23. Hawaiʻi and U.S. Affiliated Pacific Islands

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Key Messages

1. **Ocean warming and acidification are producing changes in coastal and ocean ecosystems. Warmer seas are leading to increased coral bleaching events and disease outbreaks in coral reefs, and changed distribution patterns of tuna fisheries. Ocean acidification will lead to reduced calcification rates for corals and coralline algae. Both factors, combined with existing stresses, will strongly affect the fish community of coral reefs.**

2. **Freshwater supplies are already constrained and will be more limited on many Pacific Islands, especially low-lying islands. The quantity and quality of freshwater in aquifers and surface catchments will decline in response to warmer and drier conditions, coupled with increased occurrences of saltwater intrusion associated with sea level rise.**

3. **Increasing temperatures, and in some areas reduced rainfall, will stress native Pacific Island plant and animal populations and species, 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 tropical and extra-tropical 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, and public health and safety are expected to lead to increasing human migration from low to high elevation islands and continental sites. Under these circumstances, it will become increasingly difficult for Pacific Islanders to sustain the region’s many unique customs, beliefs, and languages.**

Introduction

The U.S. Pacific Islands region is vast, comprising more than 2,000 islands spanning millions of square miles of ocean. The largest group of islands in this region, the Hawai‘ian Archipelago, is located nearly 2,400 miles from any continental land mass, which makes it one of the most remote archipelagos on the globe (Loope 1998). The Hawai‘ian 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 every aspect of life. Rising air and ocean temperatures, shifting rainfall patterns, changing frequencies and intensities of storms and drought, decreasing base flow in streams, rising sea levels, and changing ocean chemistry will affect marine and terrestrial ecosystems, as well as local communities, livelihoods, and cultures. Low islands are particularly at risk.

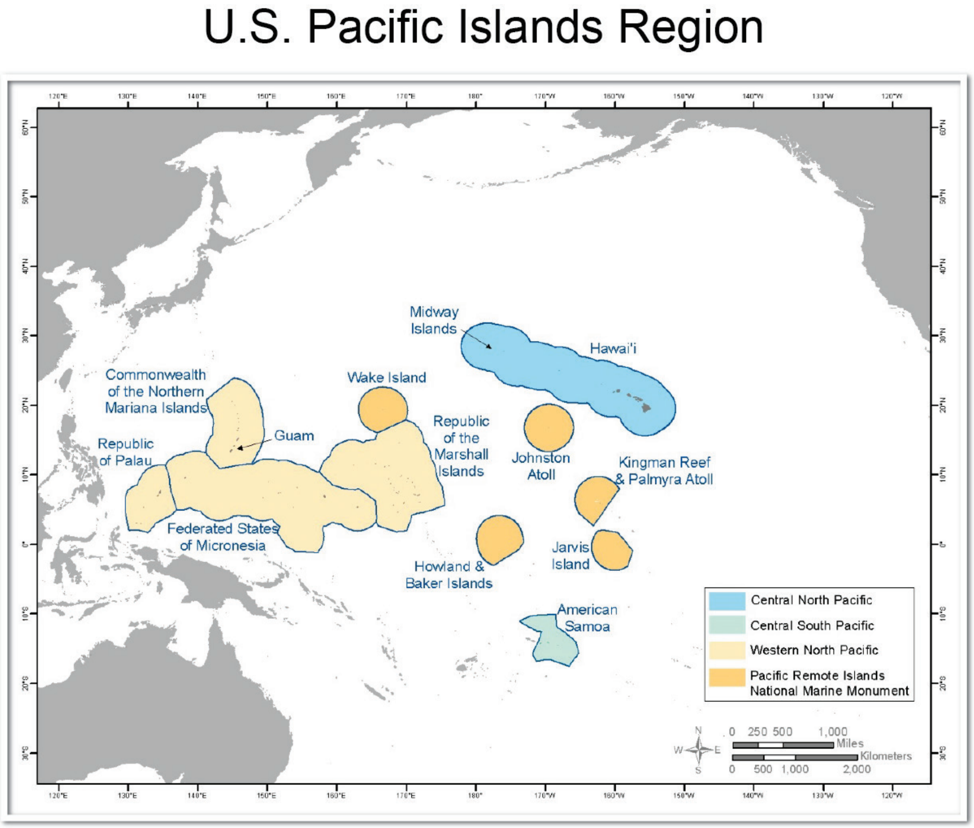

Figure 23.1: U.S. Pacific Islands Region

Caption: The U.S. Pacific Islands region includes our 50th state, Hawai‘i, as well as the Territories of Guam and 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 Marshall Islands (RMI). Citizens of Guam are U.S. citizens and citizens of American Samoa are U.S. nationals. Through the Compacts of Free Association, citizens of CNMI, 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) (Source: Keener et al. 2012). Map courtesy of Miguel Castrence/East-West Center.

U.S. 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 Hawai‘ian high Islands, as many as 10 ecozones – from alpine systems to tropical rainforests – exist within a 25-mile span (Pratt et al. 1998; Ziegler 2002). Isolation and landscape diversity in Hawai‘i brings about some of the highest concentrations of native species, found nowhere else in the world (Ziegler 2002). 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 (Allen 2008; Fautin et al. 2010). 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.

