

Chapter 4

Marine, Freshwater, and Terrestrial Ecosystems on Pacific Islands

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The islands and waters of the Pacific Islands provide the materials and means that allow the region's humans, plants, and animals to thrive. These fragile ecosystems not only support the fisheries and agriculture that the people of the region depend on for food and income, they also provide shoreline protection, places for recreation, shared cultural heritage, and many other benefits, all of which are at risk from climate change and local stress caused by human activities.

Climate variability and change threaten marine, freshwater, and terrestrial ecosystems through rising air and sea-surface temperature, sea-level rise (SLR), seasonal changes in precipitation, changes in the frequency and intensity of extreme weather events (hurricanes and typhoons, heavy rain events, and droughts), changes in solar radiation, and increasing ocean acidification (Figure 4-1). These physical and chemical changes affect many of the physical and biological processes on both land and in water and have cascading effects on water quality, species composition and diversity, wind, currents, waves, soil conditions, and habitat availability. All of these impacts will combine, often synergistically, to alter or in some cases eliminate important ecosystem function and reduce global biodiversity. Given the complex interconnectedness of these ecosystems and many of the species in them, we can only begin to understand the cascading impacts of these changes and the resultant impacts to the subsistence, culture, and way of life of the people of the Pacific Islands.

This vast region contains some of the most diverse ecosystems in the US, and in the case of the Pacific Remote Islands Marine National Monument and Papahānaumokuākea Marine National Monument, often the most pristine. Consequently, these areas offer a unique opportunity to better understand the impacts of climate change on coral reefs and on freshwater and terrestrial ecosystems of both low islands and high islands. In particular, the remote marine communities of the region allow a rare glimpse into ecosystems and ecological processes largely unaffected by human activities (Wilkinson, 2008; Pandolfi et al., 2005). In contrast, the freshwater and terrestrial environments within the region are more likely to have been significantly impacted by invasive species, and assessment of climate impacts on these ecosystems will need to consider not only changes in native ecosystems and species but also the interaction with invasive species that will also be responding to climate change.

Regional ecosystems overview

Marine ecosystems

Several key marine ecosystems in this region will be impacted by climate change, including those of the open ocean (pelagic, abyssal, deep coral) and those of insular or

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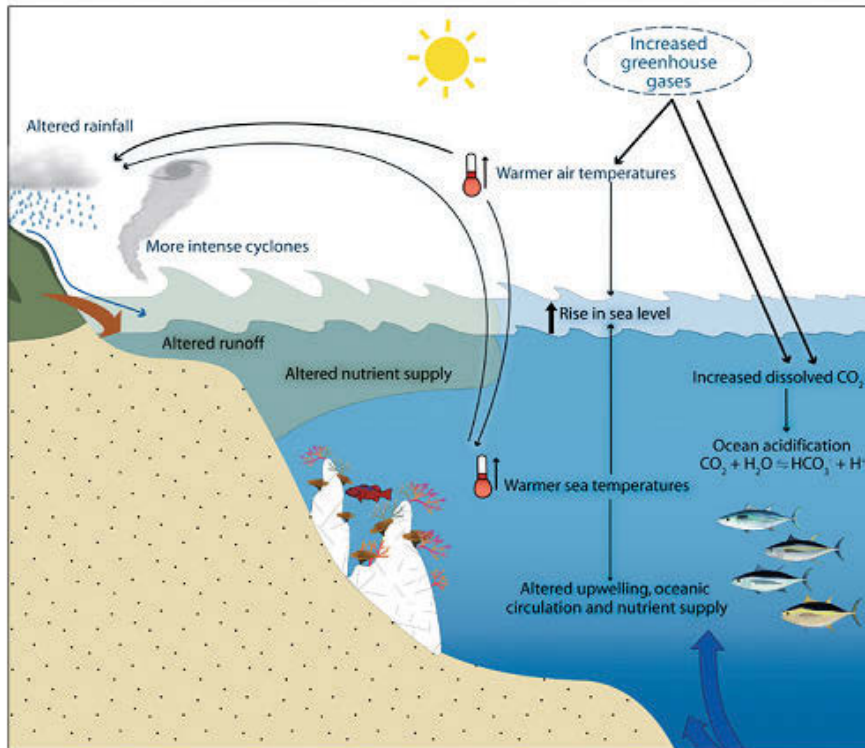


Figure 4-1 Generalized effects of increased greenhouse gases on oceanic and coastal ecosystems in the tropical Pacific. (From Bell et al., 2011.)

nearshore environments, such as shallow coral reefs, mesophotic reefs (those at water depths where light penetration is low), seagrass beds, intertidal flats, and mangroves. The communities within these ecosystems include many important species and groups of species: pelagic fish (such as tuna), reef fish, endangered sea turtles and monk seals, large marine mammals, corals, crustaceans, and phytoplankton, which form the base of the food web.

Terrestrial ecosystems

As discussed in the “Region profile” section of Chapter 1, terrestrial ecosystems in the Pacific Islands are divided between low islands and high islands. While atoll (low island) ecosystems are similar to strand and coastal plain ecosystems of high islands, they lack the elevation gradient and land area needed by species to adjust their distributions in response to climate change effects, such as SLR and changes in temperature and precipitation. Additionally, low island species have very little capacity to shelter from extreme weather events. High island species have, to varying degrees, the potential to track important habitat features as they change location with a changing climate.

Rainfall and temperature gradients on high islands (with high physical relief) offer a wide range of microclimatic conditions that support a diverse assemblage of plants and animals in coastal wetlands, high-elevation bogs, grasslands, wet, mesic and dry forests, subalpine and alpine landscapes, and intermittent and perennial streams. This is especially true in the main Hawaiian Islands, which support 86 distinct native plant

communities and 20 alien-dominated plant communities from sea level up to 13,400 feet (Wagner et al., 1990). The responses of these diverse ecosystems to climate change are largely unexplored, with only a few studies from Hawai'i. The rate of climate-driven changes to native habitats in the Pacific Islands is unknown. Changes may happen slowly, driven by press-type disturbances such as ambient temperature rise or decreasing precipitation, or rapidly, driven by pulse-type disturbances such as extreme storms. This remains one of the major topics of interest for understanding how terrestrial ecosystems will respond to climate change, and it will be made more challenging by the added effects of invasive species.

Freshwater ecosystems

Freshwater ecosystems in the Pacific Islands are a critical human resource and add significantly to native island biodiversity. Coastal wetlands, while highly disturbed by invasive species and human usage, still provide important habitat for Pacific Island waterbirds, and high-elevation wetlands support unique natural plant communities. Stream systems are found only on high islands and are home to freshwater snails and arthropods, as well as a suite of fish, snails, and shrimp that are amphidromous (whose larval stages occur in the ocean). These latter species provide a direct link between freshwater and marine environments. Consequently, the future success of these species will depend on how ocean acidification and other marine effects of climate change may impact larval development and growth, as well as recruitment of these larval stages back into freshwater streams.

Historic and projected trends

The general climate state in the Pacific Islands has been described and summarized in Chapter 1 of this report, and the “Indicators of a changing climate in the Pacific Islands region” section of that chapter summarizes the general trends in the key climate variables across the region. This section focuses on features of climate that may be particularly important to marine, freshwater, and terrestrial ecosystems in the geographic sub-regions: the Central North Pacific (CNP; Hawai'i and the Northwestern Hawaiian Islands [NWHI]), the Western North Pacific (WNP; Commonwealth of the Northern Mariana Islands [CNMI], Republic of Palau [RP], Federated States of Micronesia [FSM], and the Republic of the Marshall Islands [RMI]), and the Central South Pacific (CSP; American Sāmoa). The following section broadly describes ecosystem impacts caused by the interplay of these climate features.

Surface air temperature

Historical and current observations of surface air temperature (SAT) across the tropical and subtropical Pacific Islands provide a high level of confidence for significant warming trends in the CNP, WNP, and CSP. In the CNP, terrestrial areas of Hawai'i have warmed rapidly, especially since the 1970s, with more warming at higher elevations and at night. See the “Historic and current trends” section in Chapter 2 for a more in depth discussion on SAT.

Sea-surface temperature

Historical and current observations of sea-surface temperature (SST) across the region provide high confidence that SST is rising. Water temperatures remained relatively constant or saw weak warming from the 1950s to the 1970s in the WNP and a cooling over the same period in the CSP. Since the 1970s, more rapid warming has occurred at a rate of 0.07° to 0.23°C (+0.13° to 0.41°F) per decade depending on the location. Projected increases in SST for the region range from 0.6° to 0.7°C (1.1° to 1.3°F) by 2030, 0.9° to 1.4°C (1.6° to 2.5°F) by 2055, and 1.3° to 2.7°C (2.3° to 4.9°F) by 2090 under B1 and A2 emission scenarios (Australian Bureau of Meteorology & CSIRO, 2011).

Precipitation and extreme rainfall events

Historical trends in the WNP sub-region showing changes in annual and seasonal rainfall trends for FSM and RP from the 1950s to 1990s are not statistically significant, while negative annual and dry-season trends for RMI are statistically significant. Rainfall projections for the WNP sub-region indicate that wet-season, dry-season, and annual averages of rainfall will increase (Australian Bureau of Meteorology & CSIRO, 2011). There are no clear historical trends for the CSP sub-region. Precipitation in the sub-region is projected to either change very little during the dry season or possibly decrease. An increase in rainfall is projected for the wet season (Australian Bureau of Meteorology & CSIRO, 2011). Precipitation trends in the CNP (Hawai'i) show moderate cyclical dependence on both the El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) (Chu & Chen 2005); however, Chu et al. (2010) show that droughts are increasing as the precipitation regime over the islands has become more dominated by light rainfall and fewer heavier rain events. See the "Historic and current trends" section in Chapter 2 for a more in-depth discussion on precipitation and extreme rainfall events.

Sea-level rise

Rates of sea-level rise (SLR) derived from satellite altimetry since 1993 range from 2 to 5 mm/year (~0.08 to 0.20 inches/year) within the CNP and CSP, and ≤10 mm/year (0.39 inches/year) throughout much of the WNP (see Figure 3-4 in Chapter 3). As compared to the global mean rate of 3.2 ±0.4 mm/year (0.13±0.02 inches/year) (Nerem et al., 2010), these trends are relatively high and of significant concern if they persist in the future due to the low-lying island topography. The ramped-up rates in the WNP are attributed to strengthened trade wind forcing (Merrifield, 2011; Merrifield & Maltrud, 2011). However, it is not clear whether or not the current rates in SLR and related sea-surface height pattern will remain (associated with a shift in the underlying state of the ocean-atmosphere system) or if they will eventually settle down (a function of climatic-scale variability). See the "Historic and current trends" section in Chapter 3 for a more in-depth discussion on SLR.

