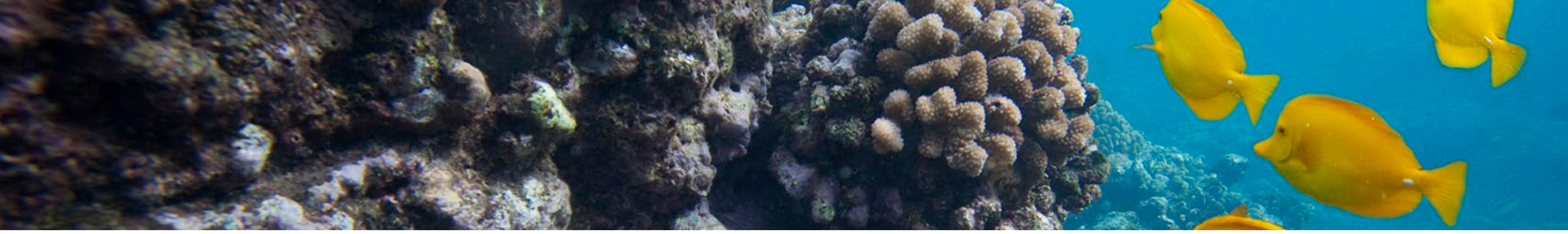

Climate Change Impacts in the United States

CHAPTER 23
HAWAI‘I
AND U.S. AFFILIATED PACIFIC ISLANDS

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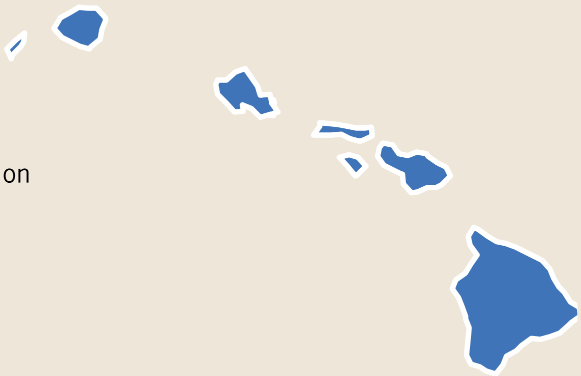

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23 HAWAI'I
AND U.S. AFFILIATED PACIFIC ISLANDS

Key Messages

1. **Warmer oceans are leading to increased coral bleaching events and disease outbreaks in coral reefs, as well as changed distribution patterns of tuna fisheries. Ocean acidification will reduce coral growth and health. Warming and acidification, combined with existing stresses, will strongly affect coral reef fish communities.**

2. **Freshwater supplies are already constrained and will become more limited on many islands. Saltwater intrusion associated with sea level rise will reduce the quantity and quality of freshwater in coastal aquifers, especially on low islands. In areas where precipitation does not increase, freshwater supplies will be adversely affected as air temperature rises.**

3. **Increasing temperatures, and in some areas reduced rainfall, will stress native Pacific Island plants and animals, especially in high-elevation ecosystems with increasing exposure to invasive species, increasing the risk of extinctions.**

4. **Rising sea levels, coupled with high water levels caused by storms, will incrementally increase coastal flooding and erosion, damaging coastal ecosystems, infrastructure, and agriculture, and negatively affecting tourism.**

5. **Mounting threats to food and water security, infrastructure, health, and safety are expected to lead to increasing human migration, making it increasingly difficult for Pacific Islanders to sustain the region's many unique customs, beliefs, and languages.**

The U.S. Pacific Islands region (Figure 23.1) is vast, comprising more than 2,000 islands spanning millions of square miles of ocean. The largest group of islands in this region, the Hawaiian Archipelago, is located nearly 2,400 miles from any continental landmass, which makes it one of the most remote archipelagos on the globe.[1] The Hawaiian Islands support fewer than 2 million people, yet provide vital strategic capabilities to U.S. defense – and the islands' biodiversity is important to the world. Hawai'i and the U.S. affiliated Pacific Islands are at risk from climate changes that will affect nearly every aspect of life. Rising air and ocean temperatures, shifting rainfall patterns, changing frequencies and intensities of storms and drought, decreasing baseflow in streams, rising sea levels, and changing ocean chemistry will affect ecosystems on land and in the oceans, as well as local communities, livelihoods, and cultures. Low islands are particularly at risk.

The Pacific Islands include volcanic islands, islands of continental crust, atolls (formed by coral reefs), limestone islands, and islands of mixed geologic origin, with tremendous landscape diversity. In the Hawaiian High Islands, as many as 10 ecozones – from alpine systems to tropical rainforests – exist within a 25 mile span.[3,4] Isolation and landscape diversity in Hawai‘i brings about some of the highest concentrations of native species, found nowhere else in the world.[4] Several U.S. Pacific Islands are marine biodiversity hotspots, with the greatest diversity found in the Republic of Palau, and the highest percentage of native reef fishes in Hawai‘i.[5] These islands provide insights into evolution and adaptation, concepts important for predicting the impacts of climate change on ecosystems. Their genetic diversity also holds the potential for developing natural products and processes for biomedical and industrial use.