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

The Ko’olau Mountains on the windward side of Oahu, Hawaii. © 2008 kstrebor via Flickr.com, used under a Creative Commons Attribution-ShareAlike license.

Laysan Island, Papahānaumokuākea Marine National Monument, courtesy of Andy Collins/NOAA.

Figure 23.2: “High” and “Low” Pacific Islands Face Different Threats

Caption: The Pacific Islands include “high” volcanic islands that reach nearly 14,000 feet above sea level and “low” atolls and islands that peak at just a few feet above present sea level.

The Pacific Islands region includes demographically, culturally, and economically varied communities of diverse indigenous Pacific Islanders, intermingled with immigrants primarily from Asia, Europe, North America, New Zealand, and Australia. 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 (Gegeo 2001; Gegeo and Watson-Gegeo 2001; Teddy et al. 2008). 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.

Box 1. High interannual and interdecadal variability of the climate in the Pacific Islands region makes it difficult to discern long-term trends.

The effects of the El Niño-Southern Oscillation (ENSO) on the region are significant. They include large variations in sea surface temperatures, the strength and persistence of the trade winds, the position of the jet streams and storm tracks, and the location and intensity of rainfall (Australian Bureau of Meteorology and CSIRO 2011; IPCC 2007; Kumar and Hoerling 1998; Trenberth 1991; Wyrtki 1975). 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 (Australian Bureau of Meteorology and CSIRO 2011; D'Aleo and Easterbrook 2010). 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 (D'Aleo and Easterbrook 2010; Mantua et al. 1997). This dramatic short-term variability (the noise) can obscure subtle long-term change (the signal) (Deser et al. 2012; Meehl et al. 2009). Despite the challenges of distinguishing natural variability from long-term change, there are several key indicators of observed change that serve as a basis for monitoring and evaluating future change (Keener et al. 2012).

Short-term Variability Continues to Obscure Trends

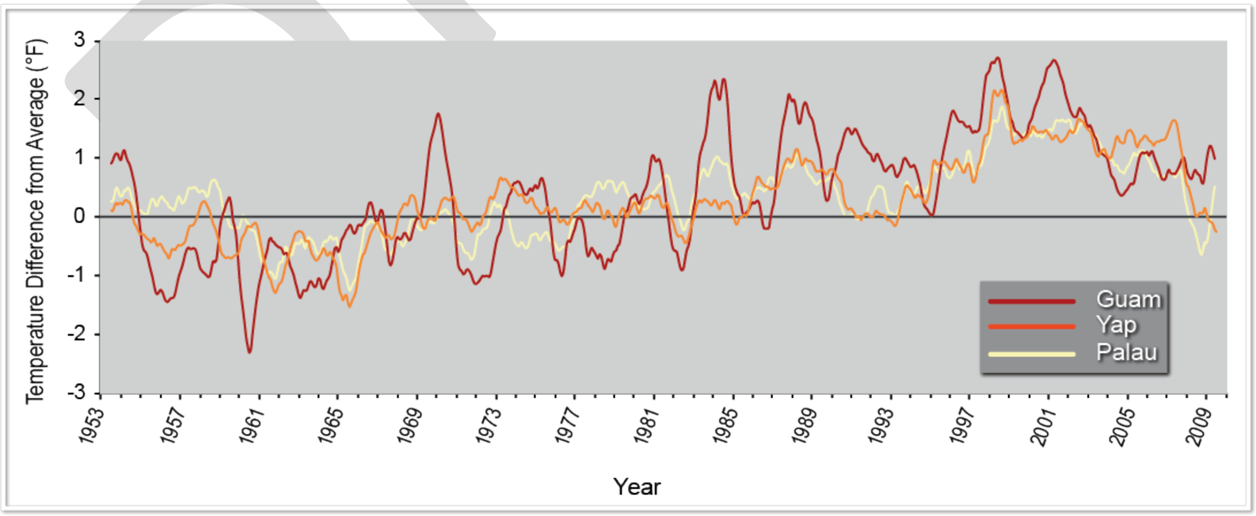

Figure 23.3: Short-term Variability Continues to Obscure Trends

Caption: Average daily maximum temperature for the month relative to the base period average over 1953 to 2010 for single monitoring stations in Yap, Guam, and Palau. The natural patterns of climate in the Pacific such as ENSO, PDO, and IPO continue to make it difficult to discern clear temperature trends on many Pacific islands, although the general trend does follow the global trend of 0.13°F per decade (IPCC 2007) (Adapted from Guard and Lander 2012).