Ocean acidification

When CO₂ is absorbed by seawater, chemical reactions occur that reduce seawater pH, carbonate ion (CO₃²⁻) concentration, and saturation states of the biologically important

CaCO_3 minerals calcite (Ω_{ca}) and aragonite (Ω_{ar}) in a process commonly referred to as ocean acidification (Feely et al., 2009). Historical and current observations of aragonite saturation state (Ω_{ar}) show a decrease from approximately 3.8 to 3.6 in the last 20 years in the CNP. In the WNP, it has declined from approximately 4.5 in the late 18th century, to 3.9 in 2000, and to 4.1 in the CSP (Australian Bureau of Meteorology & CSIRO, 2011).

Projections from CMIP3 models indicate the annual maximum aragonite saturation state will reach values below 3.5 by 2035 in the waters of the RMI, by 2030 in the FSM, by 2040 in RP, and by 2060 around the Samoan archipelago. These values are projected to continue declining thereafter (Australian Bureau of Meteorology & CSIRO, 2011).

Tropical cyclones

While there is little consensus at this point as to how storms in the Pacific Ocean may be affected by global climate change (IPCC, 2007; Collins et al., 2010; Knutson et al., 2010), most agree that increases in atmospheric and oceanic temperatures will result in changes to storm frequency, storm tracks, and the intensity of storms. These changes will, in turn, modify the timing, magnitude, and patterns of large storm waves in the ocean basin. Current information indicates that tropical cyclone activity for the CSP is projected to lessen, while activity in the WNP will increase significantly (Emanuel, 2005). The projections of potential intensity of tropical cyclones in these areas all show low, but significant, increases over the next 70 years (Yu et al., 2010). Projections for the eastern Pacific, which could affect Hawai'i, give variable results with no clear trend (Emanuel, 2005). The projected intensity of tropical cyclones in these areas shows low but significant increases over the next 70 years (Yu et al., 2010). The paths of cyclones may also shift more toward the CNP as a result of global warming (Li et al., 2010).

Impacts to marine ecosystems

In marine ecosystems, the changes in SST, SLR, ocean acidification, and precipitation lead to other physical, chemical, and biological changes in the open and nearshore waters, some of which are better understood than others. Changes in SST in conjunction with potential changes in wind, wave, and current patterns can lead to a change in stratification. This in turn can lead to changes in nutrient availability to the photic zone and therefore changes in phytoplankton abundance, size, and diversity. Because these organisms form the base of the oceanic food web, this in turn can lead to changes in patterns of abundance and distribution of key fisheries species, as can simple changes in SST alone (Le Borgne et al., 2011; Polovina et al., 2011). Population connectivity in coral reefs and other ecosystems may also shift as winds, waves, current patterns, and temperature regimes are altered. This could impact the ability of reefs to recover from bleaching events and to be reseeded by larvae from other reef areas. Larval fish distribution could also be impacted (Munday et al., 2009). Waves, both acute (storm-generated) and chronic (wind-driven waves with addition of SLR), can change the geomorphology of islands and the coral reefs that surround them. This in turn can result in the loss and/or creation of habitat, which will also affect species distribution. Changes in rainfall patterns and increasing frequency and intensity of extreme events can lead to greater runoff of sediment and land-based sources of pollution, especially in high islands. This

can lead to changes in water quality due to a decrease in water clarity and an increase in algal blooms that can impact seagrass beds and coral reefs. Rising sea level can inundate low-lying landfills, which can also affect water quality when toxicants are released into the marine environment. Impacts to specific marine ecosystems are expanded on below.

Open ocean

A recently published vulnerability assessment of tropical Pacific fisheries and aquaculture offers a succinct summary of the relationship between important pelagic fisheries, physical ocean properties, and variables that will be impacted by climate change:

The production of the four species of tuna, and other large pelagic fish, is underpinned by food webs based not only on the photosynthetic productivity of phytoplankton (called primary production) in the sunlit surface layer (photic zone) of the ocean, but also by bacteria and detritus, derived from phytoplankton. The energy produced through primary production moves through a “trophic pyramid” [Figure 4-2] via a range of zooplankton (such as copepods and larval fish), macrozooplankton (including jellyfish and salps) and micronekton (such as squid, shrimp and small fish), to sustain tuna and other large pelagic fish. The availability of the nutrients that underpin the food web for tuna, together with suitable water temperatures and dissolved oxygen levels, determine the distribution and abundance of tuna and other large oceanic fish across the Western and Central Pacific Ocean. Therefore, the responses of phytoplankton, zooplankton and micronekton to changes in the ocean processes that deliver nutrients to the photic zone, and to changes in the physical and chemical properties of the ocean projected to occur as a result of global warming and ocean acidification are expected to affect all life history stages of large oceanic fish. (Le Borgne et al., 2011)

Models project that between 2000 and 2100, the area of the subtropical biome (ecological community of plants and animals) will expand by 30%, while the area of temperate and equatorial upwelling biomes will decrease by 34% and 28%, respectively (Polovina et al., 2011). This is due primarily to enhanced stratification and a northward shift in the mid-latitude westerly winds under a changing climate. The important implication of this shift is that over the century, the total biome primary production and fish catch is projected to increase by 26% in the sub-tropical biome and decrease by 38% and 15% in the temperate and the equatorial biomes, respectively.

In addition to changes in productivity and fish catch, the boundaries of areas that are suitable for key fisheries species will shift, meaning changing availability and effort for some islanders to catch the fish. For example, two areas where the subtropical biome boundary exhibits the greatest movement is in the northeast Pacific, where it moves northward by as much as 1,000 km (621 miles) per 100 years, and at the equator in the central Pacific, where it moves eastward by 2,000 km (1,243 miles) per 100 years (Figure 4-3) (Polovina et al., 2011). Also, as SST rises, new thermal habitat will form, meaning different species distribution and composition, which will also affect fisheries. These types of impacts are already being observed as a function of ENSO on interannual scales, and this provides some insight into future impacts of climate change on food security for many of the Pacific Islands.

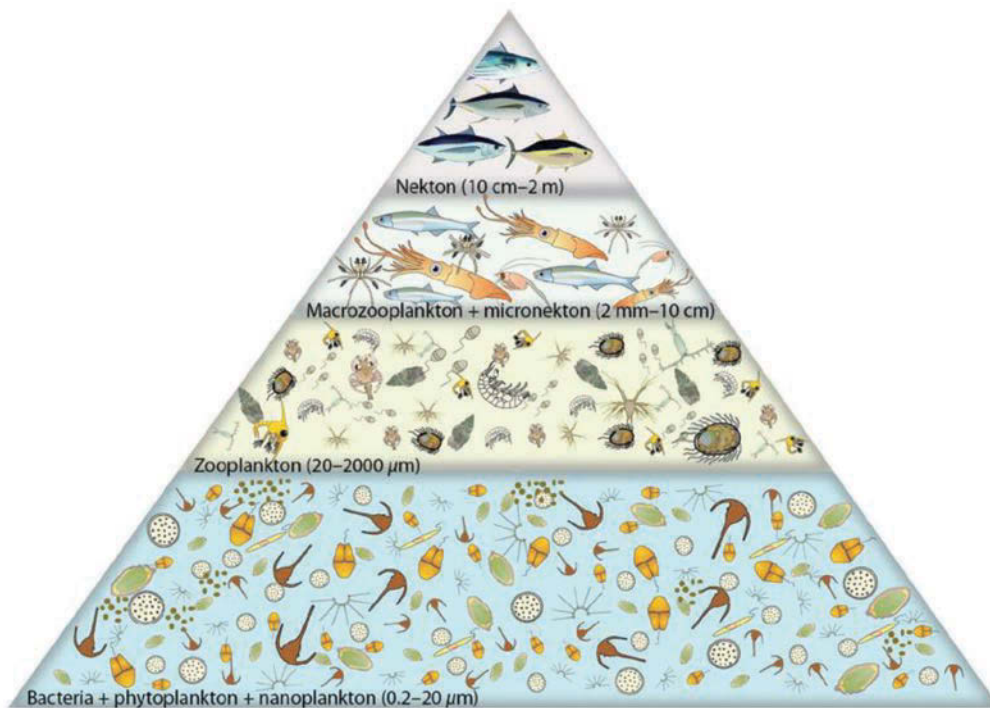


Figure 4-2 Generalized trophic pyramid for the tropical Pacific Ocean. The base of the food web consists of bacteria, small phytoplankton, and protists (nanozooplankton), 0.2 to 20 μm in size. These organisms are ingested by zooplankton, such as crustaceans, molluscs, or tuna larvae, up to a size of 2,000 μm . In turn, zooplankton are consumed by macrozooplankton, such as jellyfish, and micronekton, such as squid, shrimp, and small fish. Micronekton and, to a lesser extent, macrozooplankton are the prey for tuna and other large pelagic fish at the top of the pyramid. (From Le Borgne et al., 2011.)

There will also be impacts to the economically important tuna fishery in the Pacific Islands region. These impacts could be high, but the level of certainty about this is low. One ecosystem model coupled with a climate model indicates that under both A2 and B1 scenarios, by 2035 the total fishery catch for skipjack tuna increases by about 19% overall (11% for the western fishery and 37% for the eastern fishery), with no change for bigeye tuna. By 2100 under the A2 scenario, however, the catch for both skipjack and bigeye will decline overall by 8% and 27%, respectively, with important spatial differences within the region. The western Pacific is projected to show the greatest declines in both fisheries (21% for skipjack and 34% for bigeye), whereas the eastern Pacific is projected to show an increase of 27% for skipjack and a decline of 18% for bigeye (Lehodey et al., 2011).

