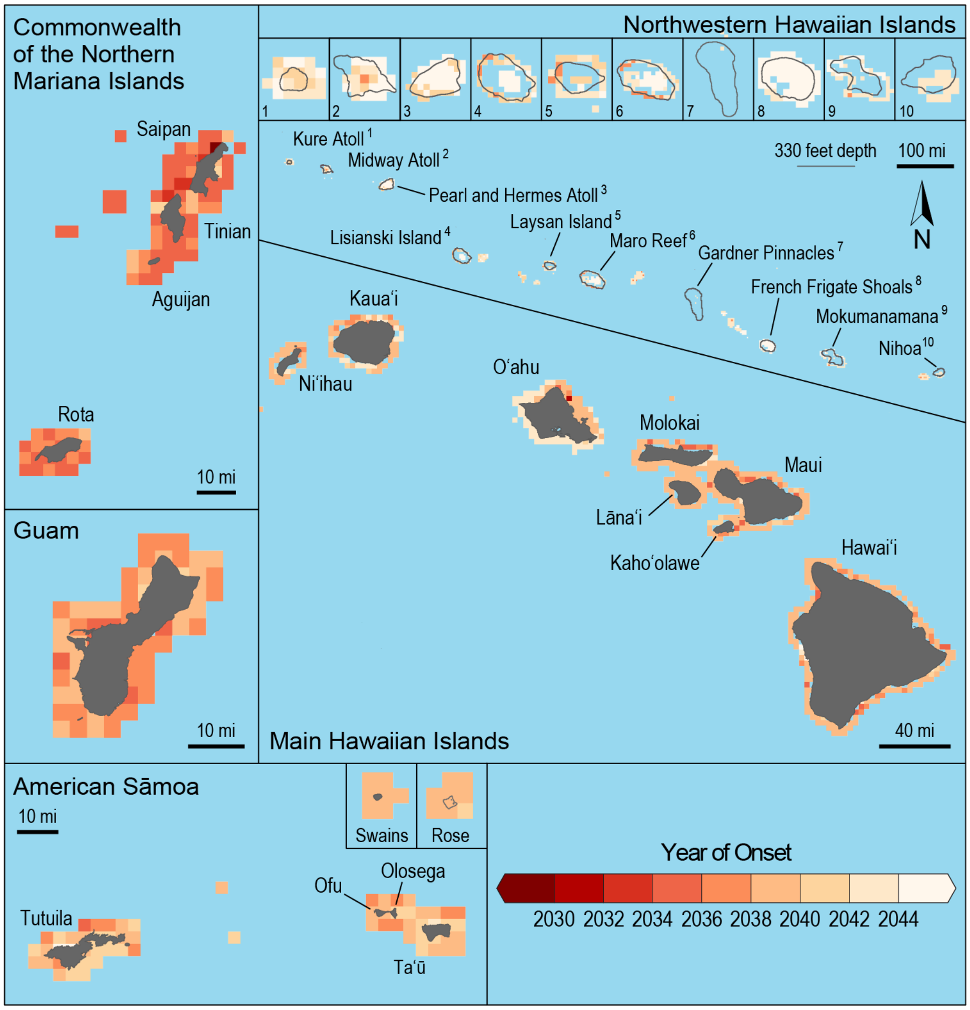
Across the region, groups are coming together to minimize damage and disruption from coastal flooding and inundation as well as other climate-related impacts. Social cohesion is already strong in many communities, making it possible to work together to take action. Early intervention can lower economic, environmental, social, and cultural costs and reduce or prevent conflict and displacement from ancestral land and resources.

Climate Indicators and Impacts



Monitoring regional indicator variables in the atmosphere, land, and ocean allows for tracking climate variability and change. (top) Observed changes in key climate indicators such as carbon dioxide concentration, sea surface temperatures, and species distributions in the U.S.-Affiliated Pacific Islands region result in (bottom) impacts to multiple sectors and communities, including built infrastructure, natural ecosystems, and human health. Connecting changes in climate indicators to how impacts are experienced is crucial in understanding and adapting to risks across different sectors. *From Figure 27.2 (Source: adapted from Keener et al. 2012).*[23]

Projected Onset of Annual Severe Coral Reef Bleaching



The figure shows the years when severe coral reef bleaching is projected to occur annually in the Hawai‘i and U.S.-Affiliated Pacific Islands region under a higher scenario (RCP8.5). Darker colors indicate earlier projected onset of coral bleaching. Under projected warming of approximately 0.5°F per decade, all nearshore coral reefs in the region will experience annual bleaching before 2050. From *Figure 27.10 (Source: NOAA)*.

Background

The U.S. Pacific Islands (Figure 27.1) are culturally and environmentally diverse, treasured by the 1.9 million people who call them home. The region comprises a vast ocean territory and more than 2,000 islands that vary in elevation, from high volcanic islands such as Mauna Kea on Hawai‘i Island (13,796 feet) to much lower islands and atolls such as Majuro Atoll in the Republic of the Marshall Islands (the highest point on Majuro is estimated at 9 feet).[24,25,26] Its environments span the deepest point in the ocean (Mariana Trench National Monument) to the alpine summits of Hawai‘i Island.[23] The region supports globally important marine and terrestrial biodiversity, as well as stunning cultural diversity (over 20 Indigenous languages are spoken).[23]

The U.S. Pacific Islands region is defined by its many contrasting qualities. While the area is a highly desirable tourist destination, with Hawai‘i and the U.S.-Affiliated Pacific Islands (USAPI) drawing more than 10 million tourists in 2015,[27]

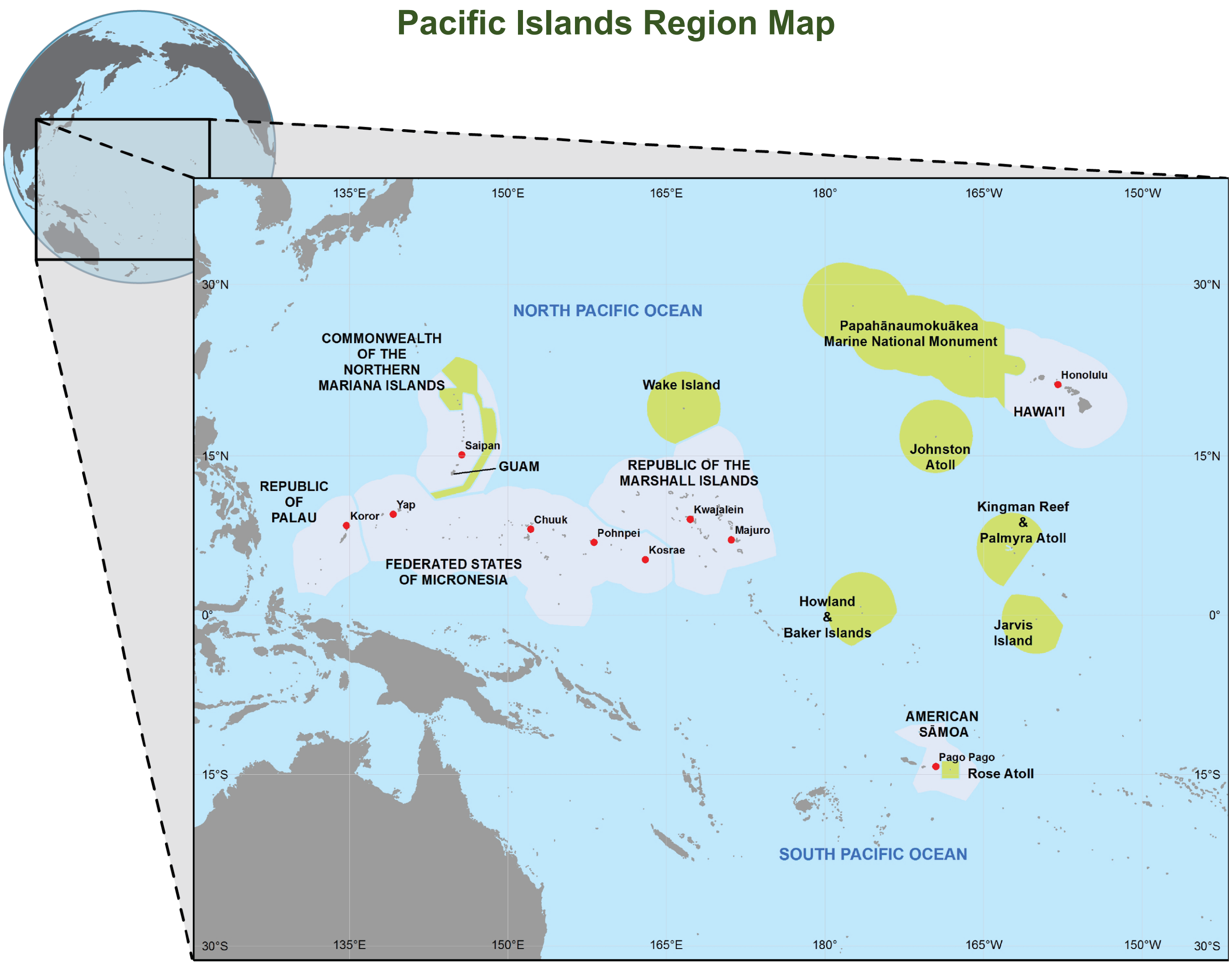

Pacific Islands Region Map

Figure 27.1: The U.S. Pacific Islands region includes the state of Hawai‘i, as well as the U.S.-Affiliated Pacific Islands (USAPI): the Territories of Guam and American Sāmoa (AS), the Commonwealth of the Northern Mariana Islands (CNMI), the Republic of Palau (RP), the Federated States of Micronesia (FSM), and the Republic of the Marshall Islands (RMI). While citizens of Guam and the CNMI are U.S. citizens, those from AS are U.S. nationals. Under the Compact of Free Association (COFA), citizens from FSM, RP, and RMI can live and work in the United States without visas, and the U.S. armed forces are permitted to operate in COFA areas. On this map, shaded areas indicate the exclusive economic zone of each island, including regional marine national monuments (in green). Source: adapted from Keener et al. 2012.[23]

living in the islands carries climate-related risks, such as those from tropical cyclones, coastal flooding and erosion, and limited freshwater supplies. Because of the remote location and relative isolation of the islands, energy and food supplies are shipped in at high costs.

For example, Hawai‘i has the highest average electricity rate in the United States (more than twice the national average),[28] and more than 85% of food is imported on most islands (see Ch. 17: Complex Systems and Ch. 20: U.S. Caribbean, Background and KM 5 for more information on the importance of regional supply chains).[29,30,31] Though the islands are small, they are seats for key military commands, with forces stationed and deployed throughout the region providing strategic defense capabilities to the United States.

Despite the costs and risks, Pacific Islanders have deep ties to the land, ocean, and natural resources, and they place a high value on the environmental, social, and physical benefits associated with living there. Residents engage in diverse livelihoods within the regional economy, such as tourism, fishing, agriculture, military jobs, and industry, and they also enjoy the pleasant climate and recreational opportunities. Important challenges for the region include improving food and water security, managing drought impacts, protecting coastal environments and relocating coastal infrastructure, assessing climate-induced human migration, and increasing coral reef resilience to warming and acidifying oceans.

New Research Validates and Expands on Previous Assessment Findings

In previous regional climate assessments, key findings focused on describing observed trends and projected changes in climate indicator variables for specific sectors.[23,32] In many cases, new observations and projections indicate that there is less time than previously thought for decision-makers to prepare for climate impacts. Regionally, air and sea surface temperatures continue to increase, sea level continues to rise, the ocean is acidifying, and extremes such as drought and flooding continue to affect the islands.[33] New regional findings include (Figure 27.2)

- a limited set of detailed statistical and dynamical downscaled temperature, rainfall, and drought projections for Hawai‘i (unlike the 48 contiguous states, Hawai‘i—like the Alaska and U.S. Caribbean regions—does not have access to numerous downscaled climate projections; see Key Messages 1 and 6);[34,35,36]

- projected future changes to winds and waves due to climate change, which affect ecosystems, infrastructure, freshwater availability, and commerce (see Key Message 3);[37,38]

- more spatially refined and physically detailed estimates showing increased sea level rise for this century (see Key Messages 3 and 6);[17,39]

- models of how central Pacific tropical cyclone tracks are shifting north (see Key Message 3);[40]

- identification of urbanized areas vulnerable to flooding from rising groundwater and erosion (see Key Messages 1, 3, and 6);[8,41]

- detailed assessment of vulnerability to sea level rise in Hawai‘i (see Key Message 3);[42]

- climate vulnerability assessments for endemic and endangered birds and plants showing shifting habitats (see Key Messages 2 and 5);[43,44] and

- projections that corals will bleach annually throughout the entire Pacific Islands region by 2045 if current warming continues (the worst bleaching event ever observed occurred during the El Niño of 2015–2016; Key Messages 4 and 6).[45,46,47,48]

Climate Indicators and Impacts

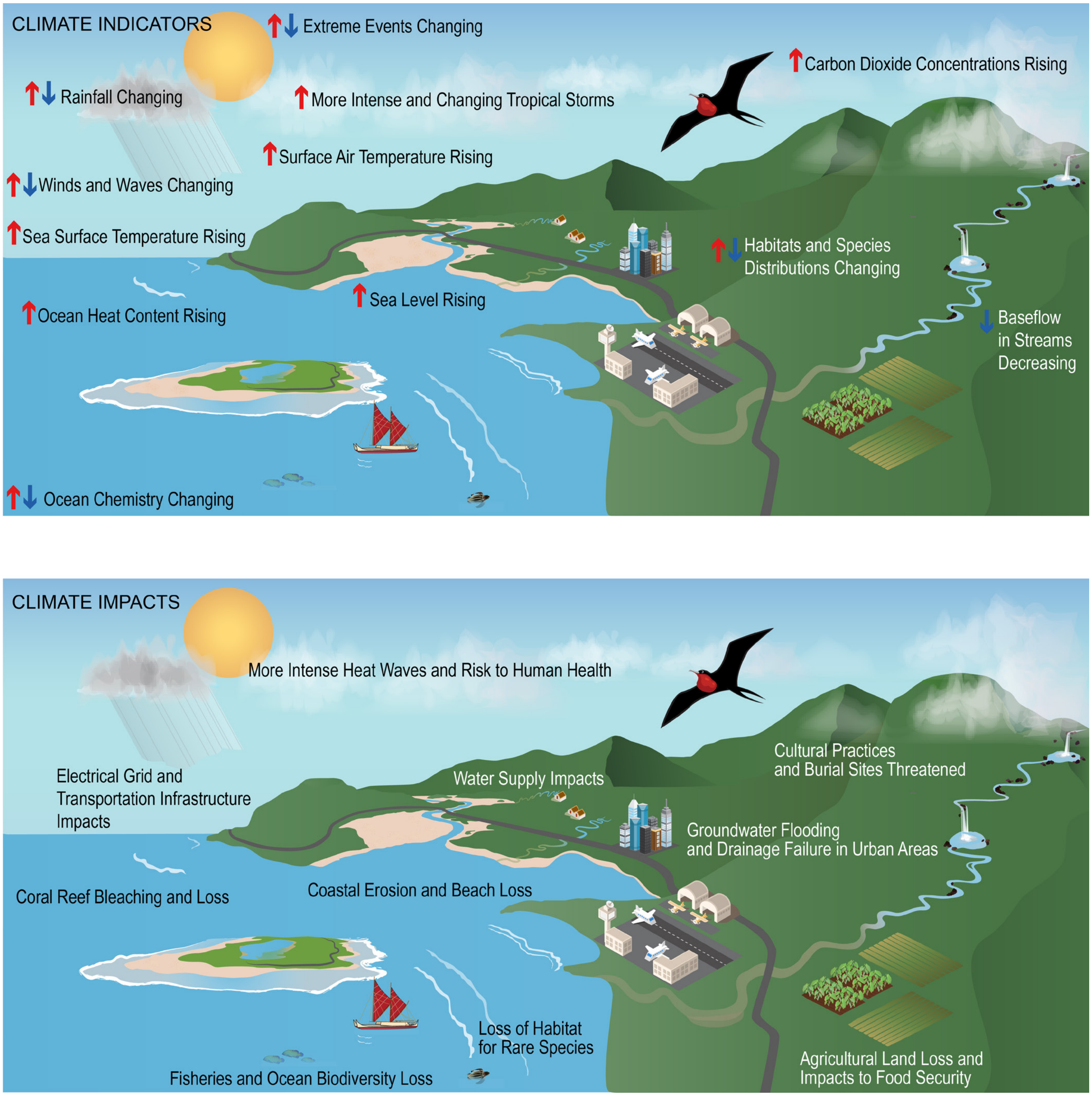


Figure 27.2: Monitoring regional indicator variables in the atmosphere, land, and ocean allows for tracking climate variability and change. (top) Observed changes in key climate indicators such as carbon dioxide concentration, sea surface temperatures, and species distributions in the Hawai‘i and U.S.-Affiliated Pacific Islands region result in (bottom) impacts to multiple sectors and communities, including built infrastructure, natural ecosystems, and human health. Connecting changes in climate indicators to how impacts are experienced is crucial in understanding and adapting to risks across different sectors. Source: adapted from Keener et al. 2012.[23]