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Changes to Marine Ecosystems

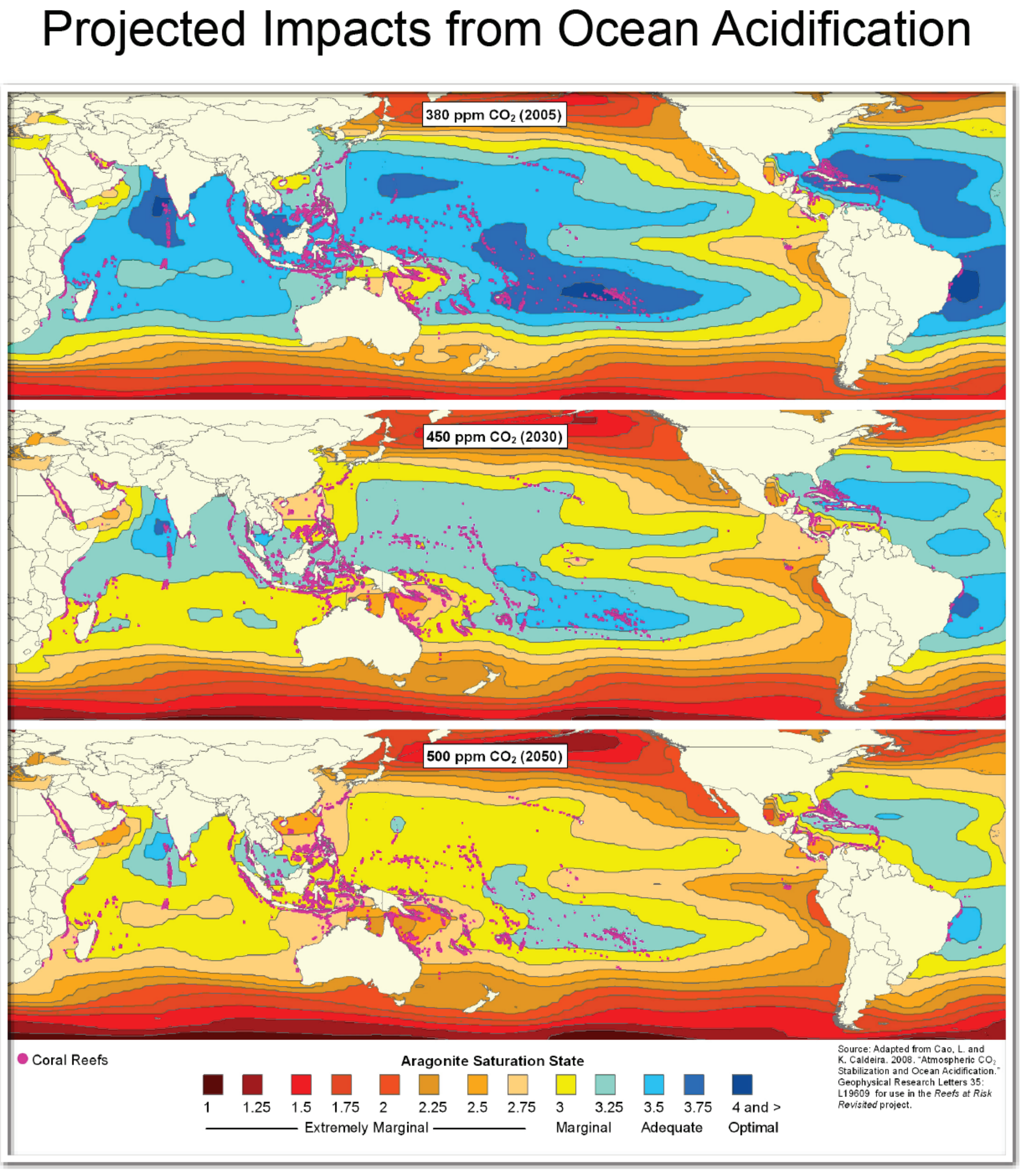
Ocean warming and acidification are producing changes in coastal and ocean ecosystems. Warmer seas are leading to increased coral bleaching events and disease outbreaks in coral reefs, and changed distribution patterns of tuna fisheries. Ocean acidification will lead to reduced calcification rates for corals and coralline algae. Both factors, combined with existing stresses, will strongly affect the fish community of coral reefs.

Ocean temperatures in the Pacific region exhibit strong interannual 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 (Ganachaud et al. 2011).

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) (Australian Bureau of Meteorology and CSIRO 2011).

Ocean acidification is also taking place in the region. Ocean acidity has increased by about 26% since the preindustrial era and is projected to further increase by 37% to 50% from present levels by 2100 (Feely et al. 2009). The amount of aragonite, the biologically important calcium carbonate mineral critical to reef-building coral and to calcifying algae, will decrease as a result of ocean acidification. Aragonite levels are projected to reach levels that reduce coral growth and survival by 2035 to 2060 around the Pacific, with continuing declines thereafter (Langdon and Atkinson 2005). Crustose coralline algae, an inconspicuous but important component of reefs that help reefs to form and that act as critical surfaces for other organisms to grow on, are also expected to exhibit reduced growth and survival (Diaz ‑ Pulido et al. 2012; Kline et al. 2012; Kuffner et al. 2008). These changes are projected to have a strong negative impact on the economies and well-being of island communities, with loss of coral biodiversity and reduced resilience (Hoegh-Guldberg et al. 2007).

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 Hawaiʻian Islands in the last decade (Jokiel and Brown 2004; Kenyon and Brainard 2006). Incidences of coral bleaching have been recorded in Micronesia and American Samoa (Fenner et al. 2008), testing the resilience of these reefs. 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 an extensive loss in both numbers and species of reef fishes (Pratchett et al. 2011). 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 (Cesar and van Beukering 2004), which could be threatened by these impacts.



Source: Adapted from Cao, L. and K. Caldeira. 2008. "Atmospheric CO_2 Stabilization and Ocean Acidification." Geophysical Research Letters 35: L19609 for use in the *Reefs at Risk Revisited* project.