Coral reefs

Mass coral bleaching is caused by unusually high water temperatures, 1° to 2°C (1.8° to 3.6°F), above the normal summer maxima lasting for 3 to 4 weeks or more, and strong El Niño events are correlated with many of the major bleaching events in recent years

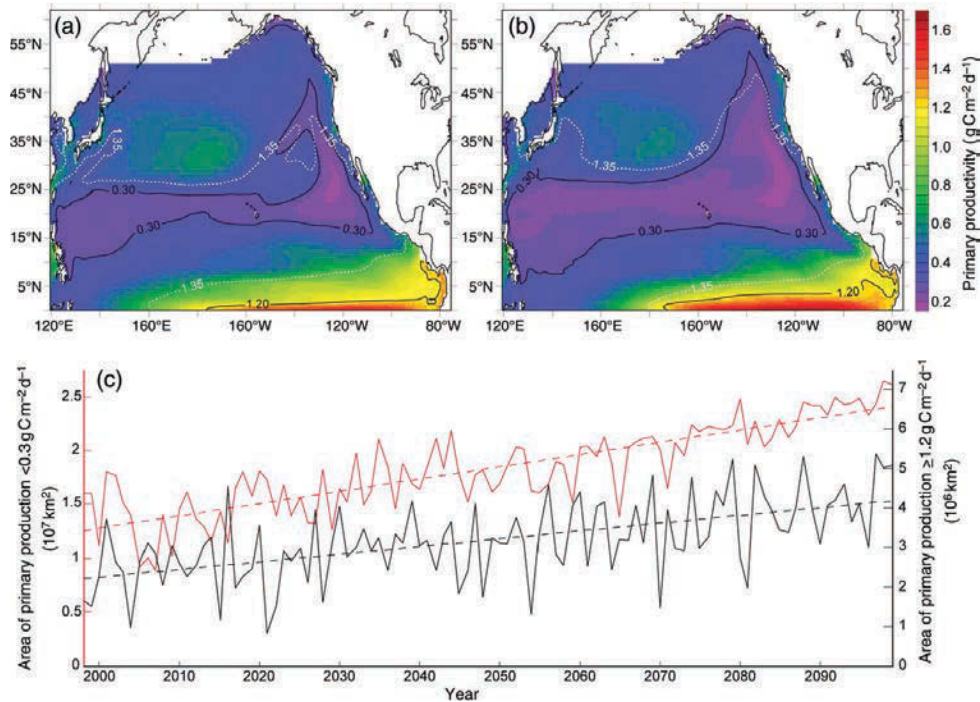


Figure 4-3 Mean depth-integrated primary production, (a) 1998–2017, (b) 2080–2099, (c) time series of the area with primary production, $<0.3 \text{ g C m}^{-2} \text{ d}^{-1}$ in the subtropical biome (red line) and the time series of the area with production $\geq 1.2 \text{ g C m}^{-2} \text{ d}^{-1}$ in the Equatorial Upwelling biome. Dashed white lines in (a) and (b) indicate the biome boundaries. (From Polovina et al. [2011] by permission of Oxford University Press.)

(Hoegh-Guldberg, 1999; Strong et al., 1997). These conditions result in the breakdown of the symbiotic partnership between the zooxanthellate algae, which live in the tissue of coral, and the coral itself. The algae are expelled, which results in the loss of one of the main energy sources for the coral. While corals can recover from bleaching events of short duration, mortality can result from longer or more intense events. The increased frequency and intensity of bleaching events projected with increasing SST will leave corals little time for recovery (Sheppard, 2003), and the stress of bleaching events may impact their reproductive success, leave corals more susceptible to disease, and reduce their resilience to the next bleaching event. Recent predictions are that by 2050, many of the reefs in the Pacific will bleach annually (Figure 4-4) based on the A1B emissions scenario (Burke et al., 2011). Annual bleaching has already been reported from some warm pools in American Sāmoa (Fenner & Heron, 2008).

The process of ocean acidification reduces the availability of biologically important calcium carbonate minerals, which are the building blocks for the skeletons and shells of many marine organisms. Aragonite is particularly important to reef-building coral; an aragonite saturation state that is optimal for corals to form their skeleton is greater than 4.0, a state of 3.5 to 4.0 is adequate, 3.0 to 3.5 is marginal, and less than 3.0 is extremely marginal (Langdon & Atkinson, 2005). A recent report estimated aragonite saturation state for CO₂ stabilization levels of 380ppm, 450ppm, and 500ppm, which correspond

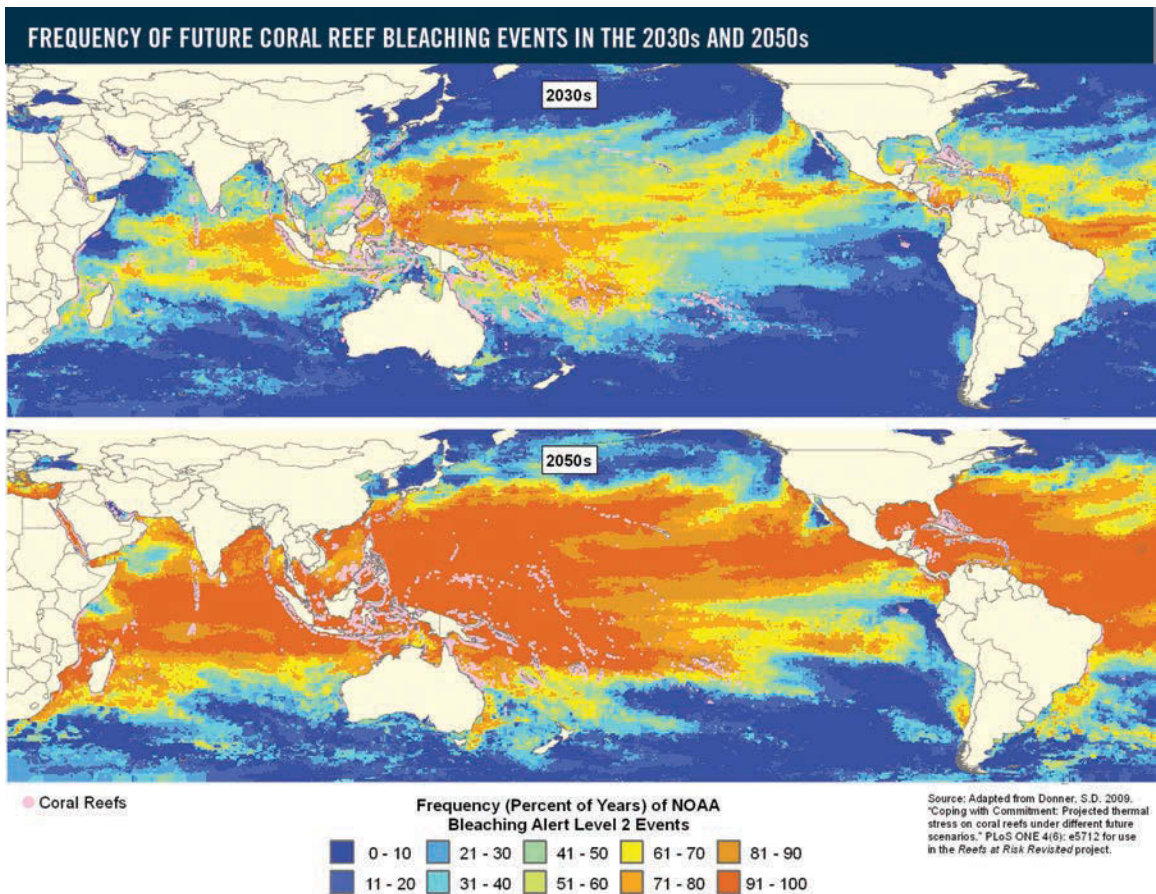


Figure 4.4 Frequency of future bleaching events in the 2030s and 2050s, as represented by the percentage of years in each decade where a NOAA Bleaching Alert Level 2 (i.e., severe thermal stress) is predicted to occur. Predictions are based on an IPCC A1B (business-as-usual) emissions scenario and adjusted to account for historical temperature variability but not adjusted by any other resistance or resilience factors. (From Burke et al., 2011. Data adapted from Donner [2009], "Coping with Commitment: Projected thermal stress on coral reefs under different future scenarios.")

approximately to the years 2005, 2030, and 2050 under the IPCC A1B (business-as-usual) emissions scenario (Figure 4-5) (Burke et al., 2011). By 2030, conditions around most coral reefs are only adequate or marginal for calcification to take place. Observed and experimental impacts of ocean acidification on coral reefs include lower calcification rates; more fragile reef structures; reductions in coral diversity, recruitment, and abundance of structurally complex reef framework builders; and shifts in competitive interactions among taxa, which can change the complexity of the reef structure (De'ath et al., 2009; Fabricius et al., 2011). Ocean acidification could have more far-reaching implications; recent work by Montenegro et al. (2011) suggests that the largest mass extinction event on record (Permian-Triassic Boundary extinction) corresponded to a period of an acidic ocean, and it puts forth this acidity as one of the potential kill mechanisms.

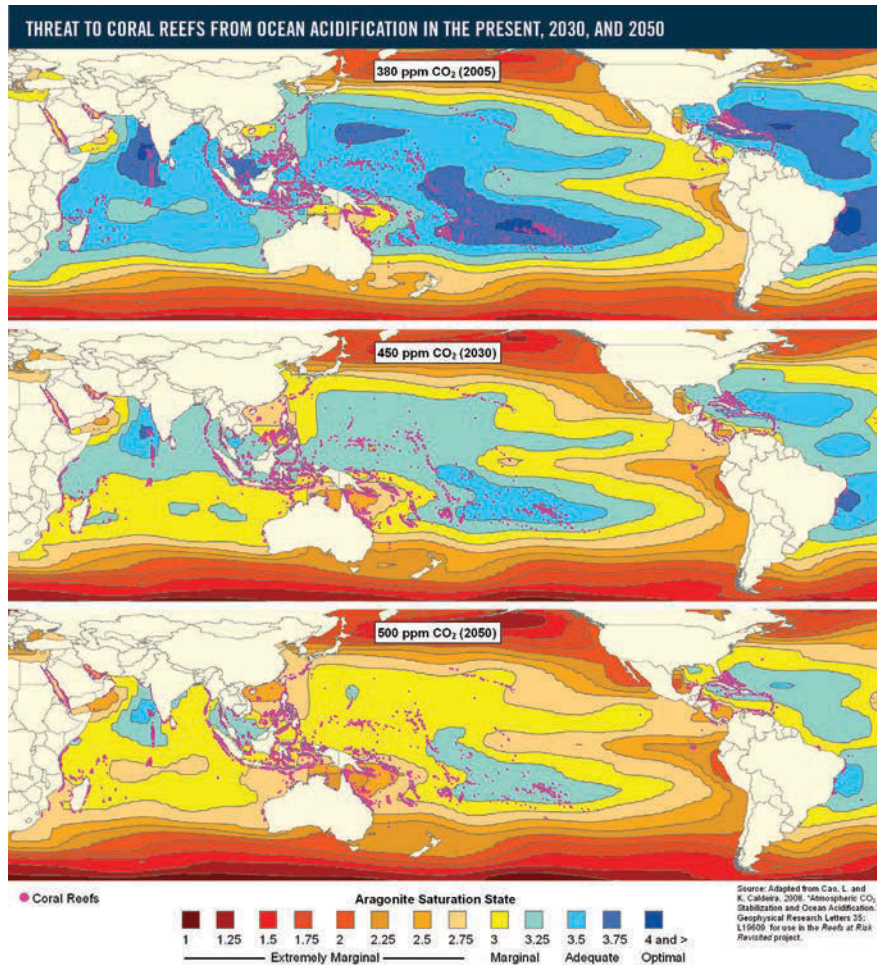


Figure 4-5 Estimated aragonite saturation state (an indicator of ocean acidification) for CO₂ stabilization levels of 380 ppm, 450 ppm, and 500 ppm, corresponding approximately to the years 2005, 2030, and 2050 under the IPCC A1B (business-as-usual) emissions scenario. (From Burke et al., 2011.)