Box 27.1: El Niño–Southern Oscillation (ENSO) and Year-to-Year Climate Variability

The El Niño–Southern Oscillation (ENSO) phenomenon is a prevalent cause of year-to-year changes in climate patterns globally[1] and in the Pacific Islands region.[2] The effects of ENSO can be magnified when it is in phase with longer periodic cycles such as the Pacific Decadal Oscillation and the Interdecadal Pacific Oscillation.[49] The El Niño and La Niña phases of ENSO can dramatically affect precipitation, air and ocean temperature, sea surface height, storminess, wave size, and trade winds (for details about the different patterns of global climate variability, see Perlwitz et al. 2017).[1]

Figure 27.3 shows how the typical seasonal patterns of rainfall, sea level, and storminess in El Niño and La Niña play out across the region, during which severe droughts can occur in the central and western Pacific and large areas of coral reefs can experience bleaching.[50,51] The strength of these ENSO-related patterns in the short term can make it difficult to detect the more gradual, long-term trends of climatic change. Understanding and anticipating ENSO effects, however, is important for planning for climate impacts on island communities and natural resources. Already, increases in the strength of El Niño and La Niña events have been observed (though the link between these observed changes and human causes is unclear).[3,52] It is unknown exactly how the timing and intensity of ENSO will continue to change in the coming decades, but recent climate model results suggest a doubling in frequency of both El Niño and La Niña extremes in the 21st century as compared to the 20th century under scenarios with more warming, including the higher scenario (RCP8.5).[3,4]

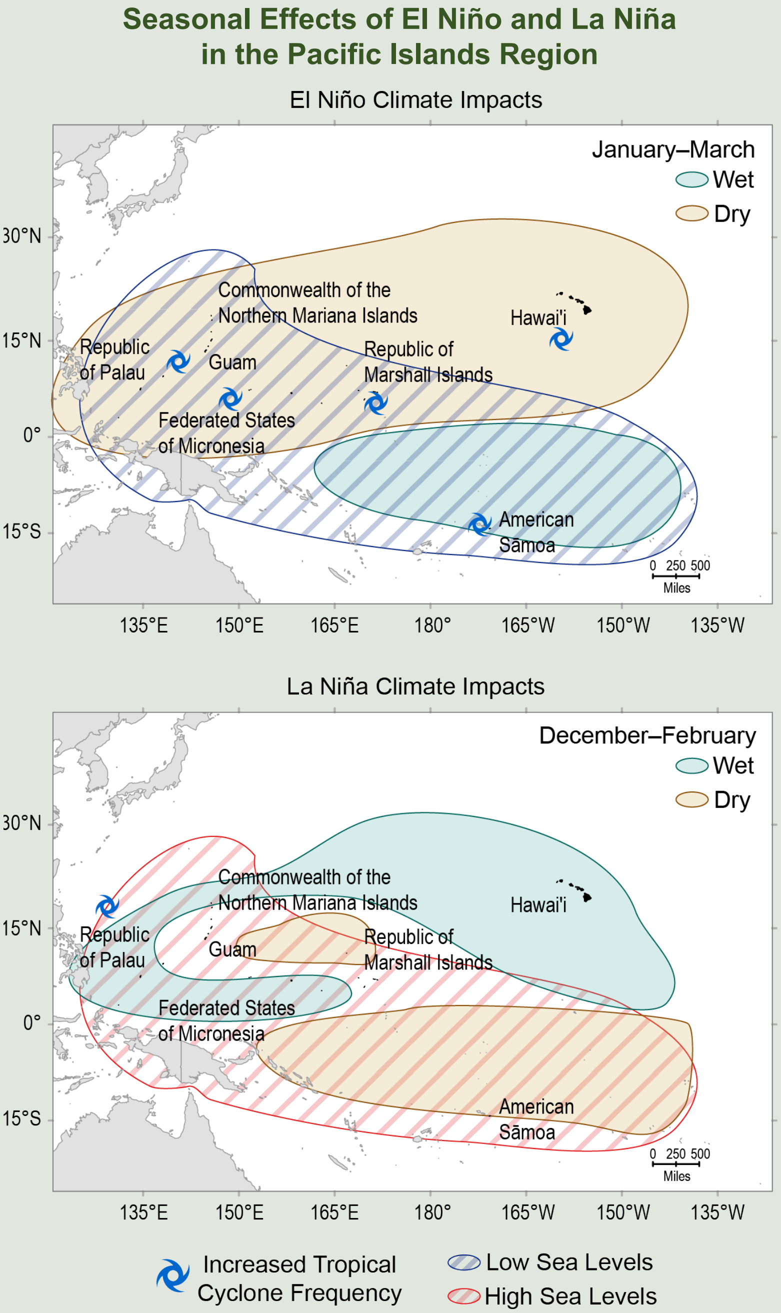


Figure 27.3: A prevalent cause of year-to-year changes in climate patterns in the U.S. Pacific Islands region is the El Niño–Southern Oscillation (ENSO) phenomenon. These maps show how (top) El Niño and (bottom) La Niña most commonly affect precipitation, sea level, and storm frequency in the Pacific Islands region in the year after an ENSO event. During certain months in the boreal (northern) winter, El Niño and La Niña commonly produce patterns that are different from those following an ENSO neutral year. After an El Niño, islands in the central Pacific (such as Hawaiʻi) and islands in the western Pacific (such as the Republic of Palau and Guam) experience drier than normal conditions from January to March, while the western and southern Pacific see abnormally low sea levels. After a La Niña, the patterns are reversed and occur earlier (December through February).[50] Source: East-West Center.

Risks and Adaptation Options Vary with Geography

In the U.S. Pacific Islands region, the severity of the impacts of climate change differ among communities. A number of factors affect both the level of risk and a community's approach to responding to that risk: geography (for example, high-elevation islands versus low-elevation atolls), the proximity of critical infrastructure to the coast, governance structure, cultural practices, and access to adaptation funding. As in the U.S. Caribbean (see Ch. 20: U.S. Caribbean), climate change is projected to impact the U.S. Pacific Islands through changes in ecosystem services, increased coastal hazards, and extreme events. Adaptation options in both regions are unique to their island context and more limited than in continental settings.

While uncertainty will always exist about future climate projections and impacts, communities and governments in the U.S. Pacific Islands region are planning proactively. Already, policy initiatives and adaptation programs are significant and include the accreditation of the Secretariat of the Pacific Regional Environment Programme (SPREP) to the Green Climate Fund,[53] the passage of the Hawaiʻi Climate Adaptation Initiative Act,[54] and the creation of separate climate change commissions for the City and County of Honolulu (established 2018) and the State of Hawaiʻi (established 2017). To increase coordination of adaptation and mitigation initiatives across the region and foster future climate leadership, island nations and the State of Hawaiʻi signed the Majuro Declaration.[55] These initiatives are moving adaptation science forward, for example, by increasing freshwater supply, upgrading vulnerable infrastructure, and creating legal frameworks for state and local governments to build climate resilience into current and future plans and policies.

Key Message 1

Threats to Water Supplies

Dependable and safe water supplies for Pacific island communities and ecosystems are threatened by rising temperatures, changing rainfall patterns, sea level rise, and increased risk of extreme drought and flooding. Islands are already experiencing saltwater contamination due to sea level rise, which is expected to catastrophically impact food and water security, especially on low-lying atolls. Resilience to future threats relies on active monitoring and management of watersheds and freshwater systems.

On islands, all natural sources of freshwater come from rainfall received within their limited land areas. Piping water from neighboring states is not an option, making islands uniquely vulnerable to climate-driven variations and changes in rainfall, rates of evaporation, and water use by plants. The reliability of precipitation is a key determinant of ecosystem health, agricultural sustainability, and human habitability.

Severe droughts are common, making water shortage one of the most important climate-related risks in the region.[5] In water emergencies, some islands rely on temporary water desalination systems or have water sent by ship, both of which are costly but life-saving measures (Figure 27.4).[56] Droughts occur naturally in this region and are often associated with El Niño events. Rainfall in Hawaiʻi and the U.S.-Affiliated Pacific Islands (USAPI) is strongly affected by seasonal movement of the intertropical convergence zone and ENSO (see Box 27.1). Similarly, other patterns of climate variability, such as the Pacific Decadal Oscillation, produce strings of wet or dry years lasting decades in the region. Because of this natural

Emergency Drought Response Action for Island Residents

Figure 27.4: U.S. Navy sailors unload reverse osmosis water supply systems in the Republic of the Marshall Islands in 2013 to provide relief from severe drought. The systems will produce potable water for more than 15,000 Ebeye Island residents. Photo credit: Mass Communication Specialist 2nd Class Tim D. Godbee, U.S. Navy.

variability, including dry seasons and frequent dry years, Pacific islands are highly vulnerable to any climate shifts that reduce rainfall and increase the duration and severity of droughts.

Compounding the direct effects of climate change, such as changing rainfall patterns, are the impacts of sea level rise on groundwater and groundwater-fed surface environments, such as wetlands and open lakes and ponds in low islands. For atoll islands, residents depend on shallow aquifers for some of their domestic water needs and for food production.[57] Rising sea level leads to a higher frequency of overwash events,[58] during which seawater inundates large parts of the islands and contaminates freshwater aquifers, wetlands, and other aquifer-fed environments. Overwash events already periodically occur during unusually high tides as a result of storm-driven waves or because of tsunamis. Rising sea level greatly increases the risk of groundwater contamination when these events occur.

Climate shifts have already been observed in the region, with increases in temperature and changes in rainfall. In Hawai‘i, temperature has risen by 0.76°F over the past 100 years (Figure 27.5),[59] and 2015 and 2016 were the warmest years on record. Higher temperatures increase evaporation, reducing water supply and increasing water demand. Hawai‘i rainfall has been trending downward for decades, with the period since 2008 being particularly dry.[60] These declines have occurred in both the wet and dry seasons and have affected all the major islands (Figure 27.6). In Micronesia, rainfall has generally decreased in the east, remained steady for some islands in the west (for example, Guam), and increased for other islands in the west.[23,32,61,62]

The set of global and regional climate model outputs available for the U.S. Pacific Islands region shows a range of possible future precipitation changes, with implications for economic and policy choices. In Hawai‘i, end-of-century rainfall projections under a higher scenario (RCP8.5) range from small increases to increases of to up to 30% in wet areas, and from small decreases to decreases of up to 60% in dry areas.[34,35]

Using global climate model results for the lower scenario (RCP4.5) (see the Scenario Products section of App. 3), rainfall in Micronesia is projected to become as much as 10% lower to as much as 20% higher than at present within the next several decades, changes that are within the range of natural variability.[63] Changes are projected to be slightly greater by the end of the century but still within the –10% to +20% range for Micronesia.[63] In American Sāmoa, rainfall is projected to increase by up to 10% by mid-century compared with the present, with additional slight increases by the end of the century.

While rainfall in Hawai‘i generally has been decreasing, it is also becoming more extreme.[64,65] Both extreme heavy rainfall events (causing increased runoff, erosion, and flooding) and droughts (causing water shortages) have become more common.[66] The number of consecutive wet days and the number of consecutive dry days are both increasing in Hawai‘i.[66] In American Sāmoa, drought magnitude and duration have minimal decreasing trends.[23]

Hawai‘i Annual Average Temperature Changes

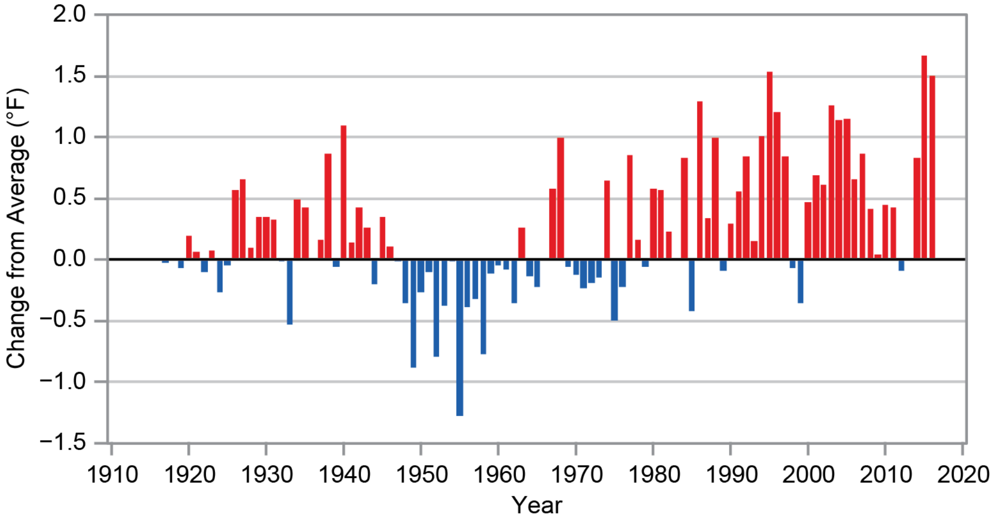


Figure 27.5: In Hawai‘i, annual average temperatures over the past century show a statistically significant warming trend, although both warming and cooling periods occurred. Based on a representative network of weather stations throughout the islands, this figure shows the difference in annual average temperature as compared to the average during 1944–1980 (this period was selected as the baseline because it has the greatest number of index stations available), with red bars showing years with above average temperatures and blue bars showing years with below average temperatures. As temperature continues to rise across the region and cloud cover decreases in some areas, evaporation is expected to increase, causing both reduced water supply and higher water demand. Source: University of Hawai‘i at Mānoa, Department of Geography and Environment.

Hawai‘i Rainfall Trends

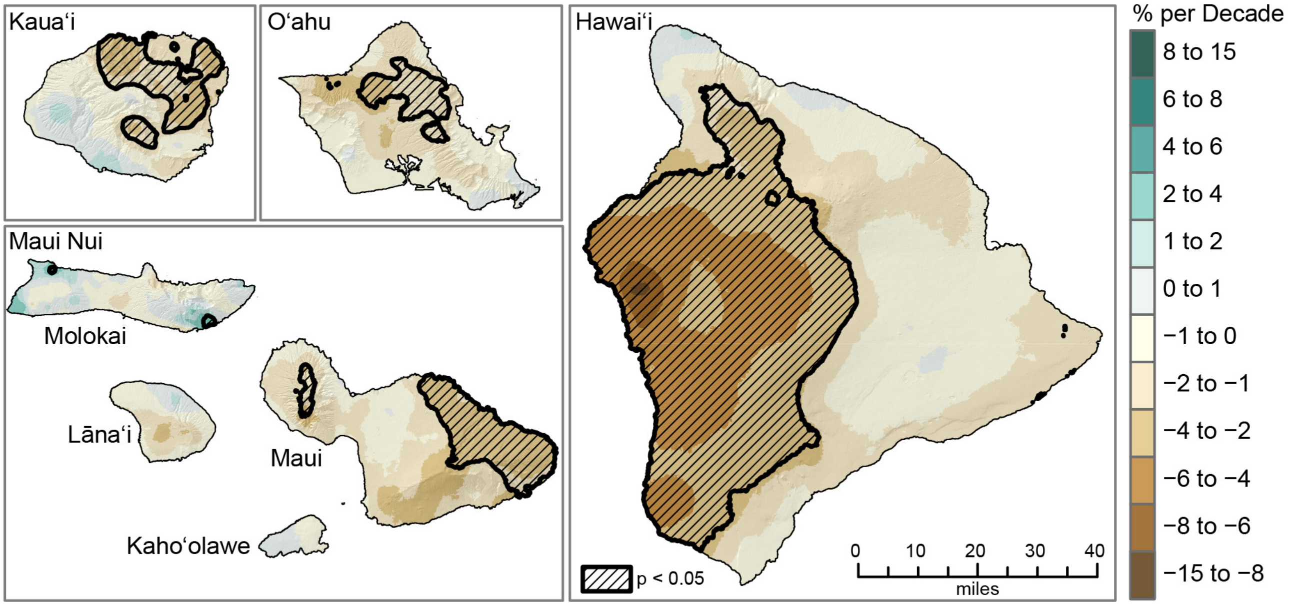


Figure 27.6: The figure shows the changes in annual rainfall (percent per decade) from 1920 to 2012 for the State of Hawai‘i. Statistically significant trends are indicated with black hatching. Almost the entire state has seen rainfall decreases since 1920. The sharpest downward trends are found on the western part of Hawai‘i Island. On other islands, significant decreases have occurred in the wetter areas. Source: adapted from Frazier & Giambelluca 2017.[60] © Royal Meteorological Society.