U.S. Pacific Islands Region

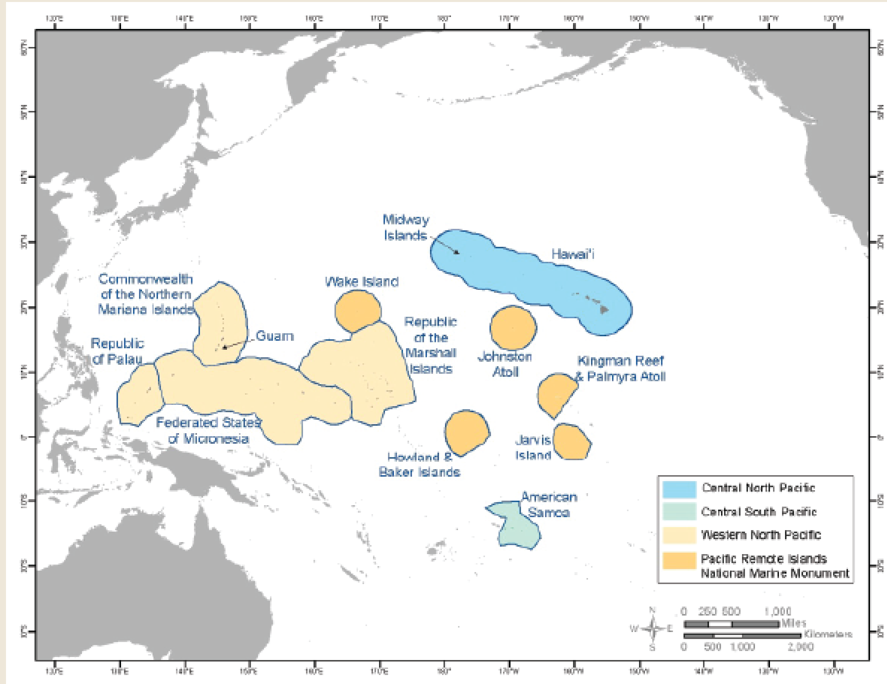

Figure 23.1. The U.S. Pacific Islands region includes our 50th state, Hawai‘i, as well as the Territories of Guam, American Samoa, the Commonwealth of the Northern Mariana Islands (CNMI), the Republic of Palau (RP), the Federated States of Micronesia (FSM), and the Republic of the Marshall Islands (RMI). Citizens of Guam and CNMI are U.S. citizens, and citizens of American Samoa are U.S. nationals. Through the Compacts of Free Association, citizens of RP, FSM, and RMI have the right to travel to the U.S. without visas to maintain “habitual residence” and to pursue education and employment. The map shows three sub-regions used in this assessment and the islands that comprise the Pacific Remote Islands National Monument. Shaded areas indicate each island’s Exclusive Economic Zone (EEZ) (Figure source: Keener et al. 2012[2]).

The Pacific Islands region includes demographically, culturally, and economically varied communities of diverse indigenous Pacific Islanders, intermingled with immigrants from many countries. At least 20 languages are spoken in the region. Pacific Islanders recognize the value and relevance of their cultural heritage and systems of traditional knowledge; their laws emphasize the long-term multigenerational connection with their lands and resources.[6] Tourism contributes prominently to the gross domestic product of most island jurisdictions, as does the large U.S. military presence. Geographic remoteness means that the costs of air transport and shipping profoundly influence island economies. Natural resources are limited, with many communities relying on agriculture and ecosystems (such as coral reefs, open oceans, streams, and forests) for sustenance and revenue.

Key Message 1: Changes to Marine Ecosystems

Warmer oceans are leading to increased coral bleaching events and disease outbreaks in coral reefs, as well as changed distribution patterns of tuna fisheries. Ocean acidification will reduce coral growth and health. Warming and acidification, combined with existing stresses, will strongly affect coral reef fish communities.

Ocean temperatures in the Pacific region exhibit strong year-to-year and decadal fluctuations, but since the 1950s, they have also exhibited a warming trend, with temperatures from the surface to a depth of 660 feet rising by as much as 3.6°F.[7]

Future sea surface temperatures are projected to increase 1.1°F (compared to the 1990 levels) by 2030, 1.8°F by 2055, and 2.5°F by 2090 under a scenario that assumes substantial reductions in emissions (B1), or 1.7°F by 2030, 2.3°F by 2055, and 4.7°F by 2090 under a scenario that assumes continued increases in emissions (A2).[8]

Bleaching events (as a result of higher ocean temperatures) can weaken or kill corals. At least three mass bleaching episodes have occurred in the northwestern Hawaiian Islands in the last decade.[9] Incidences of coral bleaching have been recorded in

“High” and “Low” Pacific Islands Face Different Threats

Figure 23.2. The Pacific Islands include “high” volcanic islands, such as that on the left, that reach nearly 14,000 feet above sea level, and “low” atolls and islands, such as that on the right, that peak at just a few feet above present sea level. (Left) Koʻolau Mountains on the windward side of Oahu, Hawaiʻi (Photo credit: kstrebor via Flickr.com). (Right) Laysan Island, Papahānaumokuākea Marine National Monument (Photo credit: Andy Collins, NOAA).

Micronesia and American Samoa,[10] testing the resilience of these reefs. Coral disease outbreaks have also been reported in the Hawaiian archipelago,[11] American Samoa,[12,13] the Marshall Islands, and Palau,[14] correlated with periods of unusually high water temperatures.[15] Despite uncertainties, advanced modeling techniques project a large decline in coral cover in the Hawaiian Archipelago during this century. However, there are significant differences in the projected time frames and geographic distribution of these declines, even under a single climate change scenario.[16] By 2100, assuming ongoing increases in emissions of heat-trapping gases (A2 scenario), continued loss of coral reefs and the shelter they provide will result in extensive losses in both numbers and species of reef fishes.[17] Even with a substantial reduction in emissions (B1 scenario), reefs could be expected to lose as much as 40% of their reef-associated fish. Coral reefs in Hawaiʻi provide an estimated $385 million in goods and services annually,[18] which could be threatened by these impacts.

Ocean acidification is also taking place in the region, which adds to ecosystem stress from increasing temperatures. Ocean acidity has increased by about 30% since the pre-industrial era and is projected to further increase by 37% to 50% from present levels by 2100 (Ch. 2: Our Changing Climate, Key Message 12).[19] The amount of calcium carbonate, the biologically important mineral critical to reef-building coral and to calcifying algae, will decrease as a result of ocean acidification. By 2035 to 2060, levels of one form of the mineral (aragonite) are projected to decline enough to reduce coral growth and survival around the Pacific, with continuing declines thereafter.[20] Crustose coralline algae, an inconspicuous but important component of reefs that help reefs to form and that act as critical surfaces on which other living things grow, are also expected to exhibit reduced growth and survival.[21,22] Ocean acidification reduces the ability of corals to build reefs and also increases erosion,[23] leading to more fragile reef habitats. These changes are projected to have a strong negative impact on the econo-

El Niño and Other Patterns of Climate Variability

The Pacific region is subject to various patterns of climate variability. The effects of the El Niño-Southern Oscillation (ENSO) and other patterns of oceanic and atmospheric variability on the region are significant. They include large variations in sea surface temperatures, the strength and persistence of the trade winds, the position of jet streams and storm tracks, and the location and intensity of rainfall.[8,29,30] The ENSO-related extremes of El Niño and La Niña generally persist for 6 to 18 months and change phase roughly every 3 to 7 years.[8,31] The Pacific Decadal Oscillation (PDO) and the Interdecadal Pacific Oscillation (IPO) are patterns that operate over even longer time horizons and also influence the weather and climate of the region.[31,32] Such dramatic short-term variability (the “noise”) can obscure the long-term trend (the “signal”).[33] Despite the challenges of distinguishing natural climate variability from climate change, there are several key indicators of observed change that serve as a basis for monitoring and evaluating future change.[2]

mies and well-being of island communities, with loss of coral biodiversity and reduced resilience.[24]

Similarly, there will be large impacts to the economically important tuna fishery in the Pacific Island region. Surface chlorophyll data obtained by satellites indicate less favorable conditions resulting in reduced productivity for tuna in the subtropical South and North Pacific[26] due to warming. This trend is projected to continue under future climate change.[27] One fishery model, coupled with a climate model, forecasts that the overall western and central Pacific fishery catch for skipjack tuna would initially increase by about 19% by 2035, though there would be no change for bigeye tuna. However, by 2100, skipjack catch would decline by 8% and bigeye catch would decline by 27% if emissions continue to rise (A2 scenario); geographic variations are projected within the region.[28]

These changes to both corals and fish pose threats to communities, cultures, and ecosystems of the Pacific Islands both directly through their impact on food security and indirectly through their impact on economic sectors including fisheries and tourism.