While increasing SST and ocean acidification will have significant impacts to coral reefs, other climate change impacts could potentially contribute to reef degradation, including SLR, changes in storm frequency and intensity, and changes in ocean circulation and upwelling. Though coral growth and reef accretion rates in the Indo-Pacific are highly variable (Montagioni, 2005), current rates of SLR are thought to not directly threaten healthy coral reefs, and in the case of some reef flats, an increase in SLR has resulted in increased coral cover (Brown et al., 2011). However, SLR can lead to greater coastal erosion, especially during storm events, exposing reefs located adjacent to less stable shorelines to greater rates of sedimentation and re-suspension of seabed sediments, resulting in more turbidity (Field et al., 2011; Storlazzi et al., 2011). Furthermore, given other factors on growth (bleaching and ocean acidification), rapid SLR would represent an extreme challenge for coral reefs. Changes in storm frequency and intensity

and storm tracks will also modify the timing, magnitude, and patterns of large storm waves in the ocean basin. There have been a number of efforts illustrating that coral reef morphology and coral species distribution in the Pacific Ocean are strongly controlled by wave energy (Storlazzi et al., 2003, 2005; Engels et al., 2004). Therefore, these changes may result in not only direct physical damage, increased runoff, and reduced water quality but also potential long-term impacts to species distribution and patterns of reef growth. Finally, ocean circulation patterns are important drivers of the productivity, functions, and connectivity of coral reefs and many of the organisms that inhabit them. Projected changes in the magnitude, location, and patterns of currents and associated upwelling zones could lead to changes in the genetic structure and connectivity of coral reefs and alter nutrient availability, which may alter the local ecosystems (Hoegh-Guldberg et al., 2011).

The threats that climate change presents to coral reefs are further compounded by the fact that coral reefs are also threatened by local stressors, such as fishing practices, land-based sources of pollution, sedimentation, disease, physical damage from anchors and vessels, coastal development, and invasive species. The impacts from these threats lower the resilience of reefs to climate change. In *Reefs at Risk Revisited* (Burke et al., 2011), maps showing reefs classified by present integrated threats from local stressors with projected thermal stress and ocean acidification for 2030 and 2050 indicate that many of the western Pacific reefs are highly or very highly threatened presently, and that increased threat will spread across the Pacific in coming decades (Figure 4-6). Based on the rate of coral loss reported over the past 20 years as well as the projected effects of more frequent coral bleaching and ocean acidification, average coral cover throughout the Pacific is expected to decline to 15% to 35% by 2035 compared with 20% to 40% in 2007 (Bruno & Selig, 2007; Hoegh-Guldberg et al., 2011). Coral death will cause changes in the complexity and structure of reef habitat. This in combination with other stressors will also affect coastal fisheries, including those coral dependent and reef associated, by contributing to a further loss of habitat (Figure 4-7).

Seagrass beds, mangroves, and intertidal flat complexes

The mosaic of seagrass beds, intertidal flats, and mangroves in the Pacific provides nursery areas and feeding grounds for fish species, habitat for crustaceans and invertebrates, shoreline protection and wave dampening, and improved water quality due to trapping of nutrients, sediments, and pollutants that run off from land (Waycott et al., 2011). These areas already face the threat of coastal development, and further losses are expected to occur as a result of climate change impacts, including heat stress due to rising air and water temperature, loss of suitable habitat due to sea-level rise, increased sedimentation due to greater runoff, and damage from potentially more severe cyclones and storms (Waycott et al., 2011).

Mangrove forests usually occur along low-energy shorelines between low-tide and high-tide levels, and species have evolved to exist along a continuum of salinities and inundation with sea water (Waycott et al., 2011). Mangroves will potentially be impacted by increasing air temperatures, SLR, changes in frequency and intensity of storms, and changes in rainfall patterns (Grantham et al., 2011). Mangroves have a high tolerance for

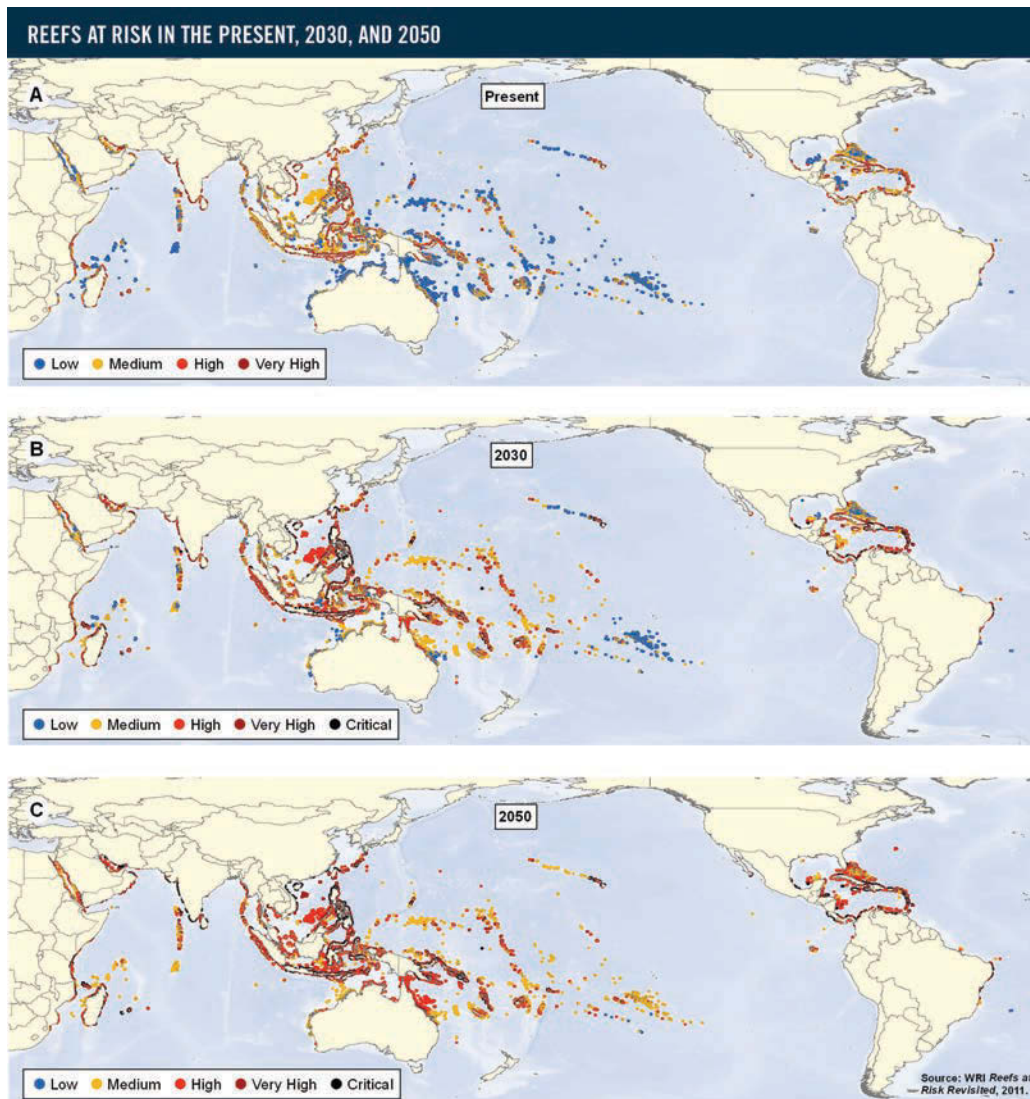


Figure 4-6 Map A (top) shows reefs classified by present integrated threats from local activities (i.e., coastal development, overfishing/destructive fishing, marine-based pollution, and/or watershed-based pollution). Maps B and C show reefs classified by integrated local threats combined with projections of thermal stress and ocean acidification for 2030 and 2050, respectively. Reefs are assigned their threat category from the integrated local threat index as a starting point. Threat is raised one level if reefs are at high threat from either thermal stress or ocean acidification, or if they are at medium threat for both. If reefs are at high threat for both thermal stress and acidification, the threat classification is increased by two levels. The analysis assumed no increase in future local pressure on reefs, and no reduction in local threats due to improvements in management. (From Burke et al., 2011.)

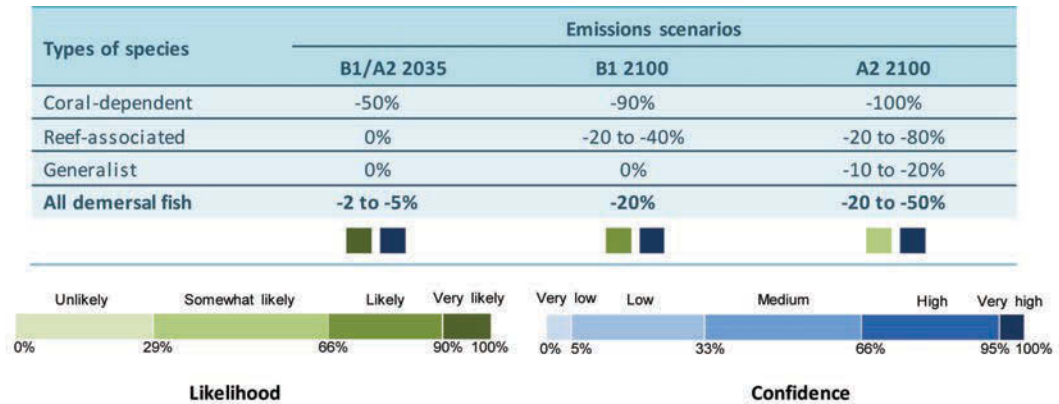


Figure 4-7 Projected changes in productivity of the demersal fish component of coastal fisheries under low (B1) and high (A2) emissions scenarios in 2035 and 2100. The estimated responses of broad types of demersal fish are also shown. The likelihood of these responses (especially for A2 in 2100) is low to medium. (From Pratchett et al., 2011.)

heat stress compared to many plants, though changes in SAT and SST may affect species distribution and composition and growth rate, and potentially change the timing of flowering and fruiting (Field, 1995; Ellison, 2000). SLR-induced erosion and inundation is a major threat to mangroves, especially if it is sudden or there is no path for landward migration (Ellison, 2000). Mangroves may also be able to move landward in response to SLR (Gilman et al., 2008). However, an extrapolation of current data indicates SLR in American Sāmoa will result in a 0.2% annual loss of mangrove area over the next century (Gilman et al., 2008). Changes in rainfall patterns can alter the magnitude and timing of freshwater flows to the nearshore environment, leading to changes in salinity and mangrove community composition (Field, 1995), and much like coral reefs and seagrass beds, mangroves can be destroyed by intense storms and cyclones.