Higher rates of evaporation can strongly affect water resources by reducing the amount of water available (water supply) and by increasing the amount of water needed for irrigation and outdoor residential uses (water demand). Increasing temperatures throughout the Hawaiʻi–USAPI region and decreased cloud cover in some areas will cause increases in rates of evaporation. These increases will worsen effects of reduced rainfall by further reducing water supply and simultaneously increasing water demand.

Streamflow in Hawaiʻi has declined over approximately the past 100 years, consistent with observed decreases in rainfall.[6] Trends showing low flows becoming lower indicate declining groundwater levels. On islands such as Oʻahu, water supply is mainly derived from groundwater.[67] If these declines continue due to further reductions in rainfall and/or increases in evaporation, groundwater availability will be impaired. Chronic water shortages are possible as rainfall decreases and both evaporation and the water requirements of a growing human population increase.

Given the small land areas and isolation of islands, and the current high level of year-to-year climate variability, even small changes in average climate are likely to cause extreme hardship. In the USAPI, subsistence-based agriculture persists, but the cultural and economic conditions that provided resilience have been eroded by the effects of colonization and globalization.[68] Hence, especially severe impacts of climate shifts are expected in these communities. Decreases in precipitation, together with saltwater contamination of groundwater systems due to sea level rise, threaten water and food security in some locations.[18,69,70]

Adaptation. Impacts and risks from climate change will vary due to differences in hydrological characteristics and the governance and adaptive capacity of each island. To address ongoing and future impacts of these changes, adaptive capacity can be enhanced by enabling individual island communities to identify and prioritize climate-related risks.[71] In Hawaiʻi, adaptation to address water shortages is already taking place through successful water conservation programs (see Case Study "Planning for Climate Impacts on Infrastructure"), watershed protection (Watershed Partnerships), drought planning (Commission on Water Resource Management), and changes in plumbing codes and policies (Fresh Water Initiative) to enhance groundwater recharge and wastewater reuse.[72,73]

In the USAPI, potential adaptation measures include development or improvement of emergency water shortage planning, including portable desalination systems and rapid-response drinking water shipments, although the high costs would prohibit larger desalination plants on most islands and atolls without international aid or other finance mechanisms.[74,75] Island communities can also improve their resilience to water shortages by increasing both rooftop water catchment and storage system capacity and by adopting drought-resistant and salt-tolerant crop varieties.

Throughout the region, the number of climate and water resources monitoring stations has declined,[23,76,77] reducing the ability of researchers to project future changes in climate. Restoring and enhancing monitoring of rainfall, evaporation-related climate variables (net radiation, air temperature, humidity, and wind speed), soil moisture, streamflow, and groundwater levels—critically important information for understanding, planning, and assessing adaptation actions—are prerequisites to building adaptive capacity to address the impacts of climate change on water resources.

Case Study: Planning for Climate Impacts on Infrastructure with the Honolulu Board of Water Supply (BWS)

The City and County of Honolulu Board of Water Supply (BWS) serves approximately one million customers on the island of Oʻahu, Hawaiʻi, with about 145 million gallons per day (mgd) of potable (drinkable) groundwater and 10 mgd of nonpotable water.[78] The municipal system supports a large urban center, but the infrastructure is deteriorating.[78] Following the release of the 2012 Pacific Islands Regional Climate Assessment,[23] the BWS was concerned that changing climate patterns would affect both the quality and quantity of the water supply. Available projections showed increasing air temperature and drought risk,[23,34,35,36,60] reduced aquifer recharge, and coastal erosion that will impact wells and infrastructure.[41]

To proactively increase their capacity to respond and adapt to impacts of climate variability and change, the BWS was already implementing holistic long-term strategies to increase supply and lessen demand, including watershed management, groundwater protection, and a water conservation program. Because of these strategies, from 1990 to 2010, per capita use decreased from 188 to 155 mgd. However, total demand is still projected to increase 5% to 15% by 2040 due in part to population growth, with the most increases in areas of existing high population density.[78]

In 2015, the BWS partnered with researchers and consultants to assess projected climate change impacts on their infrastructure and to identify vulnerabilities over the next 20 to 70 years using a scenario planning approach to consider a range of plausible future climate and socioeconomic conditions. The vulnerability assessment considers extreme heat, coastal erosion, flooding (from wave overwash, sunny-day groundwater rise, and storms), annual and seasonal drought patterns, and changes in groundwater recharge impacts. As a project outcome, the BWS will develop a prioritized set of adaptive actions to minimize the range of climate impacts, including urgent capital improvements and updates to engineering standards.[79]

Key Message 2

Terrestrial Ecosystems, Ecosystem Services, and Biodiversity

Pacific island ecosystems are notable for the high percentage of species found only in the region, and their biodiversity is both an important cultural resource for island people and a source of economic revenue through tourism. Terrestrial habitats and the goods and services they provide are threatened by rising temperatures, changes in rainfall, increased storminess, and land-use change. These changes promote the spread of invasive species and reduce the ability of habitats to support protected species and sustain human communities. Some species are expected to become extinct and others to decline to the point of requiring protection and costly management.

Island landscapes and climates differ dramatically over short distances, producing a wide variety of ecological habitats and profoundly influencing the abundance and distribution of organisms, many of which have evolved to live in very specific environments and in close association with other species. Invasive species, landscape change, habitat alteration, and reduced resilience have resulted in extinctions and diminished ecosystem function (see Ch. 7: Ecosystems, KM 1).

The Hawaiian Islands illustrate the challenges the broader Pacific region is facing. Ninety percent of the terrestrial species native to Hawaiʻi are endemic (unique to the region). New, and potentially invasive, species are arriving much more frequently than in the past.[80,81] Hawaiʻi is home to 31% of the Nation's plants and animals listed as threatened or endangered, and less than half of the landscape on the islands is still dominated by native plants.[82] A similar picture describes most of the USAPI, as well. For example, Guam is well known for the decimation of its birds by the accidental introduction of the brown tree snake.

Nesting seabirds, turtles and seals, and coastal plants in low-lying areas are expected to experience some of the most severe impacts of sea level rise.[83] As detailed in the following section, rising sea levels will both directly inundate areas near shorelines and cause low-lying areas to flood due to the upward displacement of shallow aquifers. Rising sea levels also increase the tendency of large waves to wash inland and flood areas with saltwater, making the soil unsuitable for many plants and contaminating the underlying aquifer so that the water is not fit for drinking or crop irrigation.

Atolls are projected to be inundated, impacting existing on-island ecosystems.[18] Atoll communities that depend on subsistence agriculture already experience loss of arable land for food crops such as taro and breadfruit,[70] along with the degradation of aquifers from sea level variability and extreme weather. Without dramatic adaptation steps, the challenges of sea level rise will likely make it impossible for some atolls to support permanent human residence. Wildlife that relies on coastal habitats will likely also be severely impacted. More than half of the global populations of several seabird species nest in the atolls and low islands of Northwestern Hawaiian Islands. In addition to the direct impact from the loss and degradation of habitat, Key Message 4 describes how these species are at risk from changes in prey availability and increasing land surface temperatures.[84]

On many Pacific islands, native mangroves are highly productive coastal resources that provide a number of ecosystem services, including storm protection and food and building materials for Indigenous and local communities. Mangroves also serve as fish nursery areas, trap land-based sediment that would otherwise flow to coral reefs,[85] and provide habitat for many species. They are important reservoirs of organic carbon, providing yet another ecosystem service.[86] Mangroves are already under threat from coastal development and logging. Climate change, particularly sea level rise, will likely add additional stress.[87,88]

The planning and economic implications for biodiversity management are substantial. The main islands of Hawaiʻi have more than 1,000 native plant species,[89] and many of these are vulnerable to future climate shifts. Projections under a higher scenario (RCP 8.5) suggest that by the end of the century, the current distributions of more than 350 native species will no longer be in their optimal growing climate range.[90] For example, 18 of 29 native species studied within Hawaiʻi Volcanoes National Park are projected to shrink in range, such that most of the high-priority areas managed to protect biodiversity are projected to lose a majority of the studied native species.[91] Approximately $2 million is spent annually to manage these areas (dollar year not reported),[92] so climate-driven changes in plant distribution would have significant consequences on the allocation of funds. A global analysis suggests that the displacement of native species would provide increased opportunities for the establishment and spread of invasive species and that biodiversity would decrease as a result.[93,94]

Throughout the Pacific, climate change will likely alter ecosystem services provided by agroforestry (the intentional integration of trees and shrubs into crop and animal farming systems to create environmental, economic, and social benefits). In American Sāmoa, the Republic of the Marshall Islands, and the Federated States of Micronesia, upland or inland forest services include substantial acreage in mixed agroforests (forests with various trees, lower shrubs, and row crops used for food, building, and cultural practices).[95,96] Agroforest production is impacted by drought, flooding, soil and water salinization (increased salt content in low-lying areas), wind, disease, pests, and clearing for development.[70] Climate change is projected to exacerbate these impacts in complex patterns related to the stressors present in specific locations.

Increases in air temperature are projected to have severe negative impacts on the range of Hawaiian forest birds. Avian malaria currently threatens this iconic fauna except at high elevations, where lower temperatures prevent its spread. However, as temperatures rise, these high-elevation sites will become more suitable for malaria. Model projections suggest that even under moderate warming, 10 of 21 existing forest bird species across the state will lose more than 50% of their range by 2100 (Figure 27.7). Of those, 3 are expected to lose their entire ranges and 3 others are expected to lose more than 90% of their ranges,[43,97] making them of high concern for extinction.

Hawaiian Forest Bird Species

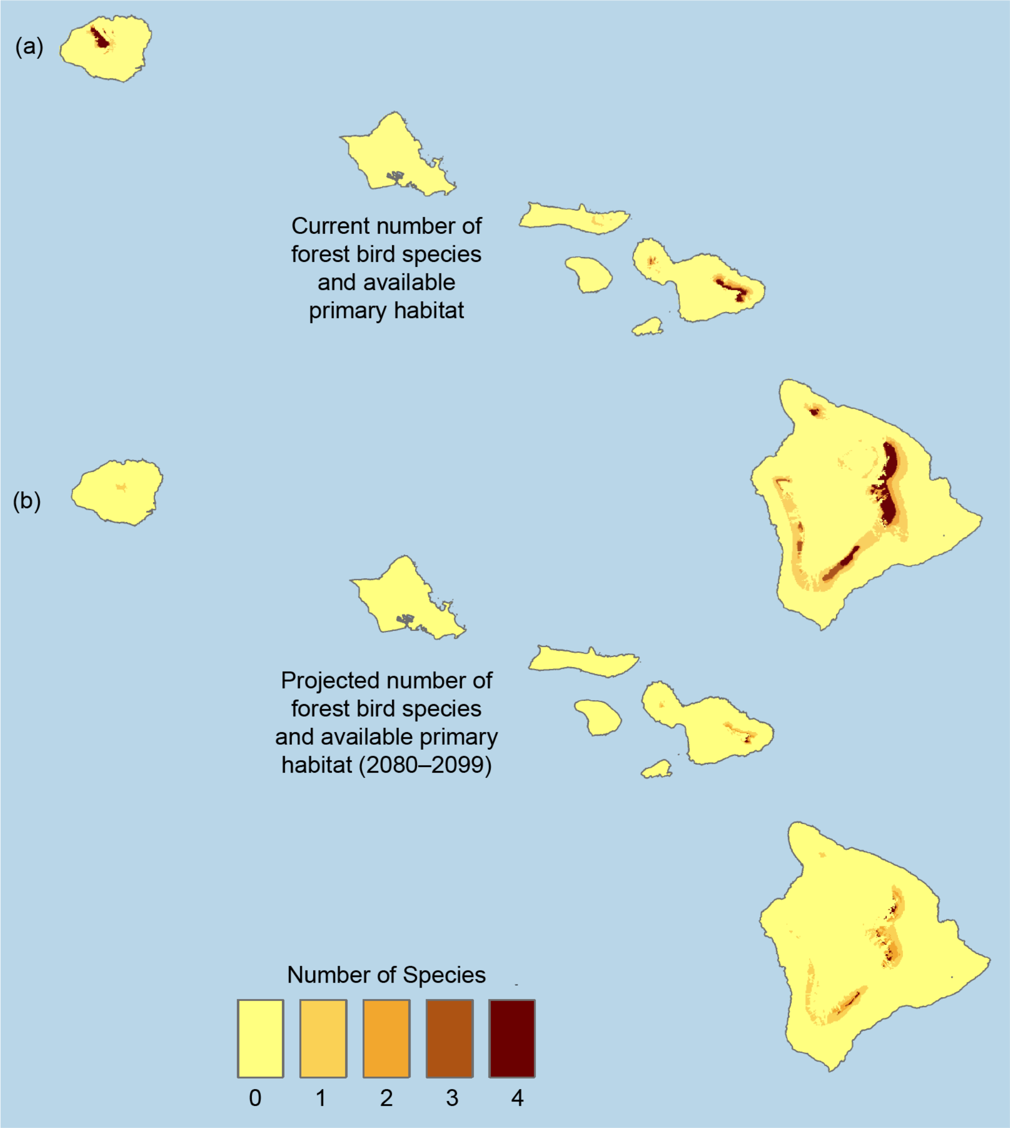


Figure 27.7: The figure shows the number of native Hawaiian forest bird species based on model results for (a) current and (b) future climate conditions. The future conditions are for the year 2100 using the middle-of-the-road scenario (SRES A1B). These projections include 10 species that represent the most rare and endangered native forest birds in Hawaiʻi. The number of these species and their available habitat are projected to be drastically reduced by 2100. Sources: adapted from Fortini et al. 2015[43] (CC BY 4.0).

Streams on U.S. Pacific Islands are also home to native fauna that are unique and typically restricted to specific island groups such as the Mariana, Sāmoan, and Hawaiian archipelagos. A model of streamflow and habitat on the Island of Maui suggests that physical habitat for stream animals will decrease by as much as 26% in some streams under a higher scenario (RCP8.5), but the overall forecast is for habitat changes of less than 5% by 2100.[98] Throughout Hawaiʻi, elevated stream water temperatures from urbanization and a warming climate will likely reduce available habitat for temperature-sensitive species. Additionally, the larvae of native Hawaiian stream animals develop in the ocean, and exposure to ocean acidification puts them at risk of physiochemical changes resulting in lower reproductive success.[99]

Adaptation. Adapting to the impacts of climate change on terrestrial ecosystems is challenging. Management measures can take years to design and fund. Currently, understanding specific impacts of climate change on a particular ecosystem is confounded by other stressors (such as land development and invasive species) and clouded by a lack of precision in forecasting how sea level, rainfall, and air temperatures will change at the ecosystem or habitat level. A recent report summarizes both vulnerabilities and potential adaptations across all Hawaiian Islands and ecosystem types.[100] Through research and collaboration with Indigenous communities and land managers, ecosystem resilience to climate change can be enhanced and the most severe climate change effects on biodiversity decreased.[101] Many Pacific island communities view the protection and management of native biodiversity as ways to reduce climate change impacts. For example, a watershed model of the windward side of Hawaiʻi Island suggested that control of an invasive tree with high water demand would partially offset decreases in streamflow that might be caused by a drier climate.[44] In another example, resource managers are now keenly aware that climate change represents a serious long-term threat to Hawaiian forest birds. As a result, discussions involving multiple federal, state, and nongovernmental organization stakeholders are underway regarding a range of management responses, such as shifting protected areas, landscape-level control of avian malaria, and captive breeding and propagation. Some of these discussions are focused on adaptation to many aspects of climate change, whereas others address the broad range of threats to Hawaiian forest birds. Preparedness and planning can strengthen the resilience of native species and ecosystems to drought, wildfire, and storm damage, which will help them to avoid extinction due to climate change.