Increasing ocean temperature and acidity threaten coral reef ecosystems.

Increased Acidification Decreases Suitable Coral Habitat

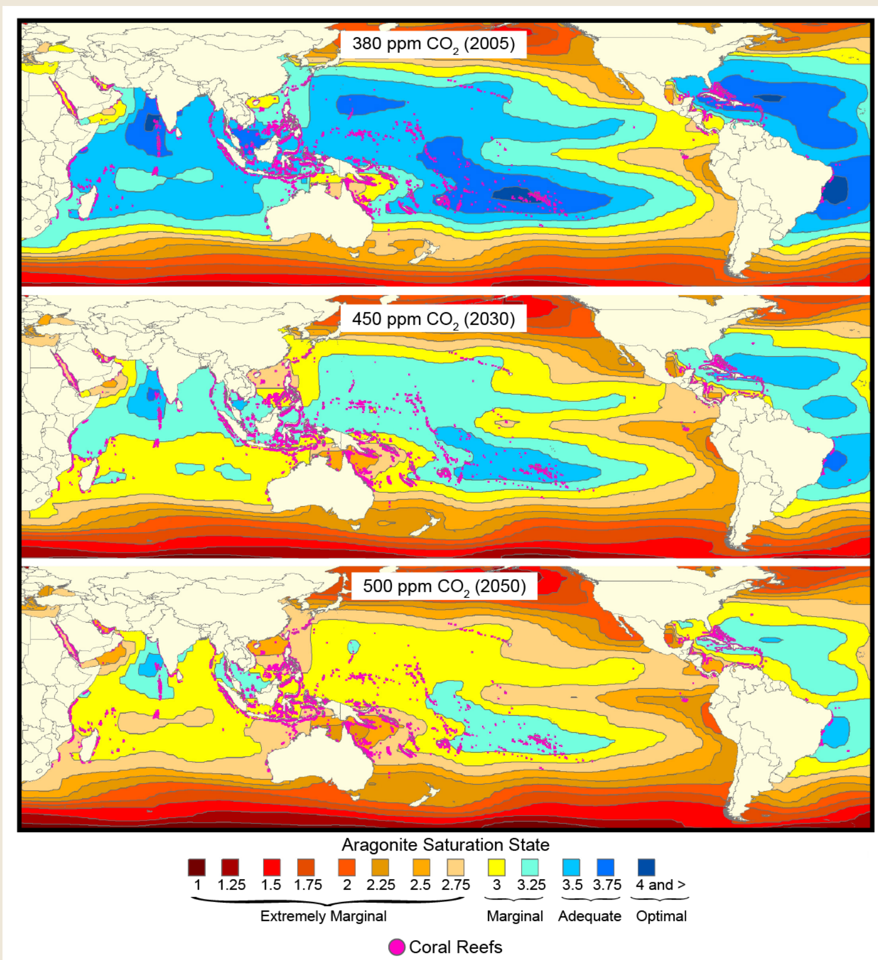

Figure 23.3. Ocean waters have already become more acidic from absorbing carbon dioxide from the atmosphere. As this absorption lowers pH, it reduces the amount of calcium carbonate, which is critical for many marine species to reproduce and grow. Maps show projections of the saturation state of aragonite (the form of calcium carbonate used by coral and many other species) if CO_2 levels were stabilized at 380 ppm (a level that has already been exceeded), 450 ppm (middle map), and 500 ppm (bottom map), corresponding approximately to the years 2005, 2030, and 2050, assuming a decrease in emissions from the current trend (scenario A1B). As shown on the maps, many areas that are adequate will become marginal. Higher emissions will lead to many more places where aragonite concentrations are “marginal” or “extremely marginal” in much of the Pacific. (Figure source: Burke et al. 2011[25]).

Key Message 2: Decreasing Freshwater Availability

Freshwater supplies are already constrained and will become more limited on many islands. Saltwater intrusion associated with sea level rise will reduce the quantity and quality of freshwater in coastal aquifers, especially on low islands. In areas where precipitation does not increase, freshwater supplies will be adversely affected as air temperature rises.

In Hawai‘i, average precipitation, average stream discharge, and stream baseflow have been trending downward for nearly a century, especially in recent decades, but with high variability due to cyclical climate patterns such as ENSO and the PDO (see "El Niño and other Patterns of Climate Variability").[34,35,36] For the Western North Pacific, a decline of 15% in annual rainfall has been observed in the eastern-most islands in the Micronesia region, and slight upward trends in precipitation have been seen for the western-most islands with high ENSO-related variability.[7] In American Samoa, no trends in average rainfall are apparent, but there is very limited available data.[7,37]

Projections of precipitation are less certain than those for temperature.[2,38] For Hawai‘i, a scenario based on statistical downscaling projects a 5% to 10% reduction for the wet season and a 5% increase in the dry season for the end of this century.[39] Projections for late this century from global models for the region give a range of results. Generally they predict annual rainfall to either change little or to increase by up to 5% for the main Hawaiian Islands and to change little or decrease up to 10% in the Northwestern Hawaiian Islands. They also project increases in the Micronesia region (Ch. 2: Our Changing Climate, Figure 2.6),[40] though there is low confidence in all these projections.