Figure 23.4: Projected Impacts from Ocean Acidification

Caption: Ocean waters have already become more acidic from absorbing carbon dioxide from the atmosphere. In addition to lowering ocean pH, the absorption of CO_2 also has altered the amount of aragonite saturation, which is critical for many marine organisms to reproduce and grow. Maps show projections for aragonite saturation state if CO_2 levels are 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 some decrease from current emissions trend (scenario A1B). Higher emissions will lead to many more places where aragonite concentrations are "marginal" or "extremely marginal" in much of the Pacific. (In scenario A1B, emissions are similar to scenario A2 through 2050, then reduce towards scenario B1 levels, with emissions in 2100 midway between A2 and B1, while temperatures in 2100 are the same as with A2). Figure used with permission, from Burke and Spalding (2011), (adapted from Cao and Caldeira 2008).

Similarly, impacts to the economically important tuna fishery in the Pacific Island region will be high. Surface chlorophyll data obtained by satellites indicate a decline in an index of productivity in the subtropical South and North Pacific (Polovina et al. 2008) due to warming. This trend is projected to continue under future climate change (Polovina et al. 2011). One fishery model, coupled with a climate model, forecasts that the total fishery catch for skipjack tuna will initially increase by about 19% by 2035 with no change for bigeye tuna. However, by 2100 the catch for both skipjack and bigeye will decline overall by 8% and 27%, respectively, under current emissions trend (A2) for the western and central Pacific, with important spatial differences within the region (Lehodey et al. 2011).

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.

Decreasing Freshwater

Freshwater supplies are already constrained and will be more limited on many Pacific Islands, especially low islands. The quantity and quality of freshwater in aquifers and surface catchments will decline in response to warmer, drier conditions coupled with increased occurrences of saltwater intrusion associated with sea level rise.

Surface air temperature has increased and is expected to continue to increase over the entire region (Giambelluca et al. 2008). In Hawaiʻi, the rate of increase has been greater at high elevations (Giambelluca et al. 2008). In Hawaiʻi 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) (Christensen et al. 2007; Meehl et al. 2007). In the Western North Pacific, the projected increases are 1.9°F and 2.6°F by 2055 under the B1 and A2 scenarios, respectively (Australian Bureau of Meteorology and CSIRO 2011). In the Central South Pacific, projected annual surface air temperature increases are 1.9°F and 2.5°F by 2055 under the B1 and A2 scenarios (Australian Bureau of Meteorology and CSIRO 2011).

In Hawaiʻi, average precipitation, average stream discharge, and stream base flow 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 (Bassiouni and Oki 2012; Chu and Chen 2005; Oki 2004). 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 (Bailey and Jenson 2011; Ganachaud et al. 2011). In American Samoa, no trends in average rainfall are apparent, but there is very limited available data (Ganachaud et al. 2011; Young 2007).

Projections of precipitation are less certain than those for temperature (Keener et al. 2012). For Hawaiʻi, 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 (Timm and Diaz 2009). 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 Hawaiʻian Islands, change little or decrease up to 10% in the Northwest Hawaiʻian Islands, and increase 5% to 15% in the U.S.-affiliated islands of Micronesia (Christensen et al. 2007).

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. 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. On most islands, increased temperatures coupled with decreased rainfall and increased drought will increase the need for, and reduce the amount of, freshwater available for drinking and crop irrigation (Döll 2002; Sivakumar and Hansen 2007). Low-lying islands will be particularly vulnerable due to their small land mass, geographic isolation, limited potable water sources, and agricultural resources (Barnett and Adger 2003). Also, as sea level rises over time, increasing intrusion of saltwater from the ocean during storms will exacerbate the situation. 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 (Storlazzi et al. 2011).

Observed Changes in Annual Rainfall in the Western North Pacific

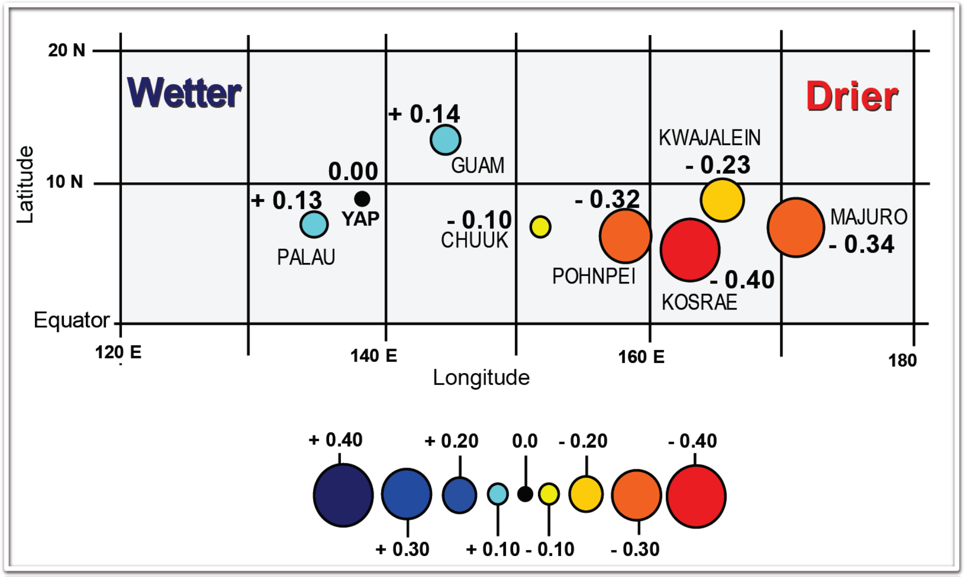


Figure 23.5: Observed Changes in Annual Rainfall in the Western North Pacific

Captions: Islands in the west are getting slightly more rainfall than in the past, while islands in 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 as per the inset scale. (Source: Modified and updated from Lander 2004; Lander and Guard 2003).