Key Message 3

Coastal Communities and Systems

The majority of Pacific island communities are confined to a narrow band of land within a few feet of sea level. Sea level rise is now beginning to threaten critical assets such as ecosystems, cultural sites and practices, economies, housing and energy, transportation, and other forms of infrastructure. By 2100, increases of 1–4 feet in global sea level are very likely, with even higher levels than the global average in the U.S.-Affiliated Pacific Islands. This would threaten the food and freshwater supply of Pacific island populations and jeopardize their continued sustainability and resilience. As sea level rise is projected to accelerate strongly after mid-century, adaptation strategies that are implemented sooner can better prepare communities and infrastructure for the most severe impacts.

The rate of global average sea level rise has accelerated[102,103] and has become very damaging in the region (Figure 27.8). Impacts include coastal erosion,[7,8] episodic flooding,[9,10] permanent inundation,[11] heightened exposure to marine hazards,[12] and saltwater intrusion to surface water and groundwater systems.[13,14] Already apparent on many shorelines, these problems endanger human communities by negatively impacting basic societal needs, such as food and freshwater availability, housing, energy and transportation infrastructure, and access to government services.[104]

Sea level could rise by as much as 1 foot by 2050 and by as much as 4 feet by 2100. Emerging science suggests that, for the Extreme sea level rise scenario, sea level rise of more than 8 feet by 2100 is physically possible. It is extremely likely that sea level rise will continue beyond 2100.[17,105]

Communities in Hawaiʻi and the USAPI typically live in low-lying settings clustered around the coastal zone. Whether on high volcanic islands or low reef islands (atolls), exposure to marine hazards and dependency on global trade mean escalating vulnerability to climate change (Ch. 16: International, KM 1).[18]

Roadways Flood Periodically on Oʻahu

Figure 27.8: The photo shows North Shore, Oʻahu, in the winter of 2016. Episodic flooding in the Pacific Islands will increase as sea level rises. Photo credit: Steven Businger.

Until recently, global sea level rise of about 3 feet by the end of the century was considered a worst-case scenario, becoming more likely without reductions in global greenhouse gas emissions.[106] However, new understanding about melting in Antarctica,[107,108,109] Greenland,[110] and alpine ice systems;[111] the rate of ocean heating;[112,113] and historical sea level trends[103] indicates that it is physically possible to see more than double this amount this century (see Ch. 2: Climate, KM 4).[17,114]

The Intermediate sea level rise scenario predicts up to 3.2 feet of global sea level rise by 2100; however, recent observations and projections suggest that this magnitude of sea level rise is possible as early as 2060 in a worst-case scenario.[17] Studies in Hawai‘i show that the value of all structures and land projected to be flooded by 3.2 feet of sea level rise amounts to more than $19 billion (in 2013 dollars; $19.6 billion in 2015 dollars) statewide (Figure 27.9).[42] Across the state, nearly 550 Hawaiian cultural sites would be flooded or eroded, 38 miles of major roads would be chronically flooded, and more than 6,500 structures and 25,800 acres of land located near the shoreline would be unusable or lost, resulting in approximately 20,000 displaced residents in need of homes.[42]

Potential Economic Loss from Sea Level Rise, O‘ahu, Hawai‘i

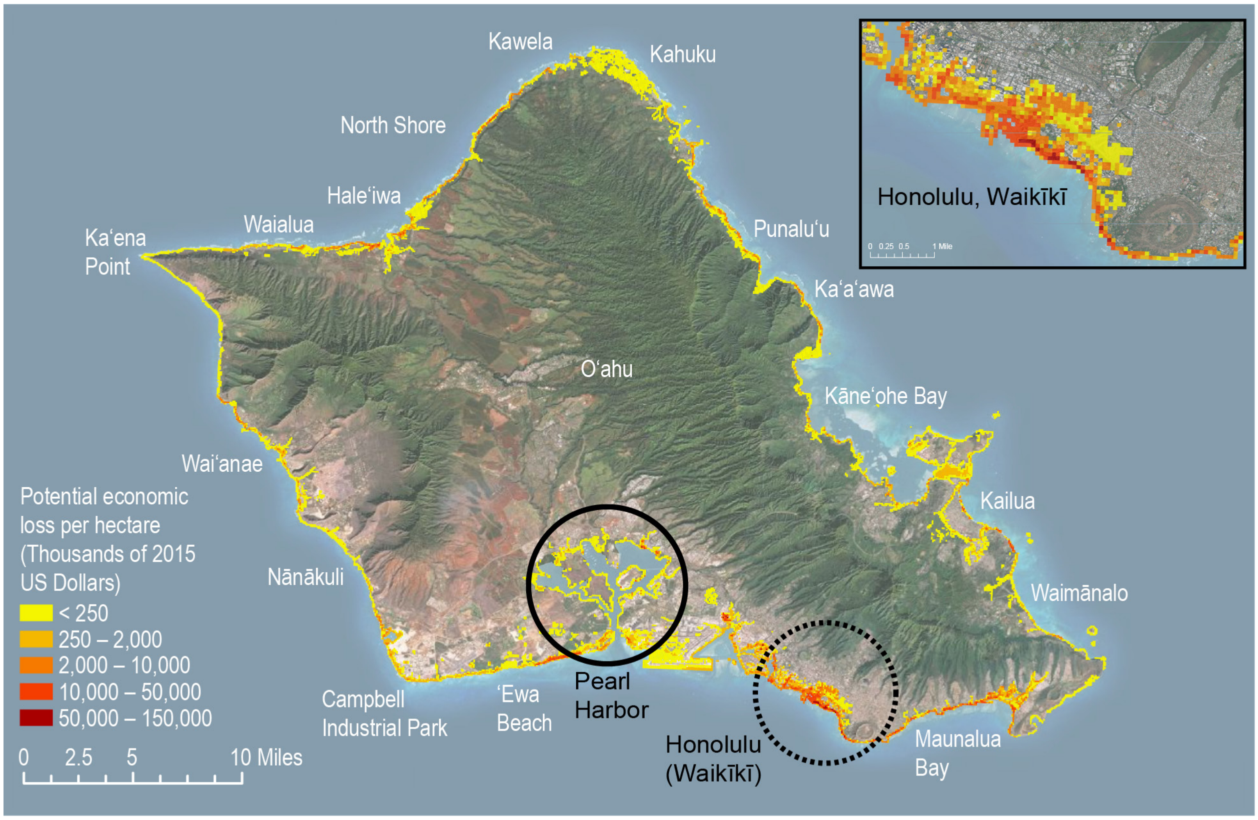


Figure 27.9: This map highlights potential economic losses (in 2015 dollars) in the exposure area associated with 3.2 feet of sea level rise on the island of O‘ahu, Hawai‘i. Potential economic losses are estimated from impacts to land and residential and commercial infrastructure. Highly impacted areas at risk of large economic losses include the U.S. Pacific Command and military infrastructure concentrated in Pearl Harbor (black circle) and the vulnerable tourist areas surrounding Waikīkī (dashed black circle). Source: adapted by Tetra Tech Inc. from the Hawai‘i Climate Change Mitigation and Adaptation Commission 2017.[42]

Owing to global gravitational effects, sea level rise will disproportionately affect the tropical Pacific[15] and potentially exceed the global average.[16] This, plus sea level variability internal to the Pacific Basin (see Figure 27.3), means that parts of the region are likely to experience the highest rates of sea level rise on the planet.[115] Scientific understanding of the timing and magnitude of future global sea level rise continues to improve,[116,117] making regular updates of management plans and engineering codes an important activity for island communities.

Because of accelerating sea level rise, coastal communities are projected to experience saltwater intrusion of aquifers and agricultural resources. As sea level rise continues in coming decades, freshwater sources will become increasingly at risk in communities dependent on restricted groundwater supplies.[69] Saltwater intrusion, which is amplified by climate variability and changing precipitation patterns (see Key Message 1),[12] is difficult to prevent, and, once damaged, water and food resources are challenging to restore.[13]

Future changes in global and regional precipitation vary among current climate models,[34,35,118] but the potential for changes in precipitation and the projected impacts of saltwater intrusion cast uncertainty over the sustainability of freshwater resources throughout the region. Because many island groups are very isolated, severe drought punctuated by saltwater intrusion can displace communities and produce feedback effects, such as failure of cultural, health, education, and economic systems (Ch. 17: Complex Systems).[119] However, strategic planning for the inevitability of these events can greatly reduce their impact.

In many areas, Pacific island coastal populations already exist on the edge of sustainability. Urban areas typically cluster around port facilities, as nearly all Pacific communities are tied to goods and services delivered by cargo ships. As the world’s most isolated chain of islands, Hawai‘i imports nearly 90% of its food at a cost of more than $3 billion per year (in 2004–2005 dollars),[120] resulting in government programs focused on food security.[121] Without adaptation measures, the additional stress on sustainable practices related to sea level rise is likely to drive islanders to leave the region and make new homes in less threatened locations (see Key Message 6 and Case Study “Bridging Climate Science and Traditional Culture”).[122]

Away from urban areas, many island communities rely on food gathered from the ocean and land. Populations on remote reef islands throughout Micronesia depend on water, food, and medical assistance that are often in question and are a source of persistent community stress. Extreme water levels accompanied by high waves have swept over remote atoll communities and destroyed taro patches, contaminated fragile aquifer systems, and deeply eroded island shores.[9,10,58]

In 2007, extreme tides coupled with high waves flooded the Federated States of Micronesia and triggered a national emergency. Food, water, and medical supplies had to be immediately delivered to dozens of communities in widely distributed locations to prevent famine (see Key Message 1) (see also Ch. 14: Human Health, KM 1).[57] It is likely that events of this type will increase in frequency as sea level rise accelerates in the future.

Rising sea surface temperatures are shifting the location of fisheries (Ch. 9: Oceans, KM 2).[123] Ocean warming [124] and acidification,[125,126] coupled with damaging watershed[127] and reef practices,[128] converge on island shores to increasingly limit the food resources that can be gathered from the sea (see Key Message 4).[129] Growing exposure to coastal hazards, such as storm surges,[130] compounds this threat to sustainability.

The Pacific Ocean is highly variable; fundamental characteristics of ENSO (see Box 27.1) appear to be changing.[131] Both El Niño and La Niña episodes are projected to increase in frequency and magnitude as the world warms.[3,52] Patterns of variability are complex,[132,133] and as climate changes over the long term, the oceanic and atmospheric forces that cause shorter-term climate variability (such as ENSO) also will be changing. Model projections indicate changing future wave conditions that will vary in complex ways spatially, by season, and with shoreline exposure and orientation.[37,38,134] These changes will challenge community efforts to define adaptation plans and policies.

The 2015–2016 El Niño was a Pacific-wide event with widespread impacts.[135] As warm water shifted from west to east, Palau, Yap, and other western Pacific communities experienced deep drought, requiring water rationing, as well as falling sea level that exposed shallow coral reefs.[136] In the central Pacific, Hawaiʻi experienced 11 days of record-setting rainfall that produced severe urban flooding,[137] while American Sāmoa faced long-term dry conditions punctuated by episodic rain events. Honolulu experienced 24 days of record-setting heat that compelled the local energy utility to issue emergency public service announcements to curtail escalating air conditioning use that threatened the electrical grid (Ch. 4: Energy, KM 1).[138] Nine months of drought stressed local food production, and a record tropical cyclone season saw Hawaiʻi monitoring three simultaneous hurricanes at one point.[139]

There is great uncertainty about how Pacific variability occurring on shorter timescales (for example, El Niño and La Niña) will combine with multidecadal changes in temperature, waves, rainfall, and other physical factors. This variability affects sea level extremes, which are likely to become more frequent this century,[4,12] along with changes in precipitation,[140] ocean temperature,[113] and winds.[141] These, in turn, drive difficult-to-forecast stressors that challenge the sustainability of coastal communities.

To date, tropical cyclone frequency and intensity have not been observed to change in the region of the USAPI. Trade winds and monsoon wind characteristics are expected to change in the future, but projections for specific geographic locations are unclear.[142] Under scenarios with more warming (for example, SRES A1B),[143] wind speeds are projected to decrease in the western Pacific and increase in the South Pacific;[142] central Pacific tropical cyclone frequency and intensity are expected to increase;[40,142] and in the western and South Pacific, tropical cyclone frequency is projected to decrease, while cyclone intensity is projected to increase.[142] Combined with continued accelerations in sea level rise, storm surge associated with a tropical cyclone has the potential to deliver a profound shock to a community beyond any ability to meaningfully recover.

Adaptation. Despite these threats, many Pacific communities are growing more resilient with renewed focus on conservation,[144] sustainably managing natural resources,[145] adapting to climate change,[146] and building more resilient systems.[147] Pacific island governments are taking steps to anticipate marine flooding (securing food and water resources) and doing so in the context of environmental conservation. Islanders throughout the USAPI are committing to demonstrate climate leadership, identifying sector vulnerabilities, and calling on their international partners to support their implementation of climate change resilience and adaptation actions.[55,148,149,150,151,152]

Key Message 4

Oceans and Marine Resources

Fisheries, coral reefs, and the livelihoods they support are threatened by higher ocean temperatures and ocean acidification. Widespread coral reef bleaching and mortality have been occurring more frequently, and by mid-century these events are projected to occur annually, especially if current trends in emissions continue. Bleaching and acidification will result in loss of reef structure, leading to lower fisheries yields and loss of coastal protection and habitat. Declines in oceanic fishery productivity of up to 15% and 50% of current levels are projected by mid-century and 2100, respectively, under the higher scenario (RCP8.5).

The ocean around Hawai‘i and the USAPI supports highly diverse marine ecosystems that provide critical ecosystem services.[123] Coral reef ecosystems are vitally important for local subsistence, tourism, and coastal protection. The pelagic (open ocean) ecosystem supports protected species, including sea turtles, sea birds, and marine mammals, as well as economically valuable fisheries for tunas and other pelagic fishes. In Hawai‘i, for example, coral reefs inject an estimated $364 million in goods and services annually (in 2001 dollars) into the local economy,[19] while the landings from the pelagic longline fisheries are worth over $100 million annually (in 2012–2013 dollars).[153]

Climate change is already being observed in the Pacific Ocean. Sea surface temperatures and ocean pH, an indicator of acidity, are now beyond levels seen in the instrument record.[154] Additionally, oxygen levels in the subtropical Pacific have been declining over the past five decades, negatively impacting fishes that draw oxygen from the water.[155] Impacts from sea level rise on coastal habitats and infrastructure have already occurred in the region, and the rate of sea level rise is projected to accelerate (see Key Message 3).