Climate change impacts on freshwater resources in the Pacific Islands will vary across the region. Different islands will be affected by different factors, including natural variability patterns that affect storms and precipitation (like El Niño and La Niña events), as well as climate trends that are strongly influenced by specific geographic locations. For example, surface air temperature has increased and is expected to continue to rise over the entire region.[41] In Hawai‘i, the rate of increase has been greater at high elevations.[41] In Hawai‘i and the Central North Pacific, projected annual surface air temperature increases range from 1.5°F by 2055 (relative to 1971-2000) under a scenario of substantial emissions reduction (B1), to 3.5°F assuming continued increases in emissions (A2).[40,42] In the Western North Pacific, the projected increases by 2055 are 1.9°F for the B1 scenario and 2.6°F for the A2 scenario.[8] In the central South Pacific, projected annual surface air temperature increases by 2055 are 1.9°F (B1) and 2.5°F (A2).[8]

On most islands, increased temperatures coupled with decreased rainfall and increased drought will reduce the amount of freshwater available for drinking and crop irrigation.[43] Climate change impacts on freshwater resources in the region will also vary because of differing island size and topography, which affect water storage capability and susceptibility to coastal flooding. Low-lying islands will be particularly vulnerable due to their small land mass, geographic isolation, limited potable water sources, and limited agricultural resources.[44] Also, as sea level rises over time, increasing saltwater intrusion from the ocean during storms will exacerbate the situation (Figure 23.6).[45,46] These are only part of a cascade of climate change related impacts that will increase the pressures on, and threats to, the social and ecosystem sustainability of these island communities.[47]

Observed Changes in Annual Rainfall in the Western North Pacific

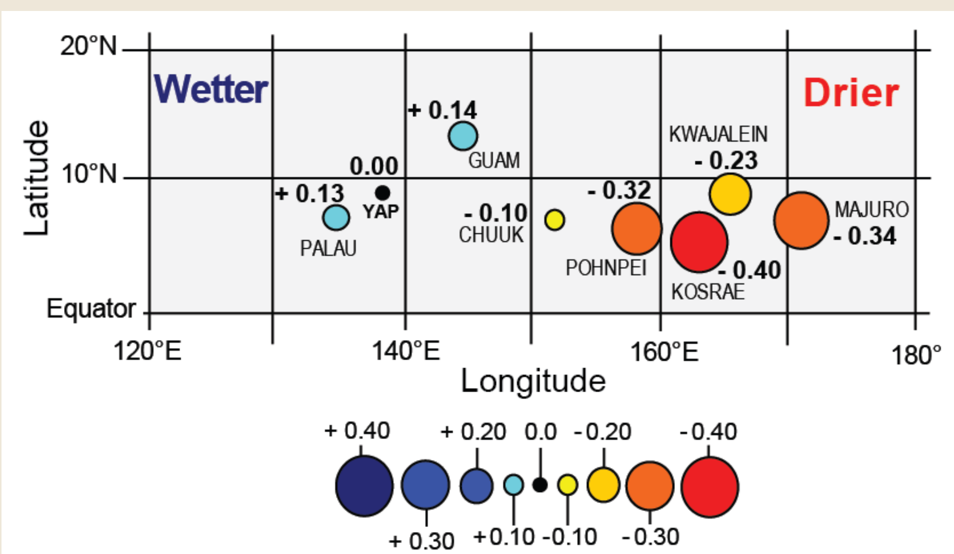

Figure 23.4. Islands in the western reaches of the Pacific Ocean are getting slightly more rainfall than in the past, while islands more to the east are getting drier (measured in change in inches of monthly rainfall per decade over the period 1950-2010). Darker blue shading indicates that conditions are wetter, while darker red shading indicates drier conditions. The size of the dot is proportional to the size of the trend on the inset scale. (Figure source: Keener et al. 2012[2]).

Key Message 3: Increased Stress on Native Plants and Animals

Increasing temperatures, and in some areas reduced rainfall, will stress native Pacific Island plants and animals, especially in high-elevation ecosystems with increasing exposure to invasive species, increasing the risk of extinctions.

Projected climate changes will significantly alter the distribution and abundance of many native marine, terrestrial, and freshwater species in the Pacific Islands. The vulnerability of coral reef and ocean ecosystems was discussed earlier. Land-based and freshwater species that exist in high-elevation ecosystems in high islands, as well as low-lying coastal ecosystems on all islands, are especially vulnerable. Existing climate zones on high islands are generally projected to shift upslope in response to climate change.[48] The ability of native species to adapt to shifting habitats will be affected by ecosystem discontinuity and fragmentation, as well as the survival or extinction of pollinators and seed dispersers. Some (perhaps many) invasive plant species will have a competitive edge over native species, as they disproportionately benefit from increased carbon dioxide, disturbances from extreme weather and climate events, and an ability to invade higher elevation habitats as climates warm.[49] Hawaiian high-elevation alpine ecosystems on Hawaiʻi and Maui islands are already beginning to show strong signs of higher temperatures and increased drought.[50] For example, the number of Haleakalā silversword, a rare plant that is an integral component of the alpine ecosystem in Haleakalā National Park in Maui and is found nowhere else on the planet, has declined dramatically over the past two decades.[51] Many of Hawaiʻi's native forest birds, marvels of evolution largely limited to high-elevation forests due to predators and diseases, are increasingly vulnerable as rising temperatures allow mosquitoes carrying diseases like avian malaria to thrive at higher elevations and thereby reduce the extent of safe bird habitat.[48,52]

Native Plants at Risk

Figure 23.5. Warming at high elevations could alter the distribution of native plants and animals in mountainous ecosystems and increase the threat of invasive species. The threatened, endemic ʻahinahina, or Haleakalā silversword (*Argyroxiphium sandwicense subsp. macrocephalum*), shown here in full bloom on Maui, Hawaiian Islands, is one example. (Photo credit: Forest and Kim Starr).

On high islands like Hawaiʻi, decreases in precipitation and baseflow are already indicating impacts on freshwater ecosystems and aquatic species.[35,37] Many Pacific Island freshwater fishes and invertebrates have oceanic larval stages in which they seasonally return to high island streams to aid reproduction.[53] Changes in stream flow and oceanic conditions that affect larval growth and survival will alter the ability of these species to maintain viable stream populations.

Key Message 4: Sea Level Rising

Rising sea levels, coupled with high water levels caused by tropical and extra-tropical storms, will incrementally increase coastal flooding and erosion, damaging coastal ecosystems, infrastructure, and agriculture, and negatively affecting tourism.

Global average sea level has risen by about 8 inches since 1900,[54] with recent satellite observations indicating an increased rate of rise over the past two decades (1.3 inches per decade) (see also Ch. 2: Our Changing Climate, Key Message 10).[55] Recent regional sea level trends in the western tropical Pacific are higher[56,57] than the global average, due in part to changing wind patterns associated with natural climate variability.[58,59] Over this century, sea level in the Pacific is expected to rise at about the same rate as the projected increase in global average sea level, with regional variations associated with ocean circulation changes and the Earth's response to other large-scale changes, such as melting glaciers and ice sheets as well as changing water storage in lakes and reservoirs.[60,61] For the region, extreme sea level events generally occur when high tides combine with changes in water levels due to storms, ENSO (see "El Niño and other Patterns of Climate Variability"), and other variations.[54,55,56,57,58,59,60]

Rising sea levels will escalate the threat to coastal structures and property, groundwater reservoirs, harbor operations, airports, wastewater systems, shallow coral reefs, sea grass beds, intertidal flats and mangrove forests, and other social, eco-

Saltwater Intrusion Destroys Crops

Figure 23.6. Taro crops destroyed by encroaching saltwater at Lukunoch Atoll, Chuuk State, FSM. Giant swamp taro is a staple crop in Micronesia that requires a two- to three-year growing period from initial planting to harvest. After a saltwater inundation from a storm surge or very high tide, it may take two years of normal rainfall to flush brackish water from a taro patch, resulting in a five-year gap before the next harvest if no further saltwater intrusion takes place. (Photo credit: John Quidachay, USDA Forest Service).