Increased Stress on Native Plants and Animals

Increasing temperatures, and in some areas reduced rainfall, will stress native Pacific Island plant and animal populations and species, 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. With respect to land-based and freshwater species, 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 (Benning et al. 2002). 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 climate events, and an ability to invade higher elevation habitats as climates warm (Bradley et al. 2010). Hawaiʻian high-elevation alpine ecosystems on Hawai`i and Maui islands are already beginning to show strong signs of increased drought and higher temperatures (Cao et al. 2007). 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 (Krushelnycky et al. 2012). Many of Hawaiʻi's native forest birds, marvels of evolution largely limited to high-elevation forests by predation and disease, are increasingly vulnerable as rising temperatures allow mosquitoes carrying diseases like avian malaria to thrive upslope and thereby reduce the extent of safe bird habitat (Benning et al. 2002; LaPointe et al. 2012).

Native Plants at Risk

Figure 23.6: Native Plants at Risk

Caption: 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, Hawaiʻian Islands, is one example. Photo courtesy of Forest & Kim Starr.

On high islands like Hawaiʻi, decreases in precipitation and base flow are already indicating that there will be impacts on freshwater ecosystems and aquatic species (Oki 2004; Young 2007). Many Pacific Island freshwater fishes and invertebrates have oceanic larval stages in which they seasonally return to high island streams to aid reproduction (Keith 2003; Maciolek 1983). 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.

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 (Church and White 2011), with recent satellite observations indicating an increased rate of rise over the past two decades (1.3 inches per decade) (Nerem et al. 2010)(See also Ch. 2: Our Changing Climate, Key Message 9). Recent regional sea level trends in the western tropical Pacific are higher (Becker et al. 2012; Merrifield 2011; Timmermann et al. 2010) than the global average, due in part to changing wind patterns associated with natural climate variability (Di Lorenzo et al. 2010; Feng et al. 2010; Merrifield and Maltrud 2011; Merrifield et al. 2012; Meyssignac et al. 2012). 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 (Stammer et al. 2012).

Rising sea levels will escalate the threat to coastal structures and property, groundwater reservoirs, harbor operations, airports, waste water systems, shallow coral reefs, sea grass beds, intertidal flats and mangrove forests, and other social, economic, and natural resources. Impacts will vary with location depending on how regional sea level variability combines with increases of global average sea level (Marra et al. 2012). 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 (Easterling et al. 2007) and periodic flooding increases the salinity of groundwater. Coastal and near shore 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 (Gilman et al. 2008). 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 (Waycott et al. 2011). Pacific seabirds that breed on low-lying atolls will lose large segments of their breeding populations (Arata et al. 2009) as their habitat is increasingly and more extensively covered by seawater.

Saltwater Intrusion Destroys Crops

Figure 23.7: Saltwater Intrusion Destroys Crops

Caption: 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 courtesy of John Quidachay/USDA Forest Service.

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 (Mimura et al. 2007), 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 Hawaiʻi, for example, where tourism comprises 26% of the state's economy, damage to tourism infrastructure – including the loss of Waikīkī Beach – could lead to an annual loss of $2 billion in visitor expenditures (Waikīkī Improvement Association 2008).

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. Under these circumstances, it will become 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 by increasing the incidence of dengue fever, for example (Lewis 2012). In addition, sea level rise and flooding are expected to overcome sewer systems and threaten public sanitation. Finally, the traditional lifestyles and cultures of indigenous communities in all Pacific Islands will be seriously affected by climate change. Sea level rise and associated flooding is expected to destroy coastal artifacts and structures (Vitousek et al. 2004) or even the entire land base associated with cultural traditions (Henry and Jeffery 2008). Drought threatens traditional food sources such as taro and breadfruit, and coral death from warming-induced bleaching will threaten subsistence fisheries in island communities (Maclellan 2009). Climate-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 a new location. 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.

Figure 23.8: Residents of Low-lying Islands at Risk

Caption: Residents of places like the Namdrik Atoll in the 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-induced human migration as sea level continues to rise. Photo courtesy of Darren Nakata.