Widespread coral bleaching and mortality occurred during the summers of 2014 and 2015 in Hawai‘i and during 2013, 2014, and 2016 in Guam and the Commonwealth of the Northern Mariana Islands. Impacts varied by location and species, but the 2015 bleaching event resulted in an average mortality of 50% of the coral cover in western Hawai‘i.[45] Coral losses exceeded 90% at the remote and pristine equatorial reef of Jarvis Island.[156]In response to the prolonged and widespread bleaching, the State of Hawai‘i convened an expert working group to generate management recommendations to promote reef recovery.[157]

Under projected warming of approximately 0.5°F per decade, coral reefs will experience annual bleaching beginning in about 2035 in the Mariana Archipelago, in about 2040 in American Sāmoa and the Hawaiian Islands, and in about 2045 at other equatorial reefs (Figure 27.10).[46] Warming reductions on the order of the aims of the 2015 Paris Agreement are projected to delay the onset of annual severe bleaching by 11 years on average.[46] Because some coral species are more resilient to thermal stress than others, low levels of thermal stress are expected to only alter the types of corals present. However, at high levels of thermal stress, most coral species experience some bleaching and mortality.[158] Ocean acidification reduces the ability of corals to build and maintain reefs,[125,159] while land-based nutrient input can substantially exacerbate acidification and reef erosion.[160] Under the higher scenario (RCP8.5), by the end of the century, virtually all coral reefs are projected to experience an ocean acidification level that will severely compromise their ability to grow.[125,161] Loss of coral reef structure results in a decline in fish abundance and biodiversity, negatively impacting tourism, fisheries, and coastal protection.[123] In the Hawaiian Archipelago under the higher scenario (RCP8.5), coral reef cover is projected to decline from the present level of 38% to 11% in 2050 and to less than 1% by the end of the century. This coral reef loss is projected to result in a total economic loss of $1.3 billion per year in 2050 (in 2015 dollars, undiscounted) and $1.9 billion per year in 2090 (in 2015 dollars, undiscounted). In 2090, the lower scenario (RCP4.5) would avoid 16% of coral cover loss and $470 million in damages per year (in 2015 dollars, undiscounted) compared to the higher scenario (RCP8.5).[162] In the central and western Pacific, coral reef cover is projected to decline by 2050 from a present-day average of 40% to 10%–20%, and coral reef fish production is expected to decline by 20% under a high emissions scenario (SRES A2).[123] Declines in maximum catch potential exceeding 50% from late-20th century levels under the higher scenario are projected by 2100 for the exclusive economic zones (EEZs) of most islands in the central and western Pacific.[163] A key uncertainty is the extent to which corals can develop resilience to the rapidly changing ocean conditions.[164,165] Changing ocean temperature and acidification will impact many other organisms that will likely alter the functioning of marine ecosystems.

Projected Onset of Annual Severe Coral Reef Bleaching

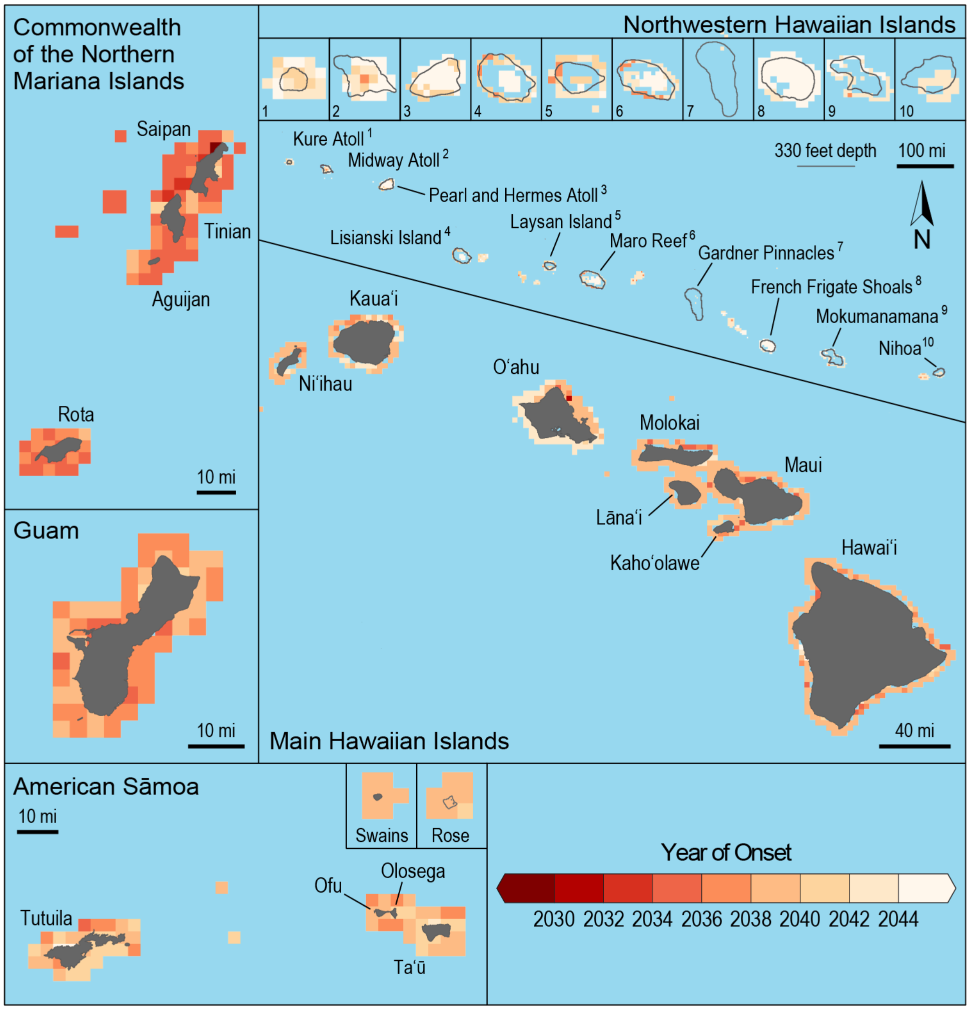


Figure 27.10: The figure shows the years when severe coral bleaching is projected to occur annually in the Hawai‘i and U.S.-Affiliated Pacific Islands region under a higher scenario (RCP8.5). Darker colors indicate earlier projected onset of coral bleaching. Under projected warming of approximately 0.5°F per decade, all nearshore coral reefs in the region will experience annual bleaching before 2050. Source: NOAA.

Mangroves provide coastal protection and nursery habitat for fishes and, in some cases, protect coral reefs from sediment and enhance the density of coral reef fishes.[166] Sea level rise has caused the loss of mangrove areas at sites in American Sāmoa[87] and is projected to further reduce mangrove area in the Pacific Islands region by 2100.[87,88]

In the open ocean, warming is projected to reduce the mixing of deep nutrients into the surface zone. Under the higher scenario (RCP8.5), increasing temperatures and declining nutrients are projected to reduce tuna and billfish species' richness and abundance in the central and western Pacific Ocean, resulting in declines in maximum fisheries yields by 2%–5% per decade.[129,167,168,169] Climate change is also projected to result in overall smaller fish sizes, further adding to the fishing impact (Ch. 9: Oceans, KM 2).[170]

Tuna habitat in the equatorial region is projected to shift eastward with changing temperatures, so that by the end of the century the availability of skipjack tuna within the EEZs of Micronesian countries will likely be 10%–40% lower than current levels.[123]

On low-lying islands and atolls, sea level rise is projected to result in the loss of resting and nesting habitat for sea birds and sea turtles and the loss of beach and pupping habitat for Hawaiian monk seals. Modeling exercises that take wave height into account project much greater habitat flooding than sea level rise alone would suggest.[18,38,171] For example, sea level rise of about 6 feet combined with both storm wave run-up and concurrent groundwater rise is projected to wash out 60% of the albatross nests across the U.S. Marine National Monuments each breeding season.[83]

Adaptation. Management actions that remove other stressors on corals (such as those recommended in Hawai‘i, Guam, and the Commonwealth of the Northern Mariana Islands after the recent bleaching events) have been proposed as strategies to enhance the resilience of corals to moderate levels of thermal stress and to aid their recovery.[157] However, experience from the 2016 extreme bleaching on the Great Barrier Reef found that water quality and fishing pressure had minimal effect on the unprecedented bleaching, suggesting that local reef protection measures afford little or no defense against extreme heat.[158] This suggests that more active intervention is necessary, such as incorporating assisted evolution and selectively breeding corals, to enhance their resilience to rapidly rising ocean temperatures and acidification,[172] as is being tested in Hawai‘i. In the case of the pelagic ecosystem, fishing and climate change work together to reduce the abundance of tunas and billfishes targeted by the fishery.[170,173] Thus, an ecosystem-based approach to international management of open ocean fisheries in the Pacific that incorporates climate-informed catch limits is expected to produce more realistic future harvest levels and enhance ecosystem resilience.[20] Lastly, relocations of seabirds to nesting sites on higher islands have been proposed to mitigate lost nesting habitat on low-lying islands and atolls.[83]

Key Message 5

Indigenous Communities and Knowledge

Indigenous peoples of the Pacific are threatened by rising sea levels, diminishing freshwater availability, and shifting ecosystem services. These changes imperil communities' health, well-being, and modern livelihoods, as well as their familial relationships with lands, territories, and resources. Built on observations of climatic changes over time, the transmission and protection of traditional knowledge and practices, especially via the central role played by Indigenous women, are intergenerational, place-based, localized, and vital for ongoing adaptation and survival.

Indigenous communities of the Pacific have an inseparable connection to and derive their sense of identity from the lands, territories, and resources of their islands. This connection is traditionally documented in genealogical chants and stories transmitted through oral history.[146] The rich cultural heritage of Pacific island communities comprises spiritual, relational, and ancestral interconnectedness with the environment[174] and provides land security, water and energy security, livelihood security, habitat security,[175] and cultural food security.[176] Climate change threatens this familial relationship with ancestral resources[177] and is disrupting the continuity that is required for the health and well-being of these communities (this experience is common to many tribal and Indigenous communities across the United States) (see Ch. 15: Tribes, KM 2).[176,177]

Sea level rise imperils Indigenous communities of the Pacific. The sea that surrounds Pacific island communities continues to rise at a rate faster than the global average,[115] with documented impacts on agriculture, coastal infrastructure, food security, livelihoods, and disaster management in the Republic of Palau[149] and the Republic of the Marshall Islands.[147]

In Hawai‘i, sea level rise impacts on traditional and customary practices (including fishpond maintenance, cultivation of salt, and gathering from the nearshore fisheries) have been observed (Figure 27.11).[177] Since 2014, Indigenous practitioners have had limited access to the land where salt is traditionally cultivated and harvested due to flooding and sea level rise. Detachment from traditional lands has a negative effect on the spiritual and mental health of the people (Ch. 14: Human Health, KM 1; Ch. 15 Tribes, KM 2).[176]

Salt Cultivation on Kaua‘i

Figure 27.11: Flooding on the island of Kaua‘i, Hawai‘i, impacts the cultural practice of pa‘akai (salt) cultivation. Photo credit: Malia Nobrega-Olivera.

Case Study: Bridging Climate Science and Traditional Culture

To identify adaptive management strategies for Molokai's loko iʻa (fishponds) built in the 15th century, the nonprofit Ka Honua Momona's fishpond restoration project gathered Hawaiʻi's climate scientists, Molokai's traditional fishpond managers, and other resource managers to share knowledge from different knowledge systems (Figure 27.12). Loko iʻa are unique and efficient forms of aquaculture that cultivate pua (baby fish) and support the natural migration patterns over the life of the fish. The lens of the ahupuaʻa (the watershed, extending from the uplands to the sea) was an important framework for this project. Sea level rise, surface water runoff, and saltwater intrusion into the freshwater springs are a few of the climate change impacts to which fishponds are vulnerable.[177] A key outcome of creating this collaborative model was strengthening relationships between diverse groups of people committed to responding to ecosystem changes and protecting cultural and natural resources.

Preparing Molokai's Fishponds for Climate Change

Figure 27.12: Ka Honua Momona hosted Molokai's loko iʻa managers, Hawaiʻi's climate scientists, and other resource managers in April 2015. Photo credit: Hauʻoli Waiau.

Ocean acidification and drought, in combination with pollution and development, are negatively affecting fisheries and ecosystems (which are drivers of tourism), directly impacting the livelihood security of Pacific communities. For example, across all Pacific island countries and territories, industrial tuna fisheries account for half of all exports, 25,000 jobs, and 11% of economic production.[178] In Hawaiʻi, between 2011 and 2015, an annual average of 37,386 Native Hawaiians worked in tourism-intensive industries; based on the 2013 U.S. census, this number represents 12.5% of the Native Hawaiian population residing in Hawaiʻi.

Climate change is impacting subsistence[18,70,95,123,175] and cultural food security[70,176] of Pacific island communities. Subsistence food security is essential for the survival of Indigenous peoples of the world and is valued socially, culturally, and spiritually.[175] Cultural food security refers to the provision of food that is a necessary part of a community's regular diet and sustains the connection with cultural and social practices and traditions.[176] Taro and fish are two examples of cultural foods important to the livelihoods of Pacific island communities and to economic development for the community and government.[123]

In Hawaiʻi, climate change impacts, such as reduced streamflow, sea level rise, saltwater intrusion, and long periods of drought, threaten the ongoing cultivation of taro and other traditional crops.[177] Identifying and developing climate-resilient taro and other crops are critical for their continued existence.[179] In Yap, taro is a key element of the diet. Groundwater salinization has resulted in smaller corms (underground tubers), causing declines in harvest yield.[180] In American Sāmoa, the Republic of the Marshall Islands, and the Federated States of Micronesia, crops grown in mixed agroforests provide important sources of nutrition, meet subsistence needs, supplement household incomes through sales at local farmers' markets, and support commercial production.[95,96] These crops include breadfruit, mango, and coconut as overstory components; citrus, coffee, cacao, kava, and betel nut as perennial components; and banana, yams, and taro. Climate change is expected to result in changes in farming methods and cultivars (Figure 27.13). Consequently, these changes will likely impact the relationship between communities and the land. These kinds of climate impacts lead to an increased dependence on imported food that is of little nutritional value.[181] This is a public health concern for Hawaiʻi and the USAPI, as Indigenous Pacific Islanders have the highest rates of obesity and chronic diseases, such as diabetes, in the region.[182]

The rich body of traditional knowledge is place-based and localized[21] and is useful in adaptation because it builds on intergenerational sharing of observations[22] of changes in climate-related weather patterns, ocean phenomena, and phenology (the study of cyclic and seasonal natural phenomena, especially in relation to climate and plant and animal life). These observations, gathered over millennia, are useful in defining baselines and informing adaptive strategies.[183] Indigenous cultures are resilient, and their resilience has empowered Pacific island communities to survive several millennia on islands.[180] These communities have survived extreme events and responded to change through adaptive mechanisms based on traditional knowledge that has evolved over many generations.[184]

Women play a vital role in ensuring that adaptation planning and action in the Pacific draw on traditional knowledge and new technologies.[184] The role of women in Indigenous communities includes maintaining crop diversity as collectors, savers, and managers of seeds and thus enhancing livelihood security for the community.[185] Indigenous women are also central in teaching, practicing, protecting, and transmitting traditional knowledge and practices.[185] Women have also been identified as a more vulnerable population to regional climate risks due to the role they have in terms of economic activities, safety, health, and their livelihoods.[147] For example, in Palau, as in the broader region, the central role of Indigenous women as lead project participants is key to the success of any project.

In Pacific island cultures, lunar calendars are tools used to identify baselines of an environment, track changes (kilo, in Hawaiian), and

Crop Trials of Salt-Tolerant Taro Varieties

Figure 27.13: Taro trials are underway in Palau, with results so far indicating that three varieties have tolerance to saltwater. Photo credit: Malia Nobrega-Olivera.

record seasonality, migration patterns, and weather.[183] In Hawai‘i, use of the traditional lunar calendar (kaulana mahina) and kilo in climate change adaptation assists communities with decision-making that allows for the best survival techniques.[183] In Mo‘omomi, Molokai, an intact coastal sand dune ecosystem in the main Hawaiian Islands, kaulana mahina has proven to be a useful tool that has enhanced the resilience of this coastline.[186,187] Similarly, a calendar for traditional Marshallese agroforestry crops recently was adapted to account for ENSO and climate conditions (see Figure 27.14).[188]

Emerging issues for Indigenous communities of the Pacific include the resilience of marine-managed areas and climate-induced human migration from their traditional lands, territories, and resources. Marine-managed areas, such as those designated under the Micronesia Challenge and the Papahānaumokuākea Marine National Monument in Hawai‘i, demonstrate a commitment by multiple partners to conserve marine resources. Over time, monitoring the ability of Indigenous peoples to continue to experience kinship and maintain traditional practices can help to preserve the cultural heritage associated with these protected areas. Documenting the kinds of governance structures or decision-making hierarchies created for their management can serve as a learning tool that can be shared with other island communities.