Residents of Low-lying Islands at Risk

Figure 23.7. Republic of the Marshall Islands, with a land area of just 1.1 square miles and a maximum elevation of 10 feet, may be among the first to face the possibility of climate change induced human migration as sea level continues to rise. (Photo credit: Darren Nakata).

nomic, and natural resources. Impacts will vary with location depending on how regional sea level variability combines with increases of global average sea level.[62] On low islands, critical public facilities and infrastructure as well as private commercial and residential property are especially vulnerable. Agricultural activity will also be affected, as sea level rise decreases the land area available for farming[45] and periodic flooding increases the salinity of groundwater. Coastal and nearshore environments will progressively be affected as sea levels rise and high wave events alter low islands' size and shape. Based on extrapolation from results in American Samoa, sea level rise could cause future reductions of 10% to 20% in total regional mangrove area over the next century.[63] This would in turn reduce the nursery areas and feeding grounds for fish species, habitat for crustaceans and invertebrates, shoreline protection and wave dampening, and water filtration provided by mangroves.[64] Pacific seabirds that breed on low-lying atolls will lose large segments of their breeding populations[65] as their habitat is increasingly and more extensively covered by seawater.

Impacts to the built environment on low-lying portions of high islands, where nearly all airports are located and where each island's road network is sited,[66] will be nearly as profound as those experienced on low islands. Islands with more developed built infrastructure will experience more economic impacts from tourism loss. In Hawai'i, for example, where tourism comprises 26% of the state's economy, damage to tourism infrastructure could have large economic impacts –the loss of Waikīkī Beach alone could lead to an annual loss of $2 billion in visitor expenditures.[67]

Higher Sea Level Rise in Western Pacific

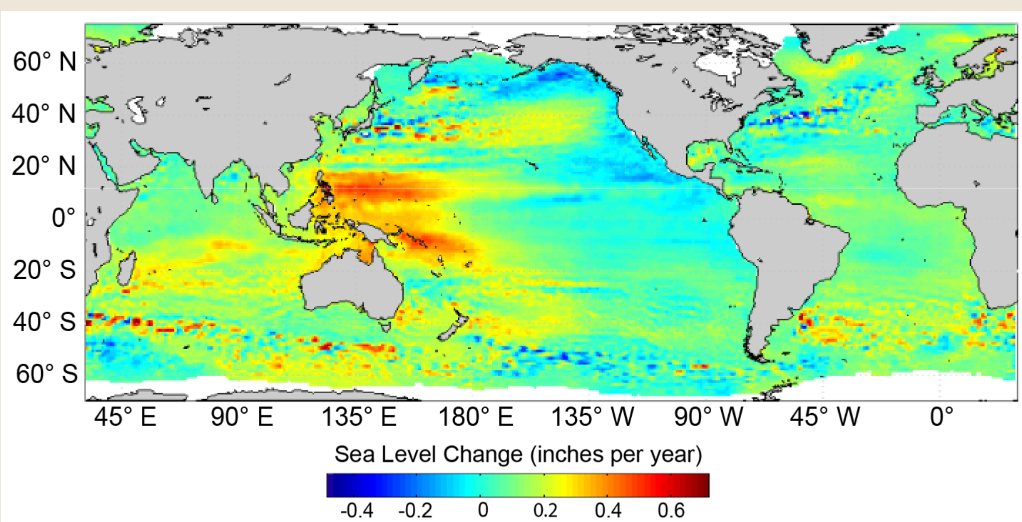

Figure 23.8. Map shows large variations across the Pacific Ocean in sea level trends for 1993-2010. The largest sea level increase has been observed in the western Pacific. (Figure source: adapted from Merrifield 2011[57] by permission of American Meteorological Society).

Key Message 5: Threats to Lives, Livelihoods, and Cultures

Mounting threats to food and water security, infrastructure, and public health and safety are expected to lead to increasing human migration from low to high elevation islands and continental sites, making it increasingly difficult for Pacific Islanders to sustain the region's many unique customs, beliefs, and languages.

All of the climate change impacts described above will have an impact on human communities in Pacific Islands. Because Pacific Islands are almost entirely dependent upon imported food, fuel, and material, the vulnerability of ports and airports to extreme events, sea level rise, and increasing wave heights is of great concern. Climate change is expected to have serious effects on human health, for example by increasing the incidence of dengue fever (Ch. 9: Human Health).[68] In addition, sea level rise and flooding are expected to overwhelm sewer systems and threaten public sanitation.

The traditional lifestyles and cultures of indigenous communities in all Pacific Islands will be seriously affected by climate change (see also Chapter 12: Indigenous Peoples). Sea level rise and associated flooding is expected to destroy coastal artifacts and structures[69] or even the entire land base associated with cultural traditions.[70] Drought threatens traditional food sources such as taro and breadfruit, and coral death from warming-induced bleaching will threaten subsistence fisheries in island communities.[46] Climate change related environmental deterioration for communities at or near the coast, coupled with other socioeconomic or political motivations, is expected to lead individuals, families, or communities to consider moving to new locations. Depending on the scale and distance of the migration, a variety of challenges face the migrants and the communities receiving them. Migrants need to establish themselves in their new community, find employment, and access services, while the receiving community's infrastructure, labor market, commerce, natural resources, and governance structures need to absorb a sudden burst of population growth.

Adaptation Activities

Adaptive capacity in the region varies and reflects the histories of governance, the economies, and the geographical features of the island/atoll site. High islands can better support larger populations and infrastructure, attract industry, foster institutional growth, and thus bolster adaptive capacity;[2] but these sites have larger policy or legal hurdles that complicate coastal planning.[71] Low islands have a different set of challenges. Climate change related migration, for example, is particularly relevant to the low island communities in the Republic of the Marshall Islands (RMI) and the Federated States of Micronesia (FSM), and presents significant practical, cultural, and legal challenges.[72]

In Hawai'i, state agencies have drafted a framework for climate change adaptation by identifying sectors affected by climate change and outlining a process for coordinated statewide adaptation planning.[73] Both Hawai'i and American Samoa specifically consider climate change in their U.S. Federal Emergency Management Agency (FEMA) hazard mitigation plans, and the Commonwealth of Northern Mariana Islands lists climate variability as a possible hazard related to extreme climate events.[74] The U.S. Pacific Island Freely Associated States (which includes the Republic of Palau, FSM, and RMI; Figure 23.1) have worked with regional organizations to develop plans and access international resources. Each of these jurisdictions has developed a status report on integrating climate-related hazard information in disaster risk reduction planning and has developed plans for adaptation to climate-related disaster risks.[75] Overall, there is very little research on the effectiveness of alternative adaptation strategies for Pacific Islands and their communities. The regional culture of communication and collaboration provides a strong foundation for adaptation planning and will be important for building resilience in the face of the changing climate.