Increasing SSTs are likely to result in changes in seagrass species distribution, sexual reproduction, growth rates, and changes in their carbon balance (Grantham et al., 2011). SLR will likely result in loss of ideal habitat along the deeper edge of meadows but result in more habitat at the landward bed edge. Changes in rainfall patterns, wave and current dynamics, and sea level can lead to changes in sedimentation and re-suspension of sediment, which reduce light availability to seagrass; these changes in water quality may be compounded by runoff of sediments, nutrients, and land-based sources of pollution (Short & Neckles, 1999; Björk et al., 2008). Additionally, while increasing levels of dissolved CO₂ could potentially have a positive effect by increasing photosynthesis, they also might stimulate epiphytic algal growth, which blocks light to the seagrass, especially in areas that are enriched in nutrients; thus, the potential benefits are likely to be outweighed by the negative impacts of climate change (Short & Neckles, 1999; Björk et al., 2008).

The role of intertidal flats—the transition zone between shoreline/sandy beach/mangrove forested areas and zones where seagrass and coral reefs can occur in the tropical

Pacific—is poorly understood. These habitats can play an important role in primary production and nutrient cycling through the benthic microalgae communities that live there; provide habitat for many organisms, including burrowing invertebrates that provide subsistence for human communities; and help mediate pollution through bacterial denitrification (Waycott et al., 2011). SLR is the largest concern for intertidal flats, especially in areas where the habitat cannot expand landward or where rates of sedimentation do not keep up with SLR. Increasing SAT and SST, changes in nutrient availability/terrestrial runoff, and changing ocean pH are all climate-related impacts that could alter species composition and distribution and levels of productivity, but more research is needed to fully understand the impacts of climate change to these habitats (Webster & Hill, 2007).

A recently published vulnerability assessment of tropical Pacific fisheries and aquaculture (Waycott et al., 2011) summarized the impacts to mangrove and seagrass ecosystems based on the B1 and A2 emissions scenarios at 2035 and 2100 with respect to different climate variables (Figure 4-8). Human activities that threaten these habitats, including unsustainable mangrove harvesting, habitat destruction, dredging, destruction of seagrass beds, and so forth, will exacerbate the impacts of climate change.

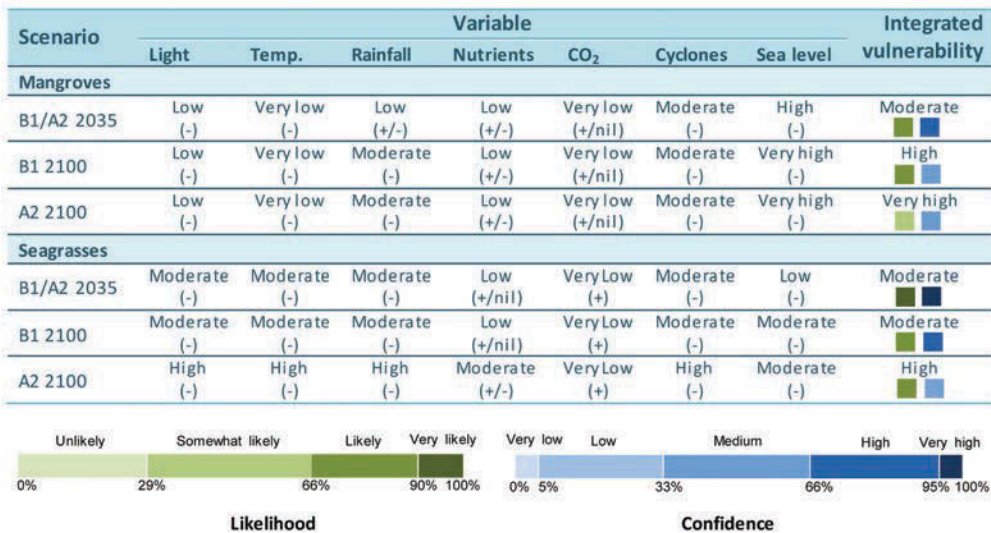


Figure 4-8 Summary of the projected effects of climate change variables on mangrove and seagrass habitats in the tropical Pacific for the B1 and A2 emissions scenarios in 2035, together with an assessment of the overall vulnerability of mangrove and seagrass habitats by integrating these effects. The likelihood and confidence associated with the integrated vulnerability assessments are also indicated. Note that the projected effects of each climate change variable can be negative (-) or positive (+); nil = no projected effect. (From Waycott et al., 2011.)

Impacts to freshwater and terrestrial ecosystems

In order to understand the potential future impacts of climate change on insular Pacific freshwater and terrestrial ecosystems, it is important to keep in mind differences between high islands with significant elevation gradients versus low islands with little or no elevation gradients, and leeward areas that receive less rainfall with more seasonal extremes versus wetter windward areas. It is also important to consider the presence and severity of other ecosystem stressors, such as invasive species, as well as resource availability and adaptive capacity. In the near term, maximizing native ecosystem resilience through intensive management of current anthropogenic stressors, especially invasive species, is critical for longer-term adaptation to climate change.

Low island ecosystems

Of critical concern is that SLR will eventually contribute to the overwash and submersion of low island ecosystems, particularly atolls. Initial effects of SLR will include changes in the location, size, and shape of the atoll islands (Webb & Kench, 2010), which will affect the type and distribution of nearshore terrestrial habitats. Continued SLR will result in the submerging of relict and wave-resistant paleoreef flats, which will subject the unconsolidated sediment cover to wave impacts and accelerate the eventual overtopping of atolls (Dickenson, 2009). Projected dates for these types of impacts are dependent upon particular atoll morphology and the rates of SLR that occur or are chosen for planning. However, it is likely that these impacts are inevitable, and will occur widely between ~2050 and 2150 (Dickinson, 2009). Terrestrial atoll ecosystems will require adaptive planning efforts well in advance for resident and migratory species dependent on these increasingly rare habitats.

Low islands are currently subjected to periodic high-wave events such as the two events recorded at Midway, Laysan, and Kure Atolls, in the NWHI, in January and February 2011. These storm-generated high-wave events were followed by the Tohoku Tsunami in March. Over the course of these events, Laysan albatross and blackfooted albatross populations lost 38% (254,000) and 45% (30,000), respectively, of their annual nests throughout the entire nesting range of these bird species (Flint et al., 2011; over 95% of nesting for each of these albatross occurs in the NWHI). With rising sea level, atoll inundation and overwash will become more frequent and will have substantial negative impacts on populations of atoll plants and animals, including the six endemic atoll terrestrial birds and plants identified in the region. Impacts include direct mortality as well as loss and/or alteration of habitat. Freshwater and brackish water wetlands will also become more saline with increasing seawater inundation and intrusion into shallow water tables. This increased salinity will impact the plants and animals that currently rely on these freshwater resources.

High island freshwater wetland and stream ecosystems

High island coastal wetlands will become more saline over time with increased inundation from high-wave events for those nearest to the shore. Unlike low island wetlands, high island wetlands have the potential to shift locations, given a sufficiently large landscape with an elevation gradient. As sea level rises, the freshwater subterranean lens

of the high island will also rise, creating new freshwater wetlands at the new locations on the landscape. The extent to which coastal wetlands are lost or gained in the Pacific Islands will depend, in part, on local geomorphology, sediment supply, and existing human habitation.

As discussed in detail in Chapter 2, decreasing rainfall is associated with decreasing stream base flow (Oki, 2004), which in turn has significant impacts on habitat availability for stream-dwelling organisms (Gingerich & Wolff, 2005; Oki et al., 2010). Generally speaking, the range of streamflow conditions will shift toward less consistent flow. For example, stream systems that currently flow year-round from headwaters to the sea may become hyporheic (flow underground) in some sections during the dry season: water will percolate through the streambed but will not flow over the land surface. Also, the flow of some currently perennial streams may become seasonally dependent or otherwise intermittent, and some already intermittent streams may eventually cease to show any surface flow. This overall decline in flow will reduce turbulent stream habitats and may increase pool habitats; the species that occupy the former may give way to those who favor the latter. Decrease in streamflow also reduces overall invertebrate biomass, interrupts movement of native species along streams, and may prevent amphidromous species from re-occupying the streams where they complete their life cycle (Gingerich & Wolff, 2005; Kinzie et al., 2006). While the effect of decreasing rainfall on stream ecosystems is clearly understood, the impact of a change in the frequency of heavy rainfall events is still uncertain. In fact, an increase in these events may actually benefit native stream fauna by flushing invasive fish species to lower reaches of the streams or out to sea. Unlike the invasive stream fishes in the Pacific Islands, native freshwater fishes (gobies) are adapted to resist these flushing events or to use them as part of their natural spawning cycle (Keith, 2003).

High island alpine and subalpine ecosystems (Hawai'i only)

In the Pacific Island region, alpine and subalpine ecosystems are found only in Hawai'i and represent some of the most fragile and unique ecosystems on Earth. The harsh environment of high elevation and the natural barrier provided by lava fields has largely but not entirely spared these ecosystems from alien species invasions (Denslow, 2003). Like low islands, these alpine and subalpine areas may serve as early indicators of climate change in the Pacific Islands. Snowfall and temperature on Mauna Kea and Mauna Loa may also show changes due to global warming, which could affect the distribution and abundance of native and invasive species at these high elevations. For instance, *wēkiu* bugs (*Nysius wekiuicola*) live up to the highest elevations on both mountains and rely on insects blown up from lower elevations and immobilized or killed by the frigid temperatures they encounter (Eiben & Rubinoff, 2010). Changes in snowfall could impact the distribution and abundance of *wēkiu* (Eiben & Rubinoff, 2010). Currently, cold, high-elevation temperatures protect Mauna Kea and Mauna Loa from many invasive species. Warming at high elevations could facilitate upslope movement of invasive species on these mountains (Eiben & Rubinoff, 2010).

Hawaiian alpine ecosystems are already beginning to show strong signs of increased drought and warmer temperatures, apparently related to increasing persistence of the trade wind inversion (Cao et al., 2007) since the 1990s. The most studied biological

indicator in this ecosystem is the Haleakalā silversword, *Argyroxiphium sandwicense* ssp. *macrocephalum* (Asteraceae). It is found only at high elevation (2,100 to 3,055 m [6,900 to 10,000 feet]) on the Haleakalā volcano on the Hawaiian island of Maui, where it grows for 20 to 90 years before the single reproductive event at the end of its life. After a precipitous decline to about 4,000 individuals in the early 1900s due to ungulate browsing and human vandalism, protection within Haleakalā National Park allowed it to recover to more than 50,000 individuals. Monitoring since 1982 (Loope & Crivellone, 1986) has documented a severe decline in plant numbers over the past two decades (Krushelnycky et al., 2011), apparently unrelated to effects of invasive species but happening in the same time frame as a documented increase in temperature and decrease in precipitation (as discussed in detail in the earlier chapters of this report). Recruitment of seedlings has almost ceased, and small to medium-sized plants are frequently dying without flowering, especially at the lower elevations of its range. The monitoring network was expanded substantially in 2010 to enable a more comprehensive assessment. Accurately documenting the silversword story may have potential for enhancing scientific and public understanding of what climate change has in store for Hawai'i.