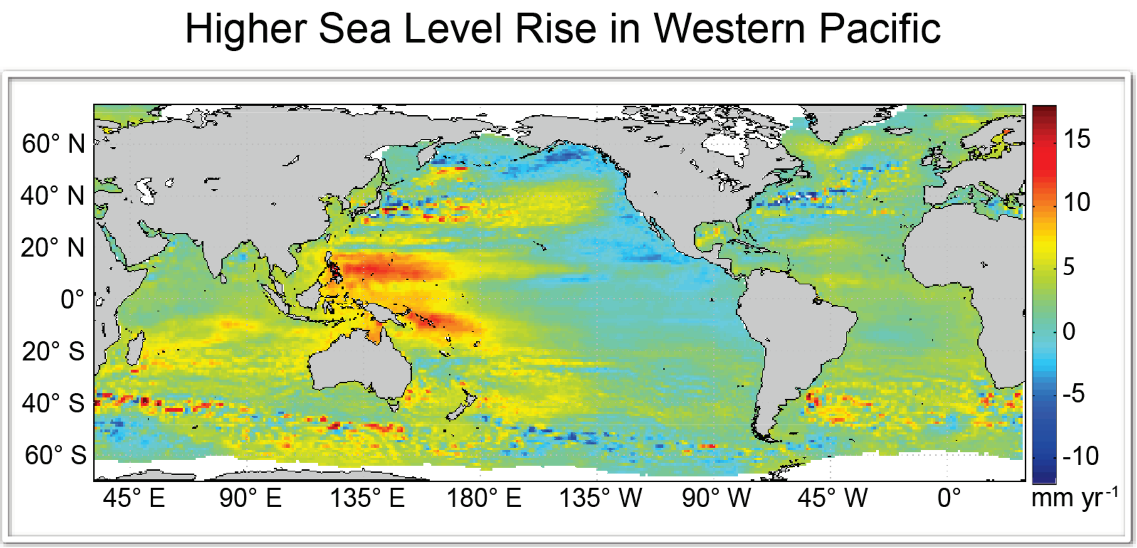


Figure 23.9: Higher Sea Level Rise in Western Pacific

Caption: Map shows large variations across the Pacific Ocean in the trend in sea level for 1993-2010. The largest increase in sea level has been observed in the western Pacific. *Source:* Merrifield (2011), by permission of American Meteorological Society.

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 (Keener et al. 2012); but these sites have larger policy or legal hurdles that complicate coastal planning (Codiga and Wager 2011). Low islands have a different set of challenges. Climate change related migration, for example, is particularly relevant to the low island communities in the RMI and the FSM, and presents significant practical, cultural, and legal challenges (Burkett 2011).

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 (Group 70 International 2009; Townscape Inc. 2009). Both Hawai‘i and American Sāmoa 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 (Anderson 2012a). The U.S. Pacific Island Freely Associated States (which includes the FSM, RP, and RMI) 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 (Anderson 2012b). 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.

Traceable Accounts

Chapter 23: Hawaiʻi and Pacific Islands

Key Message Process: 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 Hawaiʻi 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 and led to the formulation of a foundational TIR report (Keener et al. 2012). The report consists of nearly 140 pages, with almost 300 references, that were 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 (Keener et al. 2012) 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 that included several iterations of review and comment on draft key messages and associated content.

Key message #1/5	**Ocean warming and acidification are producing changes in coastal and ocean ecosystems. Warmer seas are leading to increased coral bleaching events and disease outbreaks in coral reefs, and changed distribution patterns of tuna fisheries. Ocean acidification will lead to reduced calcification rates for corals and coralline algae. Both factors, combined with existing stresses, will strongly affect the fish community of coral reefs.**
Description of evidence base	The key message was chosen based on input from the extensive evidence documented in the Hawaiʻi Technical Input (Keener et al. 2012) and additional Technical Input reports received as part of the Federal Register Notice solicitation for public input, as well as stakeholder engagement leading up to drafting the chapter. Key message 11 in Chapter 2, Our Changing Climate, and its traceable account also provides evidence for ocean acidification. 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. Assessment of the literature for the region by other governmental bodies (i.e. ABOM and CSIRO) point to continued increases under both B1 and A2 scenarios. Acidification; 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; in the Western North Pacific it has declined from approximately 4.5 to 3.9 in 2000, and to 4.1 in the Central South Pacific (Feely et al. 2009) (Figure 4 in Chapter 23, Hawaiʻi and Pacific Islands and available in the Oceans and Marine Resources chapter). 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 (Citations in (Keener et al. 2012), including those of other governmental bodies such as CSIRO). The recently published Reefs at Risk Revisited estimates aragonite saturation state (as an indicator of ocean acidification) for CO2 stabilization levels of 380 ppm, 450 ppm and 500 ppm, which correspond approximately to the years 2005, 2030, and 2050 under the IPCC A1B emissions

	scenario (Figure 4.4 from Keener et al. 2012). Bleaching events: These have been well-documented in extensive literature world-wide due to increasing temperatures, with numerous studies in Hawaiʻi and the Pacific Islands. Disease outbreaks: Reports of coral diseases have been proliferating in the past years, but few have currently been adequately described, with causal organisms identified (e.g. fulfill Koch's Postulates). Reduced growth: There is abundant evidence from laboratory experiments that lower seawater pH reduces calcification rates in marine organisms (e.g., Feely et al. 2009), 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 show that there are large regional and diel variability in pH and pCO2. The role of diel and regional variability on coral reef ecosystems requires further investigation. Distribution patterns of coastal and ocean fisheries: The effects of ocean acidification on U.S. fisheries in Hawaiʻi and the U.S. affiliated Pacific Islands is currently limited ((Lehodey et al. 2011) but which illustrates accumulating evidence for ecosystem impacts.
New information and remaining uncertainties	New information: Since the 2009 assessment, considerable effort has been employed to understand the impacts of ocean acidification (OA) on marine ecosystems, with recent ecosystem based efforts such as (Kline et al. 2012; Lehodey et al. 2011) as examples. 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, with the role of community metabolism and calcification in the face of overall reduction in aragonite saturation state must be investigated. Interaction of rising temperature and OA remains a challenge. For example, temperature simultaneously causes 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.