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SUPPLEMENTAL MATERIAL
TRACEABLE ACCOUNTS

Process for Developing Key Messages

A central component of the assessment process was convening three focus area workshops as part of the Pacific Islands Regional Climate Assessment (PIRCA). The PIRCA is a collaborative effort aimed at assessing the state of climate knowledge, impacts, and adaptive capacity in Hawai'i and the U.S. Affiliated Pacific Islands. These workshops included representatives from the U.S. federal agencies, universities, as well as international participants from other national agencies and regional organizations. The workshops led to the formulation of a foundational Technical Input Report (TIR).[2] The report consists of nearly 140 pages, with almost 300 references, and was organized into 5 chapters by 11 authors.

The chapter author team engaged in multiple technical discussions via regular teleconferences that permitted a careful review of the foundational TIR[2] and of approximately 23 additional technical inputs provided by the public, as well as the other published literature, and professional judgment. These discussions included a face-to-face meeting held on July 9, 2012. These discussions were supported by targeted consultation among the lead and contributing authors of each message. There were several iterations of review and comment on draft key messages and associated content.

Key message #1 Traceable Account

Warmer oceans are leading to increased coral bleaching events and disease outbreaks in coral reefs, as well as changed distribution patterns of tuna fisheries. Ocean acidification will reduce coral growth and health. Warming and acidification, combined with existing stresses, will strongly affect coral reef fish communities.

Description of evidence base

The key message was chosen based on input from the extensive evidence documented in the Hawai'i Technical Input Report[2] and additional technical inputs received as part of the Federal Register Notice solicitation for public input, as well as stakeholder engagement leading up to drafting the chapter.

Ocean warming: There is ample evidence that sea-surface temperatures have already risen throughout the region based on clear observational data, with improved data with the advent of satellite and in situ (ARGO & ship-based) data.[7] Assessment of the literature for the region by other governmental bodies (such as Australian Bureau of Meteorology [ABOM] and the Commonwealth Scientific and Industrial Research Organization [CSIRO]) point to continued increases under both B1 and A2 scenarios.[8]

Ocean acidification: Globally, the oceans are currently absorbing about a quarter of the carbon dioxide emitted to the atmosphere annually, and becoming more acidic as a result (Ch. 2: Our Changing Climate, Key Message 12). Historical and current observations of aragonite saturation state (Ωar) for the Pacific Ocean show a decrease from approximately 4.9 to 4.8 in the Central North Pacific (Hawaiian Islands); in the Western North Pacific (Republic of Marshall Islands, Commonwealth of Northern Mariana Islands, Federated States of Micronesia, Republic of Palau, Guam), it has declined from approximately 4.5 to 3.9 in 2000, and to 4.1 in the Central South Pacific (American Samoa) (this chapter: Figure 23.3; Ch. 24: Oceans and Marine Resources).[19] Projections from CMIP3 models indicate the annual maximum aragonite saturation state will reach values below 3.5 by 2035 in the waters of the Republic of the Marshall Islands (RMI), by 2030 in the Federated States of Micronesia (FSM), by 2040 in Palau, and by 2060 around the Samoan archipelago. These values are projected to continue declining thereafter.[2] The recently published *Reefs at Risk Revisited*[25] estimates aragonite saturation state (as an indicator of ocean acidification) for CO_2 stabilization levels of 380 ppm, 450 ppm, and 500 ppm, which correspond approximately to the years 2005, 2030, and 2050 under the A1B emissions scenario (which assumes similar emissions to the A2 scenario through 2050 and a slow decline thereafter) (Figure 4.4 from Keener et al. 2012[2]).

Bleaching events: These have been well-documented in extensive literature worldwide due to increasing temperatures, with numerous studies in Hawai'i and the Pacific Islands.[9,10]

Disease outbreaks: Reports of coral diseases have been proliferating in the past years,[11,13] but few have currently been adequately described, with causal organisms identified (for example, fulfill Koch's Postulates).

Reduced growth: There is abundant evidence from laboratory experiments that lower seawater pH reduces calcification rates in marine organisms (for example, Feely et al. 2009[19]). However, actual measurements on the effects of ocean acidification on coral reef ecosystems in situ or in complex mesocosms are just now becoming available, and these measurements show that there are large regional and diel variability in pH and pCO_2.[76] The role of diel and regional variability on coral reef ecosystems requires further investigation.

Distribution patterns of coastal and ocean fisheries: Evidence of the effects of ocean acidification on U.S. fisheries in Hawai'i and the Pacific Islands is currently limited (Lehodey et al. 2011)[28] but there is accumulating evidence for ecosystem impacts.

New information and remaining uncertainties

New information: Since the 2009 National Climate Assessment,[77] considerable effort has been employed to understand the impacts of ocean acidification (OA) on marine ecosystems, including recent ecosystem-based efforts.[22,28] Studies of OA impacts on organisms has advanced considerably, with careful chemistry using worldwide standard protocols making inroads into understanding a broadening range of organisms.

However, predicting the effect of ocean acidification on marine organisms and marine coral reef ecosystems remains the key issue of uncertainty. The role of community metabolism and calcification in the face of overall reduction in aragonite saturation state must be investigated.

Understanding interactions between rising temperatures and OA remains a challenge. For example, high temperatures simultaneously cause coral bleaching, as well as affect coral calcification rates, with both impacts projected to increase in the future.

Assessment of confidence based on evidence

There is **very high** confidence that ocean acidification and decreased aragonite saturation is taking place and is projected to continue. There is **high** confidence that ocean warming is taking place and is projected to continue; there is **medium** confidence that the thermal anomalies will lead to continued coral bleaching and coral disease outbreaks.

Confidence Level
Very High
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Key message #2 Traceable Account

Freshwater supplies are already constrained and will become more limited on many islands. Saltwater intrusion associated with sea level rise will reduce the quantity and quality of freshwater in coastal aquifers, especially on low islands. In areas where precipitation does not increase, freshwater supplies will be adversely affected as air temperature rises.

Description of evidence base

There is abundant and definitive evidence that air temperature has increased and is projected to continue to increase over the entire region,[8,41,78] as there is globally (Ch. 2: Our Changing Climate, Key Message 3).