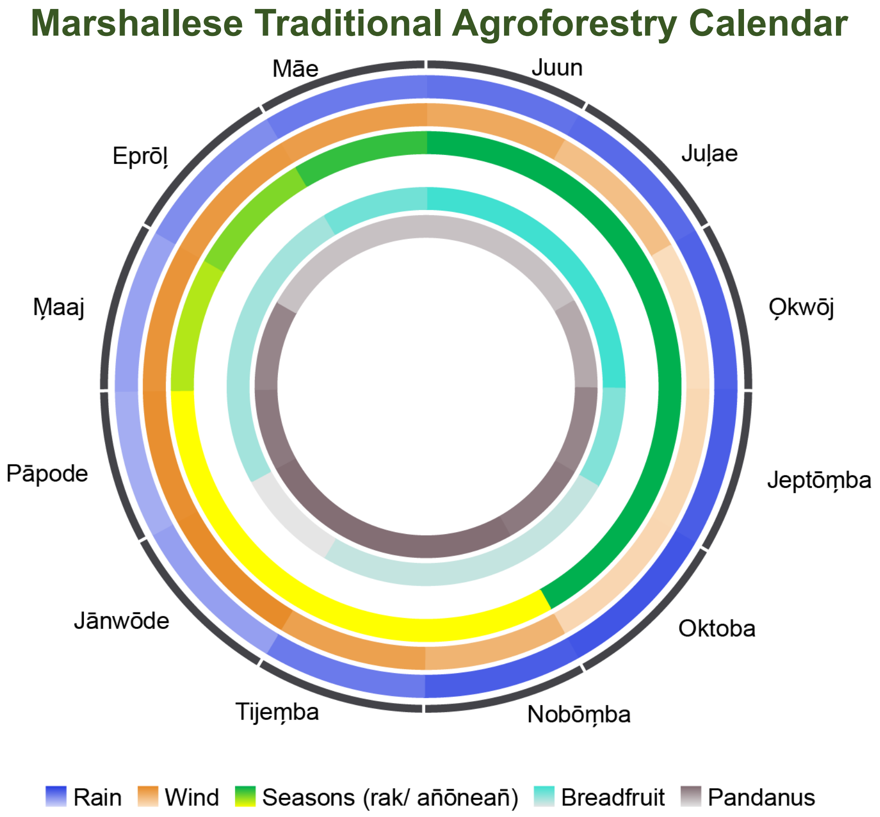


Figure 27.14: The Marshallese Traditional Agroforestry Calendar combines climate data and traditional season designations and knowledge about the harvest times of perennial crops throughout the year. Months are displayed in Marshallese on the outer ring, while inner rings show how wind and rain patterns and the harvest of two crops typically change throughout the year. The color gradients show the intensity of the harvest or the climate variable, with more intense colors representing larger amounts harvested or higher amounts of rain, for example, at various times. A web-based tool offers two versions, depending on the status of ENSO conditions. Source: adapted by Victor Garcia, Jr., from Friday et al. 2017.[188]

Key Message 6

Cumulative Impacts and Adaptation

Climate change impacts in the Pacific Islands are expected to amplify existing risks and lead to compounding economic, environmental, social, and cultural costs. In some locations, climate change impacts on ecological and social systems are projected to result in severe disruptions to livelihoods that increase the risk of human conflict or compel the need for migration. Early interventions, already occurring in some places across the region, can prevent costly and lengthy rebuilding of communities and livelihoods and minimize displacement and relocation.

Sectoral impacts act together to compound environmental, social, cultural, and economic costs. Pacific islands are particularly vulnerable to climate change impacts due to their exposure and isolation, small size, low elevation (in the case of atolls), and concentration of infrastructure and economy along the coasts. The interconnectedness of people in island communities and the interdependence between human activities and the natural environment[119] mean that extreme events cause multiple, layered impacts, intensifying their effects (see Ch.17: Complex Systems). While each of these impacts presents challenges, when combined, the environmental, social, cultural, and economic impacts will have compounding costs. In addition, as some types of extreme events become more frequent, recovery from those events will prove increasingly difficult for isolated, resource-challenged islands,[189] resulting in long-term declines in people's welfare.[190,191]

Coastal flooding is a widely recognized threat to low-lying areas (see Key Message 3).[7] Extreme sea level events—created by combinations of factors such as storm-generated waves, storm surges, king tides, and ENSO-related sea level changes (see Box 27.1), combined with ongoing sea level rise—pose multiple challenges to habitability; on atolls, they are a clear threat to communities' existence (Figures 27.15, 27.16, 27.17). In 2005, when Cyclone Percy hit the Northern Cook Islands, waves swept across the atoll from both the ocean and the lagoon sides. Fresh food supplies were destroyed due to saltwater intrusion into taro fields, 640 people were left homeless, and freshwater wells were polluted, posing a risk to public health. Saltwater contamination of the freshwater lenses lasted 11 months or longer.[13] In Tokelau, Cyclone Percy scattered human waste, trash, and other debris into the ocean and across the island. Tokelau's three atolls lost most of their staple crops, while fish habitats were destroyed.[192] The islands suffered beach erosion, and many live coral formations were covered by sand and debris. In addition, the storm damaged many of the hospitals, making treatment of the injured or displaced difficult.[193] Lack of technology and resources limits small islands' ability to adapt to these complex threats. The cascading effects on infrastructure, health, food security, and the environment result in significant economic costs.[194,195]

Sea level rise, the deterioration of coral reef and mangrove ecosystems (see Key Message 4), and the increased concentration of economic activity will make coastal areas more vulnerable to storms (see Key Message 3).[196] Pacific Islands already face underlying economic vulnerabilities and stresses caused by unsustainable development, such as the use of beaches for building materials that results in coastal erosion or the waste disposal on mangroves and reefs that undermines critical ecological functions. The compounding impacts of climate change put the long-term habitability of coral atolls at risk, introducing issues of sovereignty, human and national security,[197] and equity,[198,199,200] a subject of discussion at the international level.

An increase in the incidence of vector-borne diseases such as malaria and dengue in the Pacific Islands has been linked to climate variability and is expected to increase further as a result of climate change (see Ch. 14: Human Health, KM 1).[201,202] For example, in late 2013 and early 2014, Fiji experienced the largest outbreak of dengue in its history, with approximately 28,000 reported cases.[203]

Climate change impacts on ecological and social systems are already negatively affecting livelihoods[204,205,206] and undermining human security.[191,207] In some cases, changes in climate increase the risk of human conflict (see Ch. 16: International, KM 3).[191,207,208] However, exactly how and when these changes can lead to conflict needs further study.[208] Climate change poses a threat to human security through direct impacts on economies and livelihoods that aggravate the likelihood of conflict and risk social well-being.[209] For example, climate change puts ongoing disputes over freshwater in Hawaiʻi at risk of intensifying in the absence of policy tools to help resolve conflicts.[23] Human conflict in the Asia Pacific region is expected to increase as unequal resource distribution combines with climate impacts to affect communities that are heavily dependent on agriculture, forestry, and fishing industries.[210]

Flooding in Kosrae

Figure 27.15: A combination of heavy rain, exceptionally high tides, and waves caused flooding in Kosrae, the Federated States of Micronesia, in February 2017. Photo credit: Delia Sigrah.

Reservoirs in the Marshall Islands

Figure 27.16: A series of reservoirs that provide the main water supply on Majuro Atoll in the Republic of the Marshall Islands are filled with runoff from the Majuro airport runway. The water supply is vulnerable to drought and saltwater overwash from both the lagoon and ocean (pictured). Photo credit: Majuro Water and Sewer Company.

A Marshall Islands Storm

Figure 27.17: An unseasonable storm hit the Marshall Islands on July 3rd, 2015. Storms this strong historically have been rare in the Marshall Islands, but the frequency of the most intense of these storms is projected to increase in the western North Pacific in the future. Photo credit: Marshall Islands Journal.

Climate change is already contributing to migration of individuals and communities.[211,212] In March 2015, Marshall Islands Bikinian people gathered to discuss resettlement because of increased flooding from high tides and storms that was making the atoll of Kili uninhabitable (see Case Study "Understanding the Effect of Climate Change on the Migration of Marshallese Islanders").[213]

Climate change induced community relocation, a recognized adaptation measure, results in disruption to society–land relationships and loss of community identity.[214] Resettlement has resulted in people facing landlessness, homelessness, unemployment, social marginalization, food insecurity, and increased levels of disease.[122]

Inaction to address climate-related hazards is projected to lead to high economic costs that are preventable.[205] Remote island communities that are unprepared for extreme events would face disruptions of goods and services that threaten lives and livelihoods. Rebuilding is expensive and lengthy.[13,218,219,220] Further, due to the special connections Indigenous people have to ancestral lands and territories, any loss of these resources is a cultural loss (see Key Message 5).[221]

Case Study: Understanding the Effect of Climate Change on the Migration of Marshallese Islanders

As one of the lowest-lying island nation-states in the world, the Republic of the Marshall Islands (RMI) is acutely vulnerable to sea level rise, flooding, and the associated intrusion of saltwater into crucial freshwater supplies, traditional agriculture, and forestry. The number of Marshallese residing in the United States (excluding the U.S. Territories and Freely Associated States) has rapidly risen over the past decade, from 7,000 in 2000 to 22,000 in 2010,[215] which is equal to over 40% of RMI's current total population. There is also substantial internal migration, predominantly from outer islands to the main atoll of Majuro.[216,217] Whether migration is a potentially successful adaptation strategy is unknown. The factors triggering human migration are complex and often intertwined, making it difficult to pinpoint and address specific causes.

Decision-makers in both the RMI and the United States—for example, those who design policy related to immigrant access to services—need information to better understand the factors contributing to current migration and to anticipate possible future impacts of climate change on human migration. A current research project is studying the multiple reasons for Marshallese migration and its effects on migrants themselves and on the communities they are coming from and going to.

Early intervention, occurring already in some places across the region, can prevent costly and lengthy rebuilding of communities and livelihoods and minimize displacement and relocation (see Ch. 28: Adaptation, KM 4). Early intervention includes taking steps now to protect infrastructure, as is being done by the Honolulu Board of Water Supply (see Case Study "Planning for Climate Impacts on Infrastructure"), such as redesigning areas to allow for periodic inundation and flooding, reverting natural areas to facilitate a return to original drainage patterns, and building social networks to take immediate actions and plan future responses.[222] Policymakers prefer approaches that are low cost, yield benefits even in the absence of climate change, are reversible and flexible, and build safety margins into new investments to accommodate uncertain future changes.[196] Examples of safety margins include more climate-adapted housing, provisions to expand rainwater storage capacity in water tanks, reverse osmosis capabilities for removing salt from water (Figure 27.4), development of saline-tolerant crop varieties (Figure 27.13), and implementation of more effective early warning systems for typhoons, king tides, and coastal storms.

Across the region, groups are coming together to minimize damage and disruption from coastal flooding and inundation, as well as other climate-related impacts. In some cases, the focus is on taking preventive measures to remove exposure to hazards, rather than focusing on protection and impact reduction (for example, through relocation or increased protection of threatened infrastructure). On Kosrae, the Federated States of Micronesia, for example, the Kosrae Island Resource Management Authority has laid out a strategy to redirect development inland (such as repositioning the main access road away from the shoreline to higher ground).[7]

Social cohesion is already strong in many communities in the region, making it possible to work together to take action. Stakeholders representing academia, resource managers, and government came together across the State of Hawai‘i to summarize ecosystem-specific vulnerabilities and prioritize potential adaptations at the island scale.[100] In Molokai, a community-led effort is underway to prepare traditional fishponds for climate change (see Case Study "Bridging Climate Science and Traditional Culture"). One of the core benefits of this effort is the strengthening of relationships between the diverse people who will benefit from collaborating to address future climate change impacts on the island.

Where successful, early intervention can lower economic, environmental, social, and cultural costs and reduce or prevent conflict and displacement from ancestral land and resources.

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Opening Image Credit

Honolulu, Hawaiʻi: NOAA Teacher at Sea Program, NOAA Ship *Hiʻialakai*.

Traceable Accounts

To frame this chapter, the regional leads wanted to maximize inclusiveness and represent the key sectoral interests of communities and researchers. To select sectors and a full author team, the coordinating lead author and regional chapter lead author distributed an online Google survey from September to October 2016. The survey received 136 responses representing Hawaiʻi and all the U.S.-Affiliated Pacific Islands (USAPI) jurisdictions; respondents identified which of the National Climate Assessment (NCA) sectors they were most interested in learning about with respect to climate change in the Pacific Islands and suggested representative case studies.[223] The five top sectors were picked as the focus of the chapter, and a total of eight lead authors with expertise in those sectors were invited to join the regional team. To solicit additional participation from potential technical contributors across the region, two informational webinars spanning convenient time zones across the Pacific were held; 35 people joined in. The webinars outlined the NCA history and process, as well as past regional reports and ways to participate in this Fourth National Climate Assessment (NCA4).

A critical part of outlining the chapter and gathering literature published since the Third National Climate Assessment (NCA3)[224] was done by inviting technical experts in the key sectors to participate in a half-day workshop led by each of the lead authors. A larger workshop centered on adaptation best practices was convened with participants from all sectors, as well as regional decision-makers. In all, 75 participants, including some virtual attendees, took part in the sectoral workshops on March 6 and 13, 2017. Finally, to include public concerns and interests, two town hall discussion events on March 6 and April 19, 2017, were held in Honolulu, Hawaiʻi, and Tumon, Guam, respectively. Approximately 100 participants attended the town halls. Throughout the refining of the Key Messages and narrative sections, authors met weekly both via conference calls and in person to discuss the chapter and carefully review evidence and findings. Technical contributors were given multiple opportunities to respond to and edit sections. The process was coordinated by the regional chapter lead and coordinating lead authors, as well as the Pacific Islands sustained assessment specialist.

Key Message 1

Threats to Water Supplies

Dependable and safe water supplies for Pacific island communities and ecosystems are threatened by rising temperatures *(very high confidence)*, changing rainfall patterns *(low confidence)*, sea level rise *(very high confidence)*, and increased risk of extreme drought and flooding *(medium confidence)*. Islands are already experiencing saltwater contamination due to sea level rise, which is expected to catastrophically impact food and water security, especially on low-lying atolls *(medium confidence)*. Resilience to future threats relies on active monitoring and management of watersheds and freshwater systems.

Description of evidence base

Vulnerability of water supplies to climate change: With their isolation and limited land areas, Hawaiʻi and the USAPI are vulnerable to the effects of climate change on water supplies.[72,225] Ongoing and projected changes in temperature and precipitation will have negative effects on water supplies in Hawai‘i and some parts of the USAPI. For example, stream low flow and base flow in Hawai‘i decreased significantly over the period 1913–2008, which is at least partly explained by a decline in precipitation.

Temperature change: In Hawai‘i, air temperature increased by 0.76°F (0.42°C) over the past 100 years. The year 2015 was the warmest on record at 1.43°F (0.79°C) above the 100-year average. Mean and minimum (nighttime) temperatures both show long-term, statistically significant increasing trends, while the diurnal temperature range (the average difference between daily minimum and maximum temperature) shows a long-term, statistically significant decreasing trend.[59] Estimates of historical temperature changes in Hawai‘i are based on the relatively few observing stations with long records and represent the best available data. Further temperature increases in the Hawai‘i–USAPI region are highly likely. Northern tropical Pacific (including Micronesia) sea level air temperatures are expected to increase by 2.2°–2.7°F (1.2°–1.5°C) by mid-century and by 2.7°–5.9°F (1.5°–3.3°C) by 2100.[63] Southern tropical Pacific (including American Sāmoa) sea level air temperatures are expected to increase by 1.8°–3.1°F (1.0°–1.7°C) by mid-century and by 2.5°–5.8°F (1.4°–3.2°C) by 2100.[63] Increasing temperatures throughout the Hawai‘i–USAPI region might cause increases in potential evapotranspiration,[226] with consequent negative impacts on water supplies.