High island wet, mesic, and dry forest ecosystems

Terrestrial forest ecosystems support the great majority of terrestrial Pacific Island biodiversity, yet most of these forest ecosystems remain largely unstudied, especially in American Sāmoa, the Mariana Islands, and the freely associated States. Initial bioclimate modeling of potential future plant distributions in Hawai'i, based on climate change projections of temperature and precipitation, has shown that by 2100 climate change may result in new, coastal low-elevation growth conditions that have never before occurred in the main (high) Hawaiian Islands (Price et al., 2009). Most of these new, non-analog, ecosystems will occur in areas that are already dominated by invasive species that are not native to Hawai'i. At higher elevations near the summit of the mountains on each of the main islands (and below the alpine/subalpine zones on Maui and Hawai'i), the same bioclimate modeling (Price et al., 2009) shows that wet native ecosystems that currently and naturally occupy limited areas will no longer exist by 2100. The implications for native plant species found only in these ecosystems include contraction of their ranges in part or in whole, which may contribute to the extinction of the most vulnerable species. An initial analysis of the potential bioclimatic range in 2100 of Hawaiian plants indicates that some species will experience a contraction of their bioclimatic envelope, up to and including its elimination, while others will experience no significant change or an expansion of the envelope (Figure 4-9) (Price et al., 2009).

Of great concern is the climate change response of invasive plants, animals, and diseases and their interaction with the native species of the Pacific Islands. As ecosystems are created, are lost, or shift in location and area, the potential for expansion of invasive species exists, especially if increased fire risk associated with the expansion of alien grasses (Litton et al., 2006; Varga & Asner, 2008) accompanies climate change. The potential impact of disease on native species has been characterized for avian malaria and Hawaiian forest birds. Climate change threatens to greatly expand the range of mosquitoes that transmit avian malaria and also increase the viability of the malaria parasite at high elevations (Benning et al., 2002; Atkinson & LaPointe, 2009a).

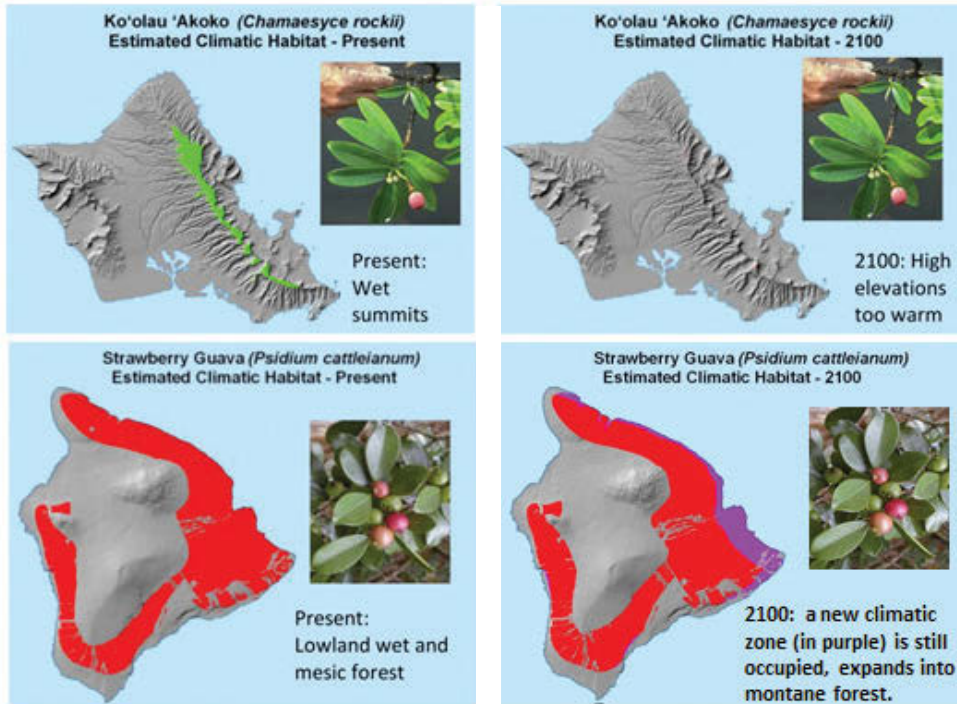


Figure 4-9 Climate-induced changes in the bioclimate envelope of plant species in Hawai'i. The bioclimate envelope of the Hawaiian endemic *'akoko* (*Chamaesyce rockii*) is projected to become greatly reduced in area and fragmented into two isolated locations. In contrast, the bioclimate envelope of the alien and invasive strawberry guava (*Psidium cattleianum*) is expected to expand into the montane forest and also occupy the new lowland climate zone produced by climate change (From Price et al., 2009.)

Implications of climate change for management

The importance of effective management of marine, freshwater, and terrestrial ecosystems cannot be overemphasized, but neither can reduction in greenhouse gas (GHG) emissions. Ultimately, without substantial reductions in GHG emissions, management actions will only succeed to a limited degree, and marine, freshwater, and terrestrial ecosystems in the Pacific Islands will be highly altered by climate change and ongoing human-induced effects. Dramatic examples of these impacts already exist in both the marine and terrestrial ecosystems of the Pacific. Figure 4-10 illustrates that, for coral reefs, strong management could result in a much better outcome for reefs under a scenario where we strongly reduce GHG emissions, but without reduced emissions, no amount of effective management will result in reefs, as they currently exist, in the future. Modeling efforts to better understand the interactions between ecological and hydrodynamic processes and human impacts for the Great Barrier Reef in Australia (Wolanski et al., 2004; Wolanski & De'ath, 2005) combined with varying management and GHG emission reduction scenarios (Richmond & Wolanski, 2011) support this conclusion. The bottom line is that while management activities to reduce local stressors can increase

resilience, slow the effects of climate change, and buy time for vulnerable ecosystems, the only scenario that results in the recovery of key marine, freshwater, and terrestrial ecosystems in the Pacific Islands is one that combines effective local management and a global reduction in GHGs.

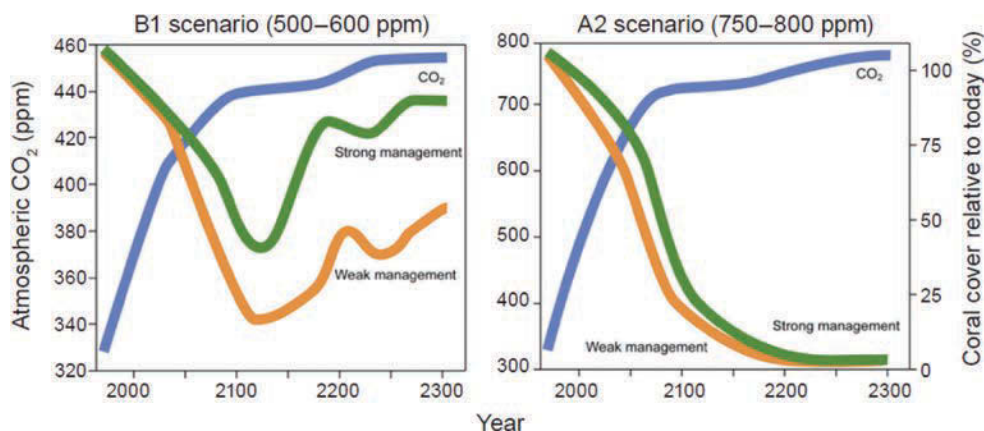


Figure 4-10 Indicative potential changes in CO₂ and coral cover over the next three centuries in a world that strongly reduces greenhouse emissions under the B1 scenario (left panel) or does not and follows the A2 scenario (right panel). The orange lines indicate likely changes to the percentage of coral cover for reefs if they are managed poorly. Green lines depict how coral cover is expected to change where strong policies and actions to manage and reduce local threats are implemented. (From Hoegh-Guldberg et al. [2011] by permission of CSIRO Publishing.)

Summary

Sound scientific information to inform management decisions in the face of climate change is needed, but there are some key challenges to providing this needed information for the Pacific Islands region. These are summarized below for marine, freshwater, and terrestrial ecosystems.

- **High quality, long-term ecological and climate monitoring with adequate spatial coverage:** Understanding the changes that Pacific Islanders are experiencing, and will experience in the future, requires consistent ecological monitoring and observations. Given the expense of long-term monitoring and considering ever-tightening budgets, the number of stations is declining. In addition, the continued reduction of long-term environmental (climate) monitoring efforts degrades the validation and refinement of modeling and downscaling approaches. Such degradation critically endangers not only our ability to accurately understand the magnitude of change that is happening, but also our ability to identify, forecast, and respond to extreme environmental conditions that may cause irreparable damage to ecosystems and the communities/economies that depend upon them.

- **Terrestrial and aquatic research sites across the region:** A major observation of this assessment is the lack of adequate ecosystem-monitoring long-term study sites throughout the Pacific Islands. If climate change impacts on freshwater and terrestrial ecosystems are to be effectively assessed in the Pacific Islands, a well-designed ecological program is needed. Currently, studies on the long-term stability and biodiversity of terrestrial and aquatic ecosystems are conducted only in limited locations in Hawai'i. Additional study sites are needed throughout the Pacific Islands.
- **Downscaled models for the Pacific Islands:** One of the challenges of the Pacific Islands is that many of the global climate models (GCMs) are not adequate for the region. Downscaling of global models, taking into consideration the regional and local phenomena that influence the regional climate system, needs to be done (for further summary of modeling efforts, see Appendix B of this report). Alternatively, nesting regional climate models into future GCM runs is a viable alternative to post-GCM downscaling. This would provide much more comprehensive capture of air-sea fluxes and boundary-layer conditions than traditional downscaling approaches.
- **Integrated biogeochemical and physical models:** Biological responses to a changing climate can have cascading and interactive effects that we cannot predict. Consequently, direct impacts to one organism will affect many other organisms in the system. Integrating biogeochemical and physical models will provide a better understanding of overall impacts.
- **Ocean acidification research:** Ocean acidification is a well-understood chemical process, but the impacts of the changing carbonate chemistry on key organisms such as larval fish, coral reefs, phytoplankton, other zooplankton, larvae of amphidromous (freshwater adults with marine larval stages) species, and other calcifying organisms are not. Research to better understand the biological response is necessary to understand and prepare for these potentially far-reaching impacts.
- **Resilience of key ecosystems and dependent communities:** The combined effects of climate change and anthropogenic stressors (e.g., the introduction of invasive species, land-use practices, land-based sources of pollution, fishing practices, and so forth) are often synergistic, with dire consequences for native ecosystems. Reducing human-caused stresses on marine, freshwater, and terrestrial ecosystems is a critical part of maintaining and restoring their resilience. Improved control and management of invasive species, along with steps toward better prevention of their introduction to native ecosystems, are necessary to achieve this goal.