In Hawai'i and the Central North Pacific (CNP), projected annual surface air temperature increases are 1.0°F to 2.5°F by 2035, relative to 1971-2000.[40,42] In the Western North Pacific (WNP), the projected increases are 2.0°F to 2.3°F by 2030, 6.1°F to 8.5°F by 2055, and 4.9°F to 9.2°F by 2090.[8] In the central South Pacific (CSP), projected annual surface air temperature increases are 1.1°F to 1.3°F by 2030, 1.8°F to 2.5°F by 2055, and 2.5°F to 4.9°F by 2090.[8] (Please note that the islands that comprise the U.S. Pacific Islands Region are shown in Figure 23.1).

In Hawai'i, mean precipitation, average stream discharge, and stream baseflow have been trending downward for nearly a century, especially in recent decades and with high variability related to El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO).[34,35] For the WNP, a decline of 15% in annual rainfall has been observed in the eastern-most islands in the Micronesia region and slight upward trends in precipitation have been seen for the western-most islands, with high ENSO-related variability.[8] In American Samoa, no trends in average rainfall are apparent based on the very limited available data.[8,37]

For the region as a whole, models disagree about projected changes in precipitation. Mostly models predict increases in mean annual rainfall and suggest a slight dry season decrease and wet season increase in precipitation.[8] However, based on statistical downscaling, one study[39] projected a 5% to 10% reduction in precipitation for the wet season and a 5% increase in the dry season for Hawai'i by the end of this century.

On most islands, increased temperatures coupled with decreased rainfall and increased drought will reduce the amount of freshwater for drinking and crop irrigation.[43] Atolls will be particularly vulnerable due to their low elevation, small land mass, geographic isolation, and limited potable water sources and agricultural resources.[44] The situation will also be exacerbated by the increased incidence of intrusion of saltwater from the ocean during storms as the mean sea level rises over time (Key Message 4, this chapter; Ch. 2: Our Changing Climate, Key Message 10).[2]

New information and remaining uncertainties

Climate change impacts on freshwater resources in the Pacific Islands region will vary because of differing island size and height, which affect water storage capability and susceptibility to coastal inundation. The impacts will also vary because of natural phase variability (for example, ENSO and PDO) in precipitation and storminess (tropical and extra-tropical storms) as well as long-term trends, both strongly influenced by geographic location.

Climate model simulations produce conflicting assessments as to how the tropical Pacific atmospheric circulation will respond in the future to climate change.

Assessment of confidence based on evidence

Freshwater systems are inherently fragile in many Pacific Islands. Historical observations show strong evidence of a decreasing trend for rainfall in Hawai'i and many other Pacific Islands (Ch. 2: Our Changing Climate).[2] There is abundant and definitive evidence that air temperature has increased and will continue to increase. All of the scientific approaches to detecting sea level rise come to the conclusion that a warming planet will result in higher sea levels. Based on the evidence base and remaining uncertainties, we have **high** confidence in the key message.

Key message #3 Traceable Account

Increasing temperatures, and in some areas reduced rainfall, will stress native Pacific Island plants and animals, especially in high-elevation ecosystems with increasing exposure to invasive species, increasing the risk of extinctions.

Description of evidence base

In Hawai'i and the Central North Pacific (CNP), projected annual surface air temperature increases are 1.0°F to 2.5°F by 2035, relative to 1971-2000.[40,42] In the Western North Pacific (WNP), the projected increases are 2.0°F to 2.3°F by 2030, 6.1°F to 8.5°F by 2055, and 4.9°F to 9.2°F by 2090.[8] In the Central South Pacific (CSP), projected annual surface air temperature increases are 1.1°F to 1.3°F by 2030, 1.8°F to 2.5°F by 2055, and 2.5°F to 4.9°F by 2090.[8] In Hawai'i the rate of increase has been greater at high elevations.[41] (Please note that the islands that comprise the U.S. Pacific Islands Region are shown in Figure 23.1).

In Hawai'i mean precipitation, average stream discharge, and stream baseflow have been trending downward for nearly a century, especially in recent decades and with high ENSO and PDO-related variability.[34,35,36] Projects based on statistical downscaling[39] suggest the most likely precipitation scenario for Hawai'i for the 21st century to be a 5% to 10% reduction for the wet season and a 5% increase in the dry season.

On high islands like Hawai'i, decreases in precipitation and baseflow[35] are already indicating that there will be impacts on freshwater ecosystems and aquatic species, and on water-intensive sectors such as agriculture and tourism.

Hawaiian high-elevation alpine ecosystems on Hawai'i and Maui islands are already beginning to show strong signs of increased drought and warmer temperatures.[50] Demographic data for the Haleakalā silversword, a unique (endemic to upper Haleakalāvolcano) and integral component of the alpine ecosystem in Haleakalā National Park, Maui, have recorded a severe decline in plant numbers over the past two decades.[51] Many of Hawai'i's endemic forest birds, marvels of evolution largely limited to high-elevation forests by predation and disease, are increasingly vulnerable as rising temperatures allow the disease-vectoring mosquitoes to thrive upslope and thereby reduce the extent of safe bird habitat.[48,52]

New information and remaining uncertainties

Climate change impacts in the Pacific Islands region will vary because of differing island size and height. The impacts will also vary because of natural phase variability (for example, El Niño-Southern Oscillation and Pacific Decadal Oscillation) in precipitation and storminess (tropical and extra-tropical storms) as well as long-term trends, both strongly influenced by geographic location.

Climate model simulations produce conflicting assessments as to how the tropical Pacific atmospheric circulation will respond in the future to climate change.[2,8]

Climate change ecosystem response is poorly understood.[2]

Assessment of confidence based on evidence

Terrestrial and marine ecosystems are already being impacted by local stressors, such as coastal development, land-based sources of pollution, and invasive species.[2,25] There is abundant and definitive evidence that air temperature has increased and will continue to increase. Historical observations show strong evidence of a decreasing trend for rainfall in Hawai‘i and many other Pacific Islands.[2] Given the evidence base and remaining uncertainties, confidence is **high** in this key message.

Key message #4 Traceable Account

Rising sea levels, coupled with high water levels caused by tropical and extra-tropical storms, will incrementally increase coastal flooding and erosion, damaging coastal ecosystems, infrastructure, and agriculture, and negatively affecting tourism.