Precipitation change: While Hawai‘i precipitation has experienced upward and downward changes across a range of timescales, more than 90% of the state had a net downward rainfall trend during 1920–2012.[60] Projections of future precipitation changes in Hawai‘i are still uncertain. Using a dynamical downscaling approach to project climate changes in Hawai‘i for the 20-year period at the end of the this century under a middle-of-the-road scenario (SRES A1B) resulted in increases in mean annual rainfall of up to 30% in the wet windward areas of Hawai‘i and Maui Islands and decreases of 40% in some of the dry leeward and high-elevation interior areas.[34] Somewhat different results were obtained using an independent statistical downscaling method.[34] For the lower scenario (RCP4.5), mean annual rainfall in Hawai‘i is projected by statistical downscaling to have only small changes in windward areas of Hawai‘i and Maui Islands, to decrease by 10%–20% in windward areas of the other islands, and to decrease by up to 60% in leeward areas for the period 2041–2070. For the same scenario, the late-century (2071–2100) projection is similar to the 2041–2070 projection, except that a larger portion of the leeward areas will experience reductions of 20%–60%. For the higher scenario (RCP8.5), windward areas of Hawai‘i and Maui Islands will see changes between +10% and −10%, and rainfall in leeward areas will decrease by 10% to more than 60% by the 2041–2070 period. By the late-century period (2071–2100), windward areas of Hawai‘i and Maui Islands will see increases of up to 20%, windward areas on other islands will have decreases of 10% to 30%, and leeward areas will have decreases of 10% to more than 60%. The number of climate and water resources monitoring stations has declined across the region,[23,76,77] reducing the ability of researchers to project future changes in climate.

Trends in hydrological extremes in Hawai‘i: Increasing trends in extreme 30-day rainfall and the lengths of consecutive dry-day and consecutive wet-day periods[66] indicate that Hawai‘i’s rainfall is becoming more extreme and suggest that both droughts and floods are becoming more frequent in Hawai‘i. With the addition of more years of observed data, and a more detailed spatiotemporal analysis from a grid-box level down to the island level, this contrasts with the earlier findings of a decreasing trend in the number of extreme rainfall events in Hawai‘i.[227]

Saltwater contamination due to sea level rise: Sea level rise exacerbates the existing vulnerability of groundwater lenses on small coral islands to contamination by saltwater intrusion by amplifying the impacts of freshwater lens-shrinking droughts and storm-related overwash events.[69]

Major uncertainties

Effects of warming on evapotranspiration: There are uncertainties in how warming will affect cloud cover, solar radiation, humidity, and wind speed. All of these affect potential evapotranspiration and changes in soil moisture, and the effects will differ by region.[228]

Future precipitation changes: Global models differ in their projections of precipitation changes for the Hawaiʻi–USAPI region.[63] For Hawaiʻi, downscaled projections differ according to the choice of global model time horizon, emissions scenario, and downscaling method.[229]

Description of confidence and likelihood

There is *very high confidence* in further increases in temperature in the region, based on the consistent results of global climate models showing continued significant increases in temperature in the Hawaiʻi–USAPI region for all plausible emissions scenarios.

There is *low confidence* regarding projected changes in precipitation patterns, stemming from the divergent results of global models and downscaling approaches and from uncertainties around future emissions. However, for leeward areas of Hawaiʻi and the eastern part of the Federated States of Micronesia (FSM), future decreases in precipitation are somewhat more likely, based on greater agreement between downscaling approaches for Hawaiʻi and greater agreement among global models for eastern FSM.

There is *very high confidence* in future increases in sea level, based on widely accepted evidence that warming will increase global sea level, with amplified effects in the low latitudes.

There is *medium confidence* in the increasing risk of both drought and flood extremes patterns, based on both observed changes (for example, increasing lengths of wet and dry periods) and projected effects of warming on extreme weather globally.

There is *medium confidence* in possible future catastrophic impacts on food and water security resulting from saltwater contamination in low atolls due to sea level rise; this is based on *very high confidence* in continuing sea level rise, the known effects of saltwater contamination on water supply and agriculture, and uncertainty regarding the effectiveness of adaptation measures.

Key Message 2

Terrestrial Ecosystems, Ecosystem Services, and Biodiversity

Pacific island ecosystems are notable for the high percentage of species found only in the region, and their biodiversity is both an important cultural resource for island people and a source of economic revenue through tourism (*very high confidence*). Terrestrial habitats and the goods and services they provide are threatened by rising temperatures (*very likely, very high confidence*), changes in rainfall (*likely, medium confidence*), increased storminess (*likely, medium confidence*), and land-use change (*very likely, very high confidence*). These changes promote the spread of invasive species (*likely, low confidence*) and reduce the ability of habitats to support protected species and sustain human communities (*likely, medium confidence*). Some species are expected to become extinct (*likely, medium confidence*) and others to decline to the point of requiring protection and costly management (*likely, high confidence*).

Description of evidence base

Projections of sea level rise have been made at both regional and local scales (see Traceable Account for Key Message 3). Based on these projections, the effects of sea level rise on coastal ecosystems have been evaluated for the Northwest Hawaiian Islands.[18,83,84,86,171,228] There has also been an assessment of the effects of climate change to many small islands across the Pacific Islands region.[70] The effect of sea level rise (and global warming) on mangroves has also been evaluated.[86,230,231,232]

Forecasts of how climate change will affect rainfall and temperature in the main Hawaiian Islands have been based on both statistical and dynamical downscaling of global climate models (GCMs; see Traceable Account for Key Message 1). Statewide vulnerability models have been developed for nearly all species of native plants[233] and forest birds,[43] showing substantial changes in the available habitat for many species. More detailed modeling within Hawai‘i Volcanoes National Park has suggested that rare and listed plants being managed in Special Ecological Areas will experience climate changes that make the habitat in these areas unsuitable.[91]

Effects of climate change on streamflow in Hawai‘i will largely be driven by changes in rainfall, although geologic conditions affect the discharge of groundwater that provides base flow during dry weather.[234] A regional watershed model from the windward side of Hawai‘i Island suggested that control of an invasive tree with high water demand would somewhat mitigate decreases in streamflow that might be caused by a drier climate.[44] Finally, it has been suggested that ocean acidification will decrease the viability of the planktonic larvae of native Hawaiian stream fishes.[99]

Major uncertainties

The timing and magnitude of sea level rise are somewhat uncertain. There is greater uncertainty on how climate change will affect the complex patterns of precipitation over the high islands of Hawai‘i. There is also high uncertainty about how plants will respond to changes in their habitats and the extent to which climate change will foster the spread of invasive species.

Description of confidence and likelihood

It is *very likely* that air and water temperatures will increase and that sea level will rise (*very high confidence*). Research indicates that global mean sea level rise will exceed previous estimates and that, in the USAPI, sea level rise is likely to be higher than the global mean (*likely*, *high confidence*). As a result, it is *likely* that climate change will affect low-lying and coastal ecosystems in Hawai‘i and other Pacific islands, with *medium confidence* in forecasts of the effects on these ecosystems.

There is *low confidence* as to how rainfall patterns will shift across the main Hawaiian Islands. It is considered *likely* that changes in rainfall will result in ecologic shifts expected to threaten some species. However, there is *low confidence* in specific ecologic forecasts, because the direction and magnitude of rainfall changes are uncertain and there is a lack of robust understanding of how species will respond to those changes. It seems *as likely as not* that the responses of terrestrial biomes and species to climate change will result in additional complexity in the management of rare and threatened species.

Key Message 3

Coastal Communities and Systems

The majority of Pacific island communities are confined to a narrow band of land within a few feet of sea level. Sea level rise is now beginning to threaten critical assets such as ecosystems, cultural sites and practices, economics, housing and energy, transportation, and other forms of infrastructure (*very likely, very high confidence*). By 2100, increases of 1–4 feet in global sea level are very likely, with even higher levels than the global average in the U.S.-Affiliated Pacific Islands (*very likely, high confidence*). This would threaten the food and freshwater supply of Pacific island populations and jeopardize their continued sustainability and resilience (*likely, high confidence*). As sea level rise is projected to accelerate strongly after mid-century, adaptation strategies that are implemented sooner can better prepare communities and infrastructure for the most severe impacts.

Description of evidence base

Multiple lines of research have shown that changes in melting in Greenland,[110] the Antarctic,[107] and among alpine glaciers,[111] as well as the warming of the ocean,[113] have occurred faster than expected. The rate of sea level rise is accelerating,[103] and the early signs of impact are widely documented.[9] Relative to the year 2000, global mean sea level (GMSL) is *very likely* to rise 0.3–0.6 feet (9–18 cm) by 2030, 0.5–1.2 feet (15–38 cm) by 2050, and 1.0–4.3 feet (30–130 cm) by 2100 (*very high confidence* in lower bounds; *medium confidence* in upper bounds for 2030 and 2050; *low confidence* in upper bounds for 2100).[17,105] Future greenhouse gas (GHG) emissions have little effect on projected average sea level rise in the first half of the century, but they significantly affect projections for the second half of the century. Emerging science regarding Antarctic ice sheet stability suggests that, for high emission scenarios, a GMSL rise exceeding 8 feet (2.4 m) by 2100 is physically possible, although the probability of such an extreme outcome cannot currently be assessed. Regardless of pathway, it is extremely likely that GMSL rise will continue beyond 2100 (*high confidence*).[105]

Changes in precipitation,[235] Pacific sea level,[4] climate variability,[3] and the unsustainable practices of many human communities among Pacific islands[127] all converge to increase the vulnerability of coastal populations[135] as climate change continues in the future.[55] As sea level rises and average atmospheric temperature continues to increase, wave events[37] associated with changing weather patterns[140] constitute a growing mechanism for delivering[12] damaging saltwater into island aquifer systems,[13] ecosystems,[129] and human infrastructure systems.[17]

In Hawaiʻi, studies by the Hawaiʻi Climate Change Mitigation and Adaptation Commission[42] reveal that with 3.2 feet of sea level rise, over 25,800 acres of land in the state would be rendered unusable. Some of that land would erode into the ocean, some would become submerged by inches or feet of standing water, and some areas would be dry most of the year but repeatedly washed over by seasonal high waves. Statewide, about 34% of that potentially lost land is designated for urban use, 25% is designated for agricultural use, and 40% is designated for conservation. The loss of urban land is expected to increase pressure on the development of inland areas, including those designated as agricultural and conservation lands. Across the state, over 6,500 structures located near the shoreline would be compromised or lost with 3.2 feet of sea level rise. Some of these vulnerable structures include houses and apartment buildings, and their loss would result in over 20,000 displaced residents in need of new homes. The value of projected flooded structures, combined with the land value of the 25,800 acres projected to be flooded, amounts to over $19 billion across the state (in 2013 dollars; $19.6 billion in 2015 dollars). However, this figure does not encompass the full loss potential in the state, as monetary losses that would occur from the chronic flooding of roads, utilities, and other public infrastructure were not analyzed in this report and are expected to amount to as much as an order of magnitude greater than the potential economic losses from land and structures. For example, over 38 miles of major roads would be chronically flooded across the state with 3.2 feet of sea level rise. Utilities, such as water, wastewater, and electrical systems, often run parallel and underneath roadways, making lost road mileage a good indication of the extent of lost utilities. This chronic flooding of infrastructure would have significant impacts on local communities as well as reverberating effects around each island.

The loss of valuable natural and cultural resources across all islands would cost the state dearly, due to their intrinsic value. Beaches that provide for recreation, wildlife habitat, and cultural tradition would erode, from iconic sites such as Sunset Beach on Oʻahu to neighborhood beach access points rarely visited by anyone except local residents. Some beaches would be lost entirely if their landward migration is blocked by roads, structures, shoreline armoring, or geology. The flooding of the more than 2,000 on-site sewage disposal systems with 3.2 feet of sea level rise would result in diminished water quality in streams and at beaches and shoreline recreation areas. The loss of and harm to native species and entire ecosystems would have implications for Hawaiian cultural traditions and practices, which are closely tied to the natural environment. Further, nearly 550 cultural sites in the state would be flooded, and many Hawaiian Home Lands communities would be impacted by flooding. In some cases, inland migration or careful relocation of these natural and cultural resources is expected to be possible. In other cases, the resources are inextricably bound to place and would be permanently altered by flooding.[42]

Marra and Kruk (2017)[142] describe climate trends for the USAPI. Globally and locally, observations of GHG concentrations, surface air temperatures, sea level, sea surface temperature, and ocean acidification show rising trends at an increasing rate. 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. A 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.

There are consistent subregional changes in the number of days with high winds. 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.[142]

Major uncertainties

Major uncertainties lie in understanding and projecting the future melting behavior of the Antarctic and Greenland ice sheets. To date, new observations attest to melting occurring at higher than expected rates. If this continues to be the case, it is plausible for future sea level rise to exceed even worst-case scenarios. Secondary feedbacks to warming, such as changes in the global thermohaline circulation; shifts in major weather elements, such as the intertropical convergence zone and the polar jet stream; and unexpected modes of heat distribution across the hemispheres risk complex responses in the climate system that are not well understood. Pacific climate variability is a governing element that amplifies many aspects of climate change, such as drought, sea level, storminess, and ocean warming. A number of mechanisms through which climate change might alter Pacific variability have been proposed on the basis of physical modeling, but our understanding of the variability remains low, and confidence in projected changes is also low. For instance, in any given Pacific region, our understanding of future TC occurrence, intensity, and frequency is low. Future physical responses to climate change that have not yet been described are possible. These uncertainties greatly limit our ability to identify the chronology of changes to expect in the future.

Description of confidence and likelihood

There is *very high confidence* that a continued rise in global temperature will lead to increases in the rate of sea level rise. There is less confidence in the projected amounts of sea level rise during this century, and there is *low confidence* in the upper bounds of sea level rise by the end of the century. Sea level rise will *very likely* lead to saltwater intrusion, coastal erosion, and wave flooding. It is *very likely* this will strain the sustainability of human infrastructure systems, limit freshwater resources, and challenge food availability. If the high-end projections of future sea level rise materialize, it is *very likely* this will threaten the very existence of Pacific island coastal communities.

Key Message 4

Oceans and Marine Resources

Fisheries, coral reefs, and the livelihoods they support are threatened by higher ocean temperatures and ocean acidification (*very likely, high confidence*).Widespread coral reef bleaching and mortality have been occurring more frequently, and by mid-century these events are projected to occur annually, especially if current trends in emissions continue (*likely, medium confidence*). Bleaching and acidification will result in loss of reef structure, leading to lower fisheries yields, and loss of coastal protection and habitat (*very likely, very high confidence*). Declines in oceanic fishery productivity of up to 15% and 50% of current levels are projected by mid-century and 2100, respectively, under the higher scenario (RCP8.5; *likely, medium confidence*).

Description of evidence base

The Key Message was developed based on input from an expert working group convened at the outset of this section development and supported by extensive literature.