Key Findings for Marine, Aquatic, and Terrestrial Ecosystems

- Surface air temperature has risen over the Pacific Islands region over the last century. This warming is spatially and temporally variable, with more warming at higher elevations and at night. Minimum and maximum temperatures and the frequency and intensity of days of extreme heat are projected to

increase across the region.

- Warming at high elevations could exacerbate invasive species problems and alter the distribution of native species in high island ecosystems.
- Average sea-surface temperature across the region has risen over the last century, with more rapid warming since the 1970s. Surface temperatures across the region are projected to increase at levels that will impact key marine ecosystems.
- Increased sea-surface temperatures are correlated with increased frequency and intensity of mass coral bleaching events and associated mortality in the region. The distribution of phytoplankton and key fisheries species is also projected to change with changes in sea-surface temperature, currents, and wind patterns.
- Changes in precipitation patterns may lead to increased coastal erosion, decreases in coastal water quality, and changes in terrestrial and aquatic species distribution.
- Sea level in the region has risen at a rate greater than the global average. Sea level is projected to continue to rise, and regional fluctuations at inter-annual to multidecadal time scales will superimpose on global sea-level rise.
- Sea-level rise is of critical concern to low-lying atolls where overwash and inundation will contribute to loss of terrestrial ecosystems. Key habitats such as mangroves and coastal wetlands could also be negatively impacted by erosion and inundation.
- CO₂ is absorbed by sea-water, resulting in a series of chemical reactions that reduce the sea-water pH, carbonate ion concentration, and the availability of the biologically important calcium carbonate minerals calcite and aragonite through a process known as ocean acidification.
- The biological impacts of ocean acidification to key organisms, including larval fish, coral reefs, phytoplankton, zooplankton, and other calcifying organisms, are thought to have potentially devastating effects and must be better understood to prepare for these potentially far-reaching impacts.
- For sensitive ecosystems like coral reefs, with high vulnerability and potentially low adaptive capacity, greenhouse gas reduction is the only meaningful response. High levels of local protection will only buy time for these ecosystems and do not provide immunity to significant climate change impacts.
- Projected increase in tropical cyclone intensity could impact the geomorphology of islands and result in habitat destruction of terrestrial ecosystems (forests) and marine ecosystems (coral reefs, seagrasses, and mangroves), influencing the spread of invasive species and reducing shoreline protection for coastal communities.

FOCUS ON IMPACTS**Case Study 4-1****Climate change threatens Hawaiian forest birds**

In Hawai'i, geographic isolation has prevented the natural establishment of mammals, terrestrial reptiles, amphibians, and many insect species, such as biting mosquitoes. Isolation has also facilitated the spectacular evolutionary radiation of Hawaiian honeycreepers from a single small flock of North American finches into more than 50 species and subspecies of endemic forest birds (Pratt, 2009).

With the arrival of humans came the clearing of forests and the introduction of non-native species and their diseases. More than 40 mosquito species have been captured in Hawai'i, and six have become established, most recently in 2004 (LaPointe & Burgett, 2005). The southern house mosquito was the first to arrive in Hawai'i in 1826 (Atkinson & LaPointe, 2009b). It is the vector for avian malaria and avian pox. The malaria parasite arrived later with the introduction of non-native birds, probably around 1871. These introduced birds are the perfect avian malaria host: they show no signs of infection and remain infectious for long periods of time.



Case Study 4-1 Photo 1 The 'Apapane honeycreeper, seen here at Hawai'i Volcanoes National Park, is one of the only remaining, relatively abundant species of Hawaiian honeycreepers. (Courtesy of Simon Bisson.)

Habitat loss, predation, and competition have taken their toll on Hawaiian honeycreepers, but this trio of invasive species—alien birds, malaria, and mosquitoes—were, and still are, a major threat to the honeycreepers' long-term survival. Almost all of these birds are vulnerable to avian malaria, with mortality rates as high as 65% to 90% after being bitten by a single infective mosquito (Atkinson & LaPointe, 2009a, 2009b). Of the 50 species and sub-species of endemic Hawaiian honeycreepers, only 22 have survived

the combined effects of habitat loss, disease, predation, and competition from alien species. The most recent victim, the *Po'ouli*, became extinct in 2004 (Pratt, 2009).

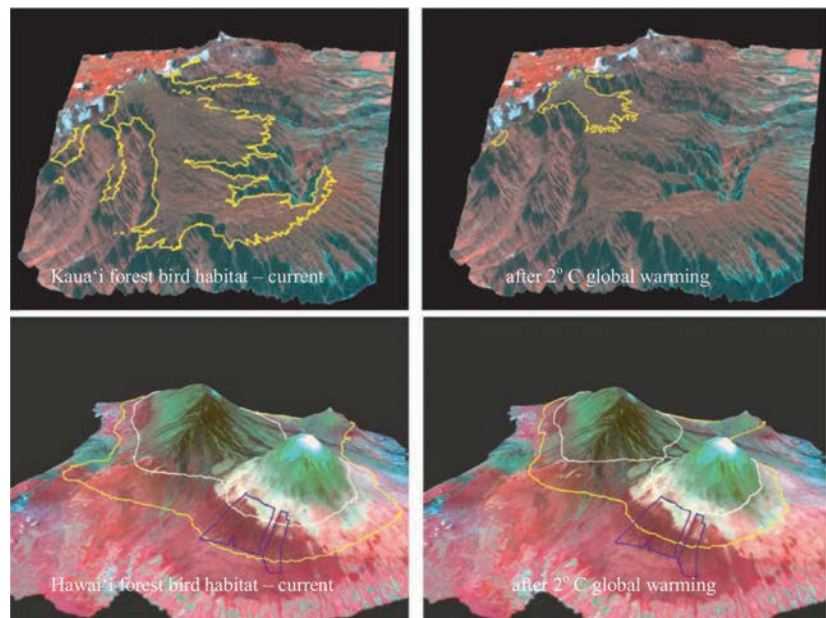
Mosquitoes and avian malaria do not do well in Hawai'i's cooler high elevations. Below 13°C (about 55°F), the malaria parasite cannot complete its maturation cycle, so the disease cannot be transmitted. In addition, the southern house mosquito, which transmits avian malaria, is active at night when temperatures are cooler. Consequently, the prevalence of avian malaria in native forest birds is low above 1,500 m (about 5,000 feet) (Atkinson & LaPointe, 2009a). At lower elevations, mosquitoes and malaria are abundant, and most honeycreepers can no longer survive in the warm mesic and wet forests that were once ideal habitats. Hawai'i's cool, high mesic and wet forests have become their last refuge. But today, climate change threatens to open up these refuges to avian malaria.

As climate change warms the air, the range of mosquitoes will expand upslope, and infective malaria parasites will develop at high elevations. Currently, at higher elevations, avian malaria transmission is seasonal, occurring during the warm summer and fall when mosquito populations are at a maximum. Thus, the cooler winter months and night temperatures are critical to the survival of honeycreepers.

As global warming raises air temperatures, their seasonal high elevation refuge will shrink and eventually disappear (Figure 4-11) (Benning et al., 2002; Atkinson & LaPointe, 2009a). It is likely that the spread of mosquitoes and avian malaria (as well as avian pox) into the high elevations of Hawai'i will eventually lead to the extinction of many, perhaps all, of the honeycreepers that currently survive in these areas.

Current temperatures at high elevations in Hawai'i have risen about 0.26°C per decade averaged over the day and night. But of greater concern is the rise in nighttime temperatures, when the southern house mosquito is most active. These have risen about 0.44°C (0.79°F) per decade since 1975 (Giambelluca et al., 2008). As a result, the

Figure 4-11 Projected changes in the location of the forest cover in relation to 17°C (yellow) and 13°C (white) isotherms under current conditions and with a 2°C warming of the climate. Changes are shown for Hakalau Forest National Wildlife Refuge (blue boundary) on Hawai'i, and the Alakai swamp region on the island of Kaua'i. (From Benning et al., 2002.)



prevalence of avian malaria in Hawaiian forest birds at Hakalau Forest National Wildlife Refuge (1,500 to 2,000 m; 5,000 to 6,500 feet elevation) on the island of Hawai'i has risen from 2.1% to 5.4% over the past decade (Freed et al., 2005). The prevalence of avian malaria at high elevations on Kaua'i has risen as much as 30% over the past decade (Atkinson & Utzurrum, 2010).

High-elevation forest restoration is needed to expand the upward range available to these forest birds. This will require addressing long-standing problems with invasive plants and animals. And there is hope for some Hawai'i honeycreepers. Natural resistance to avian malaria has developed in one species, the *Hawai'i amakihi*, which is now more abundant in low-elevation forests with high levels of mosquitoes and avian malaria than at disease-free high-elevation sites (Woodworth et al., 2005; Kilpatrick et al., 2006). The hope is that good habitat management can help other honeycreepers develop resistance to avian malaria (Kilpatrick, 2006). Unfortunately, the rate of warming in Hawai'i may not give these birds enough time to develop resistance. Without human assistance, global warming combined with avian malaria may overwhelm Hawaiian honeycreepers and other forest bird species.

FOCUS ON IMPACTS

Case Study 4-2

Fish populations respond to climate conditions

Fishing is a way of life in the Pacific Islands. Subsistence fishers ply the waters of every inhabited shore as well as many uninhabited ones; seafood consumption is high, providing a primary protein source; and fishing is prominent in cultural traditions. There are many stories, chants, and songs about fish and fishing throughout the Pacific region. In Polynesia, the most famous perhaps are those of Maui and his legendary fishing hook.

*Oh the great fish hook of Maui!
Manai-i-ka-lani ' made fast to the
heavens' its name;
An earth-twisted cord ties the hook.
Engulfed from the lofty Ka'uiki.
Its bait the red billed 'Alae,
The bird made sacred to Hina.
It sinks far down to Hawai'i,
Struggling and painfully dying.
Caught is the land under the water,
Floated up, up to the surface,*

*But Hina hid a wing of the bird
And broke the land under the water.
Below, was the bait snatched away
And eaten at once by the fishes,
The Uluu of the deep muddy places.*

"Chant of Kualii," ca. 1700 AD
(Westervelt, 1910)

Case Study 4-2 Photo 1 Fish hook collection, Bishop Museum, Honolulu, Hawai'i. (© 2008 Debbi Long, "hooked," used under a Creative Commons Attribution-NonCommercial-ShareAlike license.)



