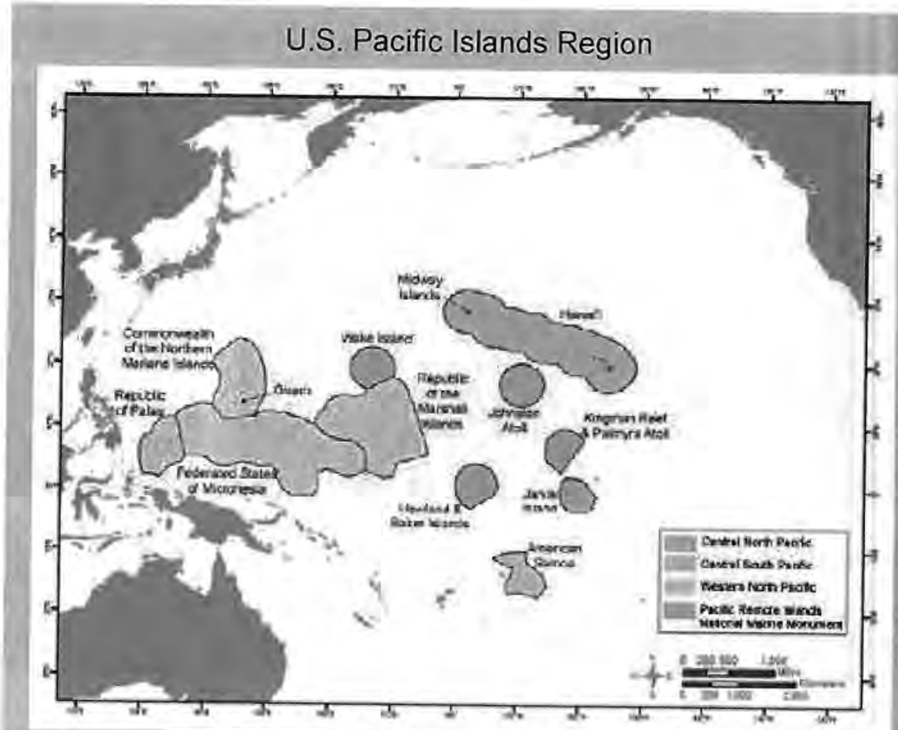

Figure 23.1. The U.S. Pacific Islands region includes our 50th state, Hawai'i, as well as the Territories of Guam, American Samoa, the Commonwealth of the Northern Mariana Islands (CNMI), the Republic of Palau (RP), the Federated States of Micronesia (FSM), and the Republic of the Marshall Islands (RMI).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

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

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

Key Message 1: Changes to Marine Ecosystems

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

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

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

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

"High" and "Low" Pacific Islands Face Different Threats

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

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

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

EL NIÑO AND OTHER PATTERNS OF CLIMATE VARIABILITY

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

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

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


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Increasing ocean temperature and acidity threaten coral reef ecosystems.