Ocean warming: NCA3 documented historical increases in sea surface temperature (SST), and current levels in much of the region have now exceeded the upper range of background natural variation.[32,154] Future increases are projected even under lower-than-current emissions rates.[123,154]

Ocean acidification: Atmospheric carbon dioxide levels recorded at Mauna Loa, Hawai‘i, have recently exceeded 400 parts per million, and oceanic pH levels measured off O‘ahu have steadily declined from an annual average of about 8.11 to 8.07 over the past 25 years (data from Hawai‘i Ocean Time Series, SOEST, University of Hawai‘i) and are projected to decrease to 7.8 by 2100.[123] As pH declines, it lowers the saturation level of aragonite (the form of calcium carbonate used by corals and many other marine organisms), reducing coral and shell growth.[125] By the end of the century, aragonite saturation is projected to decline from a current level of 3.9 to 2.4, representing extremely marginal conditions for coral reef growth.[32,123,159,161]

Bleaching events: These continue to occur—most recently over successive years—with widespread impacts.[45,158] Sea surface temperature time series from a suite of Climate Model Intercomparison Project 5 outputs that are statistically downscaled to 4 km resolution are used to project the year when coral reefs will begin to experience annual bleaching under the higher scenario (RCP8.5).[46] These data forecast that bleaching will be an annual event for the region starting in about 2035.[46]

Mortality: During the 2014–2015 bleaching events, coral mortality in western Hawai‘i was estimated at 50%[45] and over 90% at the pristine equatorial Jarvis Atoll.[156]

Coral reef ecosystem impacts: Coral reef cover around the Pacific Islands region is projected to decline from the current average level of about 40% to 15%–30% by 2035 and 10%–20% by 2050.[123] The loss of coral reef habitat is projected to reduce fish abundance and fisheries yields by 20%.[123] Loss of coral reefs will result in increased coastal erosion.[23,236] Tourism is the major economic engine in Hawai‘i, and healthy coral reef ecosystems are critical to this economy. Under the higher scenario (RCP8.5), coral reef loss is projected to result in a total economic loss of $1.3 billion per year in 2050 and $1.9 billion per year in 2090 (in 2015 dollars, undiscounted). In 2090, a lower scenario (RCP4.5) would avoid 16% of coral cover loss and $470 million per year (in 2015 dollars, undiscounted) compared to the higher scenario.[162] The confidence intervals around these loss estimates under RCP8.5 for 2050 range from a gain of $240 million to a loss of $1.9 billion, and for 2090 range from a loss of $1.7 billion to $1.9 billion (in 2015 dollars, undiscounted).[162]

Insular fisheries: Insular fishes, including both coral reef fishes and more mobile, coastal pelagics (species such as mahi mahi and wahoo), are impacted both from declines in carrying capacity and loss from migration in response to temperature change. Taken together, declines in maximum catch potential exceeding 50% from late 20th century levels under the higher scenario are projected by 2100 for the exclusive economic zones of most islands in the central and western Pacific.[163]

Oceanic fisheries: A number of studies have projected that ocean warming will result in lower primary productivity due to increased vertical stratification and loss of biodiversity as organisms move poleward.[129,167,169] Estimates of up to a 50% decline in fisheries yields are projected with two different modeling approaches.[129,169] The impact of climate change specifically on fisheries targeting bigeye, yellowfin, and skipjack tunas in the western and central equatorial Pacific has been explored with fisheries models.[123,237,238] However, there is considerable uncertainty in the projections of population trends, given our lack of understanding of how the various life stages of these species will respond and the sensitivity of the projections to the specific model used.[238,239]

Major uncertainties

A major uncertainty for coral reefs is whether they can evolve rapidly enough to keep up with the changing temperature and pH.[164,165] In the oceanic ecosystem, the impacts of changing ocean chemistry on the entire food web are not well understood but are expected to result in shifts in the composition of the species or functional groups, altering the energy flow to top trophic levels.[240,241] For example, a shift in the micronekton community composition (squids, jellyfishes, fishes, and crustaceans) was projected to alter the abundance of food available to fishes at the top of the food web.[240] The impact of climate change on the intensity and frequency of interannual and decadal modes of climate variability (such as El Niño–Southern Oscillation and Pacific Decadal Oscillation) is not well known but has very important consequences.[1]

Description of confidence and likelihood

There is *high confidence* that fisheries and the livelihoods they support are threatened by warmer ocean temperatures and ocean acidification. Widespread and multiyear coral reef bleaching and mortality are already occurring. It is *likely*, based on modeled SST projections, that by mid-century, bleaching will occur annually with associated mortality.

There is *medium confidence* in the projection of annual bleaching by mid-century, as it does not take into account any adaptation in corals.

There is *high confidence* that bleaching and rising seawater acidity will result in loss of reef structure, leading to lower fisheries yields and loss of coastal protection. This is deemed *very likely* because significant coral mortality has recently been observed in western Hawaiian coral reefs that suffered from the 2015 bleaching event. Further, the positive relationship between fish density and coral reef cover is well established. The magnitude of this impact depends on the extent that coral species exhibit adaptive or resilience capacity.

There is *medium confidence* that declines in oceanic fishery productivity of up to 15% and 50% are likely by mid-century and 2100, respectively. These declines are considered *likely* because we have seen related linkages between climate variability such as ENSO and the Pacific Decadal Oscillation and fisheries yields that provide an analog in some ways to global warming impacts. The uncertainty lies in our limited understanding of the linkages and feedbacks in the very complex oceanic food web. As temperate habitats warm, they will likely gain some tropical species, while the tropical habitats will likely only lose species.

Key Message 5

Indigenous Communities and Knowledge

Indigenous peoples of the Pacific are threatened by rising sea levels, diminishing future freshwater availability, and shifting ecosystem services. These changes imperil communities' health, well-being, and modern livelihoods, as well as their familial relationships with lands, territories, and resources (*likely, high confidence*). Built on observations of climatic changes over time, the transmission and protection of traditional knowledge and practices, especially via the central role played by Indigenous women, are intergenerational, place-based, localized, and vital for ongoing adaptation and survival.

Description of evidence base

The research supporting this Key Message examines the impacts of climate change on the lands, territories, and resources of the Pacific region and its Indigenous communities.

It is foundational to highlight the interconnectedness and important familial relationship Indigenous peoples have with their lands, territories, and resources. Native Hawaiian attorneys and professors Sproat and Akutagawa discuss the health impacts and threats that climate change poses for Indigenous communities and their relationship with ancestral resources. Sproat states that "any such loss will result in the loss of culture."[177] Further support is found in a community health assessment done by Akutagawa and others that states, "In traditional Hawaiian conceptions of health, personal harmony and well-being are deemed to stem from one's relationship with the land, sea, and spiritual world."[176]

Governments and their support institutions are also sharing outcomes of projects they've initiated over the years that document not only the successes but also the challenges, observations, and lessons learned.[149,179] This includes the recognition of the dominant role of Indigenous women in island communities as gatherers and in household activities; economic development activities like transporting and selling produce;[146] distribution of crops;[179] maintenance of crop diversity, food security, security of income, seed saving, and propagation; transmission of traditional knowledge and practices, especially spiritual practices;[185] and stewarding underwater reef patches and stone enclosures as gardens.[242]

In writing this Key Message, the authors considered the body of research focusing on the impacts of climate change on Pacific communities such as sea level rise,[104,115,147,177,243] ocean acidification,[84,115,147,177,184] and drought.[147,177,179,184,242,243,244] Clear examples used in the studies illustrate the confidence that Indigenous communities are at high risk for experiencing effects at a physical,[176,245] social,[22,175,176,177,184,244] and spiritual level.[21,84,174,175,176,177,245]

There is very strong evidence that traditional knowledge is key to the resilience and adaptive capacity of Indigenous peoples of the Pacific.[21,84,176,180,184,185,242]

Major uncertainties

There is no doubt that Indigenous communities of the Pacific are being impacted by climate change. However, the rate and degree of the impacts on the spiritual, relational, and ancestral connectedness vary from community to community and on the type of practice being impacted. This variable is difficult to document and express in certain circumstances. Additionally, the degree of the impact varies according to the livelihoods of the community and the specific climatic and socioeconomic and political circumstances of the island in question.

Description of confidence and likelihood

There is *high confidence* that climate change is having far-reaching effects on the land security, livelihood security, habitat security, and cultural food security of Indigenous peoples of the Pacific.

It is *likely* that most of these impacts will have negative effects on the cultural heritage of the Pacific island communities.

There is *high confidence* that traditional knowledge together with science will support the adaptive capacity of Pacific island communities to survive on their islands.

Key Message 6

Cumulative Impacts and Adaptation

Climate change impacts in the Pacific Islands are expected to amplify existing risks and lead to compounding economic, environmental, social, and cultural costs (*likely, medium confidence*). In some locations, climate change impacts on ecological and social systems are projected to result in severe disruptions to livelihoods (*likely, high confidence*) that increase the risk of human conflict or compel the need for migration. Early interventions, already occurring in some places across the region, can prevent costly and lengthy rebuilding of communities and livelihoods and minimize displacement and relocation (*likely, high confidence*).

Description of evidence base

For Atlantic and eastern North Pacific hurricanes and western North Pacific typhoons, increases are projected in precipitation rates and intensity. The frequency of the most intense of these storms is projected to increase in the western North Pacific and in the eastern North Pacific (see also Key Message 3).[246] Studies indicate that Hawai‘i will see an increased frequency of tropical cyclones (TCs) due to storm tracks shifting northward in the central North Pacific.[40,247]

The *Climate Science Special Report* (CSSR) summarizes extensive evidence that is documented in the climate science literature and is similar to statements made in NCA3 and international[106] assessments.[33] More recent downscaling studies have further supported these assessments,[248] though pointing out that the changes (future increased intensity and TC precipitation rates) will not necessarily occur in all basins.[246]

Damage from TCs is significant. Tropical Cyclone Evan struck Sāmoa in December 2012 and caused damage and losses of approximately $210 million dollars (dollar year not reported), representing 30% of its annual gross domestic product (GDP). Tropical Cyclone Pam struck Vanuatu, Tuvalu, and Kiribati in 2015; in Vanuatu, it killed 11 people and caused approximately $450 million (dollar year not reported) in damages and losses, equal to 64% of GDP.[196]

In the CSSR, future relative sea level rise as shown for the 3.3-feet (1 m) Interagency scenario in 2100 indicates that, because they are far from all glaciers and ice sheets, relative sea level rise in Hawaiʻi and other Pacific islands due to any source of melting land ice is amplified by the static-equilibrium effects. Static-equilibrium effects on sea level are produced by the gravitational, elastic, and rotational effects of mass redistribution resulting from ice loss.[105]

Sea level rise across Hawaiʻi is projected to rise another 1–3 feet by the end of this century. Sea level rise has caused an increase in high tide floods associated with nuisance-level impacts. High tide floods are events in which water levels exceed the local threshold (set by the National Oceanic and Atmospheric Administration’s National Weather Service) for minor impacts. These events can damage infrastructure, cause road closures, and overwhelm storm drains. Along the Hawaiian coastline, the number of tidal flood days (all days exceeding the nuisance-level threshold) has also increased, with the greatest number occurring in 2002–2003. Continued sea level rise will present major challenges to Hawaiʻi’s coastline through coastal inundation and erosion. Seventy percent of Hawaiʻi’s beaches have already been eroded over the past century, with more than 13 miles of beach completely lost. Sea level rise will also affect Hawaiʻi’s coastal storm water and wastewater management systems and is expected to cause extensive economic impacts through ecosystem damage and losses in property, tourism, and agriculture.[247]

In the Pacific Islands region, population, urban centers, and critical infrastructure are concentrated along the coasts. This results in significant damages during inundation events. In December 2008, wind waves generated by extratropical cyclones, exacerbated by sea level rise, caused a series of inundation events in five Pacific island nations.[9] An area of approximately 3,000 km in diameter was affected, impacting approximately 100,000 people. Across the islands, major infrastructure damage and crop destruction resulted, costing millions of dollars and impacting livelihoods, food security, and freshwater resources.

The increases in the frequency and intensity of climate change hazards, including cyclones, wind, rainfall, and flooding, pose an immediate danger to the Pacific Islands region. A decrease in the return times of extreme events, which will reduce the ability of systems to recover, will likely cause long-term declines in welfare.[181] For small islands states, the damage costs of sea level rise are large in relation to the size of their economies.[194,195]

The social science research on climate and conflict suggests a possible association between climate variability and change and conflict. Consensus or conclusive evidence of a causal link remains elusive. Hsiang et al. (2013)[249] find strong causal evidence linking climatic events to human conflict across a range of spatial scales and time periods and across all major regions of the world. They further demonstrate that the magnitude of climate influence is substantial.[249] Specifically, large deviations from average precipitation and mild temperatures systematically increase the risk of many types of conflict (intergroup to interpersonal), often substantially. Hsiang and Burke (2014)[250] describe their detailed meta-analysis, examining 50 rigorous quantitative studies, and find consistent support for a causal association between climatological changes and various conflict outcomes.[250] They note, however, that multiple mechanisms can explain this association and that the literature is currently unable to decisively exclude any proposed pathway between climatic change and human conflict.[249]

Evidence of the impact of climate on livelihoods is also well established. Barnett and Adger (2003, 2007)[191,197] are among a range of studies that conclude that climate change poses risks to livelihoods, communities, and cultures.[197] These risks can influence human migration. The United Nations Environment Programme finds that the degree to which climatic stressors affect decisions to migrate depend on a household's vulnerability and sensitivity to climatic factors.[206]

Major uncertainties

A key uncertainty remains the lack of a supporting, detectable anthropogenic signal in the historical data to add further confidence to some regional projections. As such, confidence in the projections is based on agreement among different modeling studies. Additional uncertainty stems from uncertainty in both the projected pattern and magnitude of future sea surface temperatures.[33,40,248]

One study projects an increase in tropical cyclone frequency (TCF) of occurrence around the Hawaiian Islands but stipulates that TCF around the Hawaiian Islands is still very low in a warmed climate, so that a quantitative evaluation of the future change involves significant uncertainties.[40]

Uncertainties in reconstructed global mean sea level (GMSL) change relate to the sparsity of tide gauge records, particularly before the middle of the twentieth century, and to the use of a variety of statistical approaches to estimate GMSL change from these sparse records. Uncertainties in reconstructed GMSL change before the 20th century also relate to the lack of geological proxies (preserved physical characteristics of the past environment that can stand in for direct measurement) for sea level change, the interpretation of these proxies, and the dating of these proxies. Uncertainty in attribution relates to the reconstruction of past changes and the magnitude of natural variability in the climate.

Since NCA3, multiple approaches have been used to generate probabilistic projections of GMSL rise. These approaches are in general agreement. However, emerging results indicate that marine portions of the Antarctic ice sheet are more unstable than previously thought. The rate of ice sheet mass changes remains challenging to project.

In sea level rise projections, Antarctic contributions are amplified along U.S. coastlines, while Greenland contributions are dampened; regional sea level is projected to be higher than if driven by a more extreme Greenland contribution and a somewhat less extreme Antarctic contribution.[17]

The degree to which climate variability and change impact conflict, and related causal pathways, remains uncertain. This is compounded by the fact that different types of conflict—social, political, civil, or violent—are conflated.[209,251] Violent conflict can describe interpersonal-, intergroup-, and international-level disputes. Some researchers contend that systematic research on climate change and armed conflict has not revealed a direct connection.[252] Gemenne et al. (2014)[208] argue that there is a lack of convincing empirical evidence or theories that explain the causal connection between climate change and security. They do, however, note that there is some evidence for statistical correlation between climatic changes and conflict, broadly referenced.

Gemenne et al. (2014)[208] also note that the relationship between climate change and security comes from observation of past patterns and that present and projected climate change have no historical precedent. In effect, understanding past crises and adaptation strategies will no longer be able to help us understand future crises in a time of significant climate change.

The degree to which climate variability and change affect migration decisions made today also remains uncertain. This is in part due to the diverse scenarios that comprise climate migration, which themselves result from multiple drivers of migration.[251] Burrows and Kinney (2016)[251] detail examples of climate extremes leading to migration conflicts since 2000, yet they note that there are surprisingly few case studies on recent climate extremes that lead to migration and conflict specifically, despite an increasing body of literature on the theory.

While researchers disagree as to the degree to which climate change drives conflict and migration and the causal pathways that connect them, there is agreement that further research is needed. Buhaug (2015)[252] and Gemenne et al. (2014)[208] argue for research to develop a more refined theoretical understanding of possible indirect and conditional causal connections between climate change and, specifically, violent conflict.[252] Hsiang and Burke (2014)[250] would like additional research that reduces the number of competing hypotheses that attempt to explain the overwhelming evidence that climatic variables are one of many important causal factors in human conflict.[250] Burrows and Kinney (2016)[251] explore the potential pathways linking climate change, migration, and increased risk of conflict and argue that future research should focus on other pathways by which climate variability and change are related to conflict, in addition to the climate–migration–conflict pathway. Kallis and Zografos (2014)[209] seek greater understanding of the potential harm of certain climate change adaptation measures that have the potential to result in maladaptation by spurring conflict.

Description of confidence and likelihood

There is *medium confidence* that climate change will yield compounding economic, environmental, social, and cultural costs. There is greater evidence of these compounding costs resulting from extreme events that are exacerbated by climate change.

There is *high confidence* that food and water insecurity will result in severe disruptions to livelihoods, including the displacement and relocation of island communities.

It is *likely* that the absence of interventions will result in the costly and lengthy rebuilding of communities and livelihoods and more displacement and relocation. Events have played out repeatedly across the region and have resulted in damage, disruptions, and displacements.

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