1

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

2

3

Chapter 23: Hawaiʻi and Pacific Islands

Key Message Process: See KM#1.

Key message #2/5	**Freshwater supplies are already constrained and will be more limited on many Pacific Islands, especially low-lying islands. The quantity and quality of freshwater in aquifers and surface catchments will decline in response to warmer and drier conditions, coupled with increased occurrences of saltwater intrusion associated with sea level rise.**
Description of evidence base	As with the US, and globally (Ch. 2: Our Changing Climate, Key Message 3), there is abundance and definitive evidence that air temperature has increased, and is projected to continue to increase over the entire region (Australian Bureau of Meteorology and CSIRO 2011; Giambelluca et al. 2008; Lander 2004; Lander and Guard 2003) In Hawai’i and the Central North Pacific (CNP) projected annual surface air temperature increases are 1.0-2.5°F by 2035 relative to 1971-2000 (Christensen et al. 2007; Meehl et al. 2007). In the Western North Pacific (WNP) the projected increases are 2.0-2.3°F by 2030, 6.1°F -8.5°F by 2055, and 4.9-9.2°F by 2090 (Australian Bureau of Meteorology and CSIRO 2011). In the Central South Pacific (CSP) projected annual surface air temperature increases are 1.1-1.3°F by 2030, 1.8-2.5°F by 2055 and 2.5-4.9°F by 2090 (Australian Bureau of Meteorology and CSIRO 2011) . 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 (Bassiouni and Oki 2012; Chu and Chen 2005; Oki 2004). For the WNP, a decline of 15% in annual rainfall has been observed in the eastern-most islands in Micronesia region and slight upward trends in precipitation have been seen for the western-most islands with high ENSO-related variability (Australian Bureau of Meteorology and CSIRO 2011; Bailey and Jenson 2011). In American Samoa, no trends in average rainfall are apparent based on the very limited available data (Australian Bureau of Meteorology and CSIRO 2011; Young 2007). For the region as a whole, models disagree. Mostly they predict increases in mean annual rainfall and suggest a slight dry season decrease and wet season increase in precipitation (Australian Bureau of Meteorology and CSIRO 2011). However, based on statistical downscaling, (Timm and Diaz 2009) projected 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 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 (Döll 2002; Sivakumar and Hansen 2007). Atolls will be particularly vulnerable due to their low elevation, small land mass, geographic isolation, limited potable water sources and agricultural resources (Barnett and Adger 2003). 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 (Keener et al. 2012). See also Key Message 4 on sea level rise in this chapter and Ch. 2: Our Changing Climate, Key Message 9).
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, 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. Historical observations show strong evidence of a decreasing trend for rainfall in Hawaiʻi and many other Pacific Islands. (see also Chapter 2 in (Keener et al. 2012)). This gives us **high** confidence in the conclusion.

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

Chapter 23: Hawai‘i and Pacific Islands

Key Message Process: See KM#1.

Key message #3/5	**Increasing temperatures, and in some areas reduced rainfall, will stress native Pacific Island plant and animal populations and species, especially in high-elevation ecosystems with increasing exposure to fire and 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-2.5°F by 2035 relative to 1971-2000 (Christensen et al. 2007; Meehl et al. 2007). In the Western North Pacific (WNP) the projected increases are 2.0°F-2.3°F by 2030, 6.1°F-8.5°F by 2055, and 4.9°F-9.2°F by 2090 (Australian Bureau of Meteorology and CSIRO 2011). In the Central South Pacific (CSP) projected annual surface air temperature increases are 1.1°F-1.3°F by 2030, 1.8°F-2.5°F by 2055 and 2.5°F-4.9°F by 2090 (Australian Bureau of Meteorology and CSIRO 2011). In Hawai’i the rate of increase has been greater at high elevations (Giambelluca et al. 2008). In Hawai’i and the Central North Pacific (CNP) projected annual surface air temperature increases are 1.0°F-2.5°F by 2035 relative to 1971-2000 (Christensen et al. 2007; Meehl et al. 2007). In the Western North Pacific (WNP) the projected increases are 2.0°F-2.3°F by 2030, 3.4°F-4.7°C by 2055, and 4.9°F-9.2°F by 2090 (Australian Bureau of Meteorology and CSIRO 2011). In the Central South Pacific (CSP) projected annual surface air temperature increases are 1.1°F-1.3°F by 2030, 1.8°F-2.5°F by 2055 and 2.5°F-4.9°F by 2090 (Australian Bureau of Meteorology and CSIRO 2011). 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 (Bassiouni and Oki 2012; Chu and Chen 2005; Frazier et al. 2011; Oki 2004). Based on statistical downscaling, (Timm and Diaz 2009) projected the most likely precipitation scenario for Hawai’i for the 21st century to be a 5%-10% reduction for the wet season and a 5% increase in the dry season. On high islands like Hawai‘i, decreases in precipitation and base flow (Oki 2004) are already indicating that there will be impacts on freshwater ecosystems and aquatic species, and water-intensive sectors such as agriculture and tourism. Hawai‘ian high-elevation alpine ecosystems on Hawai‘i and Maui islands are already beginning to show strong signs of increased drought and warmer temperatures (Cao et al. 2007). Demographic data for the Haleakalā silversword, a unique (endemic to upper Haleakalā volcano) 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 (Krushelnycky et al. 2012). 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 (Benning et al. 2002; LaPointe et al. 2012).
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, ENSO, 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. Climate change ecosystem response is poorly understood.
Assessment of confidence based on evidence	Terrestrial ecosystems are already showing signs of stress. Historical observations show strong evidence of a decreasing trend for rainfall in Hawaiʻi and many other Pacific Islands (Keener et al. 2012). Confidence is therefore **high** in this key message.