Description of evidence base

All of the scientific approaches to detecting sea level rise come to the conclusion that a warming planet will result in higher sea levels. Recent studies give higher sea level rise projections than those projected in 2007 by the Intergovernmental Panel on Climate Change[29] for the rest of this century (Ch. 2: Our Changing Climate, Key Message 10).[55]

Sea level is rising and is expected to continue to rise. Over the past few decades, global mean sea level, as measured by satellite altimetry, has been rising at an average rate of twice the estimated rate for the previous century, based on tide gauge measurements,[55] with models suggesting that global sea level will rise significantly over the course of this century. Regionally, the highest increases have been observed in the western tropical Pacific.[56] However, the current high rates of regional sea level rise in the western tropical Pacific are not expected to persist, as regional sea level will fall in response to a change in phase of natural variability.[62] Regional variations in sea level at interannual and interdecadal time scales are generally attributed to changes in prevailing wind patterns associated with El Niño-Southern Oscillation (ENSO) as well as the Pacific Decadal Oscillation (PDO) and low frequency components of the Southern Oscillation Index (SOI).[59]

For the region, extreme sea level events generally occur when high tides combine with some non-tidal residual change in water level. In the major typhoon zones (Guam and Commonwealth of the Northern Mariana Islands), storm-driven surges can cause coastal flooding and erosion regardless of tidal state. Wave-driven inundation events are a major concern for all islands in the region. At present, trends in extreme levels tend to follow trends in mean sea level.

Increasing mean water levels and the possibility of more frequent extreme water level events, and their manifestation as flooding and erosion, will threaten coastal structures and property, groundwater reservoirs, harbor operations, airports, wastewater systems, sandy beaches, coral reef ecosystems, and other social and economic resources. Impacts will vary with location, depending on how natural sea level variability combines with modest increases of mean levels.[62]

On low-lying atolls, critical public facilities and infrastructure as well as private commercial and residential property are especially vulnerable.[62] Agricultural activity will also be affected, as sea level rise decreases the land area available for farming[45] and episodic inundation increases salinity of groundwater resources. Impacts to the built environment on low-lying portions of high islands will be much the same as those experienced on low islands. Islands with more developed built infrastructure will experience more economic impacts from tourism loss. One report stated: "Our analyses estimate that nearly $2.0 billion in overall visitor expenditures could be lost annually due to a complete erosion of Waikīkī Beach."[67]

Coastal and nearshore environments (sandy beaches, shallow coral reefs, seagrass beds, intertidal flats, and mangrove forests) and the vegetation and terrestrial animals in these systems will progressively be affected as sea level rise and high wave events alter atoll island size and shape and reduce habitat features necessary for survival. Based on extrapolation from results in American Samoa, sea level rise could cause future reductions of 10%–20% of total regional mangrove area over the next century.[63] Further, atoll-breeding Pacific seabirds will lose large segments of their breeding populations[65] as their habitat is increasingly and more extensively inundated.

Major uncertainties

Sea levels in the Pacific Ocean will continue to rise with global sea level. Models provide a range of predictions, with some suggesting that global warming may raise global sea level considerably over the course of this century. The range of predictions is large due in part to unresolved physical understanding of various processes, notably ice sheet dynamics.

Changes in prevailing wind patterns associated with natural climate cycles such as ENSO and the PDO affect regional variations in sea level at interannual and interdecadal time scales. Sea level at specific locales will continue to respond to changes in phase of these natural climate cycles. The current high rates of regional sea level rise in the western tropical Pacific are not expected to persist over time, falling once the trade winds begin to weaken.

Future wind wave conditions are difficult to project with confidence given the uncertainties regarding future storm conditions.

Assessment of confidence based on evidence

Evidence for global sea level rise is strong (Ch. 25: Coasts; Ch. 2: Our Changing Climate). Confidence is therefore **very high**. Modeling studies have yielded conflicting results as to how ENSO and other climate modes will vary in the future. As a result, there is **low** confidence in the prediction of future climate states and their subsequent influence on regional sea level.[62] Recent assessments of future extreme conditions generally place **low** confidence on region-specific projections of future storminess.[61]

For aspects of the key message concerning impacts, confidence is **high**.

Key message #5 Traceable Account

Mounting threats to food and water security, infrastructure, and public health and safety are expected to lead to increasing human migration from low to high elevation islands and continental sites, making it increasingly difficult for Pacific Islanders to sustain the region's many unique customs, beliefs, and languages.

Description of evidence base

Climate change threatens communities, cultures, and ecosystems of the Pacific Islands both directly through impact on food and water security, for example, as well as indirectly through impacts on economic sectors including fisheries and tourism.

On most islands, increased temperatures, coupled with decreased rainfall and increased drought, will lead to an additional need for freshwater resources for drinking and crop irrigation.[43] This is particularly important for locations in the tropics and subtropics where observed data and model projections suggest that, by the end of this century, the average growing season temperatures will exceed the most extreme seasonal temperatures recorded from 1900 to 2006. Atolls will be particularly vulnerable due to their low elevation, small land mass, geographic isolation, and limited potable water sources and agricultural resources.[44] The situation will also be exacerbated by the increased incidence of intrusion of saltwater from the ocean during storms as the mean sea level rises over time. These are but part of a cascade of impacts that will increase the pressures on, and threats to, the social and ecosystem sustainability of these island communities.[47] On high islands like Hawai‘i, decreases in precipitation and baseflow[35] are already indicating that there will be impacts on freshwater ecosystems and aquatic species and on water-intensive sectors such as agriculture and tourism.

Increasing mean oceanic and coastal water levels and the possibility of more frequent extreme water level events with flooding and erosion will escalate the threat to coastal structures and property, groundwater reservoirs, harbor operations, airports, wastewater systems, sandy beaches, coral reef ecosystems, and other social and economic resources. Impacts will vary with location depending on how natural sea level variability combines with modest increases of mean levels.[62] On low-lying atolls, critical public facilities and infrastructure as well as private commercial and residential property are especially vulnerable. Agricultural activity will also be affected, as sea level rise decreases the land area available for farming[45] and episodic inundation increases salinity of groundwater resources.

With respect to cultural resources, impacts will extend from the loss of tangible artifacts and structures[69] to the intangible loss of a land base and the cultural traditions that are associated with it.[70]

New information and remaining uncertainties

Whenever appraising threats to human society, it is uncertain the degree to which societies will successfully adapt to limit impact. For island communities, though, the ability to migrate is very limited, and the ability to adapt is especially limited. Depending on the scale and distance of the migration, a variety of challenges face the migrants and the communities receiving them. Migrants need to establish themselves in their new community, find employment, and access services, while the receiving community's infrastructure, labor market, commerce, natural resources, and governance structures need to absorb a sudden burst of population growth.

Assessment of confidence based on evidence

Evidence for climate change and impacts is strong, but highly variable from location to location. One can be highly confident that climate change will continue to pose varied threats in the region. Adaptive capacity is also highly variable among the islands, so the resulting situation will play out differently in different places. Confidence is therefore **medium**.