In addition to their importance to traditional practices and food security for island communities, open-ocean fish populations in the Pacific play an increasingly dominant role in global fish production. The Western Pacific Regional Fishery Management Council estimates the annual catch of skipjack tuna (*Katsuwonus pelamis*), yellowfin tuna (*Thunnus albacares*), bigeye tuna (*T. obesus*), and South Pacific albacore tuna (*T. alalunga*) at about 2.7 million metric tonnes. These tuna species are highly migratory and range throughout the Pacific, and adults tolerate a relatively wide range of conditions (Brill, 1994). Yet, climatic conditions greatly influence the productivity and geographic range of Pacific tuna populations (Miller, 2007).

Tuna have been shown to respond to El Niño-Southern Oscillation (ENSO) events. Sea-surface temperature influences tuna productivity and optimal development through different life stages (Lehodey et al., 1997; Lehodey, 2001; Lu et al., 2001). ENSO-related shifts create a disadvantage for local fishers who, unlike large-scale commercial fleets, cannot follow the tuna to more productive waters thousands of miles away.

Due to projected ocean warming and other climate-associated changes in marine ecosystem productivity, it is projected that over the 21st century, tuna distributions "are likely to shift progressively towards the central and eastern Pacific" (Bell et al., 2011) (Figure 4-12). Currently, in the Western North Pacific sub-region, the domestic tuna fisheries of the Federated States of Micronesia and the Republic of the Marshall Islands are valued at \$2.67 million and \$2.44 million annually, respectively (Bell et al., 2011). The contribution of tuna fisheries to these economies may well lessen as the projected shift in populations takes place.

The complexity of marine ecosystems makes it difficult to predict how climate change will alter discrete "strands" of the food web upon which tuna and other large pelagic fish depend. There are indications that, in addition to changes in sea-surface temperature, changes in ocean circulation and ocean chemistry will heavily influence productivity throughout the region (Le Borgne et al., 2011; Polovina et al., 2011). By the end of this century, the total primary production and fish catch is projected to increase by 26% in the subtropics and decrease by 38% and 15% in the temperate and the equatorial zones,

respectively (Polovina et al., 2011). This projected decrease, in combination with shifting fish populations, may have a significant and unequal economic impact on Pacific Island sub-regions. One cannot place a monetary value, however, on how these projected changes in pelagic fisheries will impact the Pacific Island way of life.

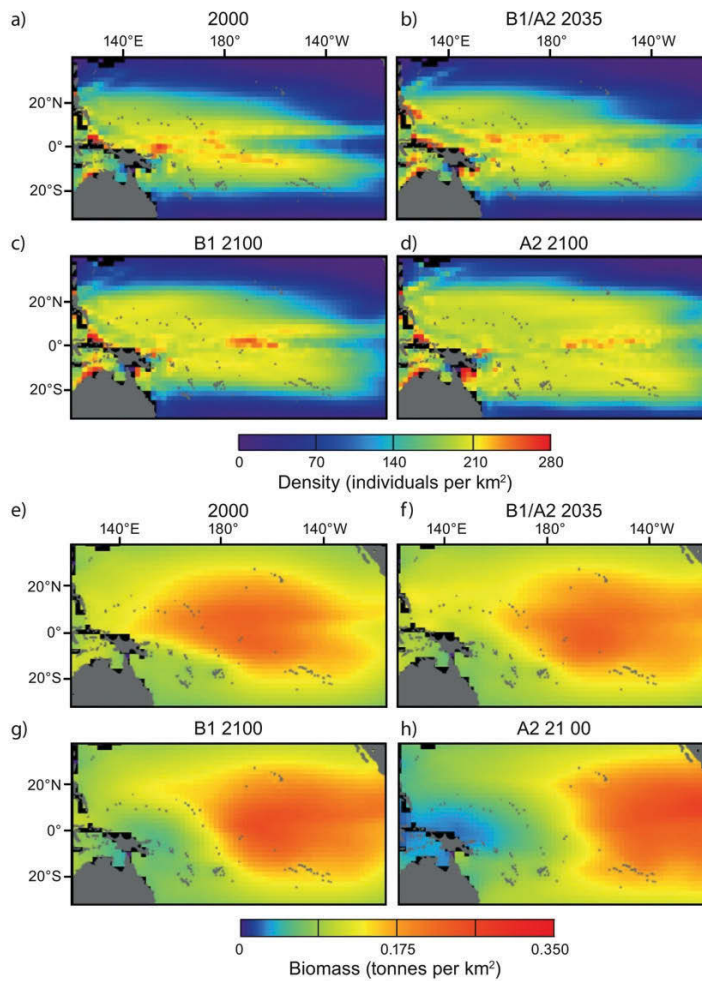


Figure 4-12 Projected distributions (density) for skipjack tuna larvae recruits from the SEAPODYM model (a) in 2000; (b) under the B1/A2 emissions scenario in 2035; (c) under B1 in 2100; and (d) under A2 in 2100. Also shown are estimates of total biomass (tonnes per square kilometer) of skipjack tuna populations based on average (1980–2000) fishing effort in (e) 2000; (f) under B1/A2 in 2035; (g) under B1 in 2100; and (h) under A2 in 2100. (From Lehodey et al., 2011.)

FOCUS ON ADAPTATION

Case Study 4-3**Pacific coral reef management in a changing climate**

Tropical coral reefs are among the most productive and diverse ecosystems in the world: thousands of species coexist in a complex structure built by living corals. Coral ecosystems are of particular ecological, economic, and cultural importance in the Pacific Islands region, and this region supports the majority of coral reefs within the United States' jurisdiction.

These ecosystems are declining due to a plethora of human impacts, including over-utilization, land-based pollutants, introduced invasive aquatic species, and climate change. Two climate-related phenomena in conjunction pose a potentially catastrophic threat to the long-term survival of coral reef ecosystems in the Pacific Islands region: rising sea-surface temperatures (SSTs) and changes in ocean chemistry.

Over the past 30 years, periods of elevated SST have become more commonplace, often correlating with coral bleaching (Donner, 2011). Coral bleaching occurs when water temperatures rise 1° to 2°C (1.8° to 3.6°F) above the warmest normal summer temperatures and persist over three to four weeks or more. This stress can cause the corals to expel their crucial, colorful symbiotic algae and thus turn white (hence the name

**Case Study 4-3 Photo 1**

A healthy tropical Pacific coral reef, Palmyra Atoll National Wildlife Refuge. (Courtesy of J. Maragos, USFWS.)

“bleaching”). Intense coral bleaching is often followed by coral death, though corals can recover from mild bleaching events.

Coral bleaching is becoming more frequent as the oceans warm (Hoegh-Guldberg, 1999). Coral bleaching in 1998 and 2010 caused large-scale coral deaths in reef systems around the globe, with the 1998 event heavily impacting Palau in the Western North Pacific sub-region, and Palmyra Atoll in the Central North Pacific sub-region (Turgeon et al., 2002). In the Republic of Palau, nearly one-half (48%) of 946 surveyed colonies were totally bleached, and a further 15% were partially bleached (Bruno et al., 2001). Coral bleaching has also been observed elsewhere in the Micronesian, Marianas, Samoan, and Hawaiian archipelagos. The *Reefs at Risk Revisited* report (Burke et al., 2011) predicts that by 2050 many of the reefs in the Pacific will bleach annually. This frequency of bleaching is worrying because it allows little time for corals to recover. Annual summer bleaching has already been reported from American Sāmoa (Fenner & Heron, 2008).

Adding to the stress of high temperatures is the increasing acidification of the ocean, caused by rising levels of carbon dioxide in the air that is absorbed by sea water. One of the impacts of ocean acidification is that less carbonate is available in the form necessary for coral reefs to build their calcium carbonate skeletons. The skeletons that these small coral polyps build are a fundamental building block of coral reef ecosystems. Based on the rate of coral loss reported over the past 20 years, and the projected effects of more frequent coral bleaching and ocean acidification, average coral cover throughout the Pacific is expected to decline to 15% to 35% by 2035 compared with 20% to 40% in 2007 (Bruno & Selig, 2007; Hoegh-Guldberg et al., 2011).

Coral reef managers have few options for preventing or reducing coral bleaching because it is not possible to cool large masses of sea water. They can focus on increasing the potential resilience of reefs by reducing human impacts such as overfishing, sediment and pollutant runoff, and invasive species. In addition, early-warning systems that predict coral bleaching and monitor the effects on reef ecosystems have made it possible to identify which reefs are perhaps more resistant to bleaching and have a better chance of recovery.

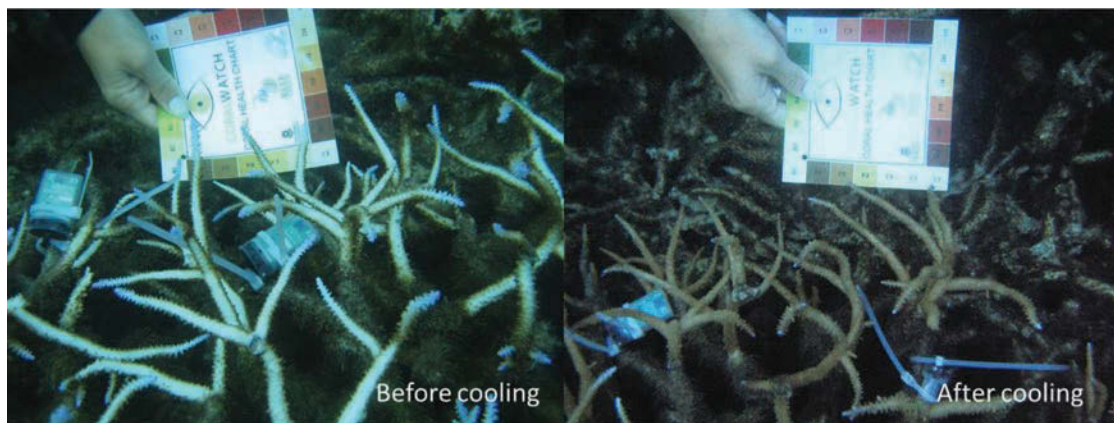


Figure 4-13 Bleached *Acropora* corals before (left) and after (right) treatment with cooled seawater for 24 hours, Tutuila, American Sāmoa. (Courtesy of B. Von Herzen, Climate Foundation.)

In an effort to expand the range of management options, researchers in American Sāmoa are testing technologies that could cool selected, important reefs and shade them from strong sunlight. Seasonally high temperatures at a particular reef on the island of Tutuila cause predictable coral bleaching (Fenner & Heron, 2008), creating an ideal test site. Initial tests have shown that reducing peak water temperatures by about 1.0°C (1.8°F) enables two sensitive species of coral to regain and retain their healthy color during periods of thermal stress (Figure 4-13). In a second set of experiments, shading was found to restore healthy color in bleached coral. In conjunction with strategies for reducing land-based stress, these and other management tools may provide Pacific Island communities with new, localized conservation measures to help combat the effects of global climate change on their valuable coral reef resources.