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

Chapter 23: Hawai'i and Pacific Islands

Key Message Process: See KM#1.

Key message #4/5	**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	Evidence for sea level rise across the U.S. is discussed in Chapter 2 (Our Changing Climate, Key Message 9) and its Traceable Accounts. All of the scientific approaches to detecting sea level rise come to the conclusion that a warming planet will result in higher sea levels. In addition, numerous recent studies (Keener et al. 2012) find realistic much higher sea level-rise projections than what the IPCC reported in 2007 (IPCC 2007) for the rest of this century. (See also Ch. 2: Our Changing Climate, Key Message 9). 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 20th century based on tide gauge measurements (Nerem et al. 2010), with models suggesting that global sea level will rise significantly over the course of this century. Regionally, the highest increases occurring in the WNP (Becker et al. 2012; Timmermann et al. 2010). However, the current regional rates are not expected to persist, as sea level will fall in response to a change in phase of natural variability (Marra et al. 2012). Regional trend variations in sea level at interannual and interdecadal time scales generally are attributed to changes in prevailing wind patterns associated with ENSO as well as the PDO and low frequency components of the Southern Oscillation Index (SOI) (Merrifield and Maltrud 2011; Merrifield et al. 2012; Meyssignac et al. 2012).On low-lying atolls, critical public facilities and infrastructure as well as private commercial and residential property are especially vulnerable (Marra et al. 2012). Agricultural activity will also be affected, as sea level rise decreases the land area available for farming (Easterling et al. 2007) 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. In Waikīkī Improvement Association. (Waikīkī Improvement Association 2008) "Our analyses estimate that nearly $2.0 billion in overall visitor expenditures could be lost annually due to a complete erosion of Waikīkī Beach." Coastal and near shore 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 in total regional mangrove area over the next century. (Gilman et al. 2008). Also, atoll-breeding Pacific seabirds will lose large segments of their breeding populations (Arata et al. 2009) as their habitat is increasingly and more extensively inundated.
Major uncertainties	Regional trend variations in sea level at interannual and interdecadal time scales generally are attributed to changes in prevailing wind patterns associated with ENSO as well as the PDO and low frequency components of the Southern Oscillation Index (SOI). Regionally, sea level will continue to rise with global sea level. However, the current regional rates are not expected to persist, as sea level will fall in response to

	a change in phase of natural variability.
Assessment of confidence based on evidence	Strong evidence for sea level rise (Keener et al. 2012) (see also Ch. 25: Coastal Zone and Ch. 2: Our Changing Climate). Confidence is therefore **very high**. For other aspects of the key message concerning impacts, confidence is **high**.

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

Chapter 23: Hawaiʻi and Pacific Islands

Key Message Process: See KM#1.

Key message #5/5	**Mounting threats to food and water security, infrastructure, and public health and safety will lead to increasing human migration from low to high elevation islands and continental sites. It will become increasingly difficult for Pacific Islanders to sustain the region's many unique customs, beliefs, and languages.**
Description of evidence base	Climate changes threats to communities, cultures, and ecosystems of the Pacific Islands both directly through their impact on food and water security, for example, as well indirectly through their impact 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 (Döll 2002; Sivakumar and Hansen 2007). This is particularly important for locations in the tropics and subtropics where observed data and model projections suggest that the average growing season temperatures will exceed the most extreme seasonal temperatures recorded from 1900 to 2006 by the end of the 21st century. Atolls will be particularly vulnerable due to their low elevation, small land mass, geographic isolation, limited potable water sources and agricultural resources (Barnett and Adger 2003). 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 (Storlazzi et al. 2011) . On high islands like Hawaiʻi, decreases in precipitation and base flow (Oki 2004) are already indicating that there will be impacts on freshwater ecosystems and aquatic species, and 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, waste water 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 (Keener et al. 2012). 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 (Easterling et al. 2007) and episodic inundation increases salinity of groundwater resources. With respect to cultural resources, impacts will extend from the loss of tangible artifacts and structures (Vitousek et al. 2004) to the intangible loss of a land base and the cultural traditions that are associated with it (Henry and Jeffery 2008).
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 especially to adapt when long-standing cultural issues cannot readily be altered.
Assessment of confidence based on evidence	Evidence for climate change and impacts is strong, but highly variable for location to location, yet 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**.

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

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