Increased Acidification Decreases Suitable Coral Habitat

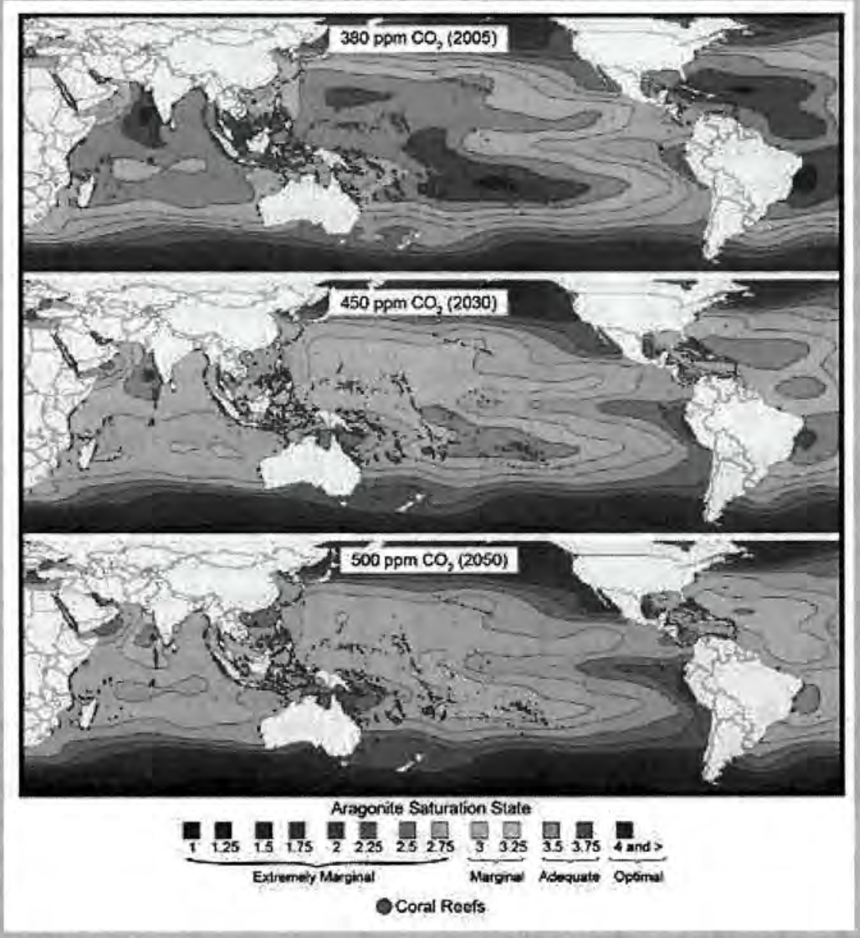

Figure 23.3. Ocean waters have already become more acidic from absorbing carbon dioxide from the atmosphere. As this absorption lowers pH, it reduces the amount of calcium carbonate, which is critical for many marine species to reproduce and grow. Maps show projections of the saturation state of aragonite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

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.

Key Message 2: Decreasing Freshwater Availability

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

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

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

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

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

Observed Changes in Annual Rainfall in the Western North Pacific

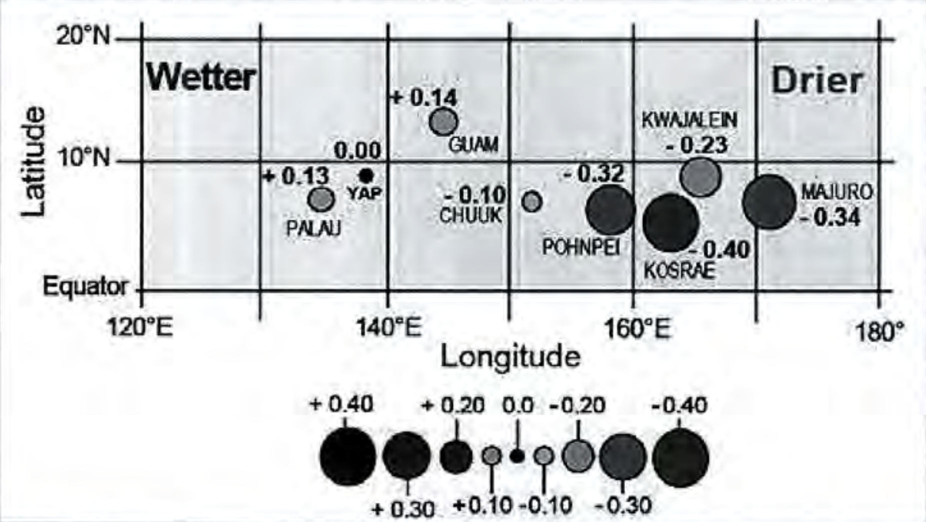

Figure 23.4. Islands in the western reaches of the Pacific Ocean are getting slightly more rainfall than in the past, while islands more to the east are getting drier (measured in change in inches of monthly rainfall per decade over the period 1950-2010). Darker blue shading indicates that conditions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

Key Message 3: Increased Stress on Native Plants and Animals

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

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

Native Plants at Risk

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

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

Key Message 4: Sea Level Rising

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

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

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

Saltwater Intrusion Destroys Crops

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

Residents of Low-lying Islands at Risk

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

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

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

Higher Sea Level Rise in Western Pacific

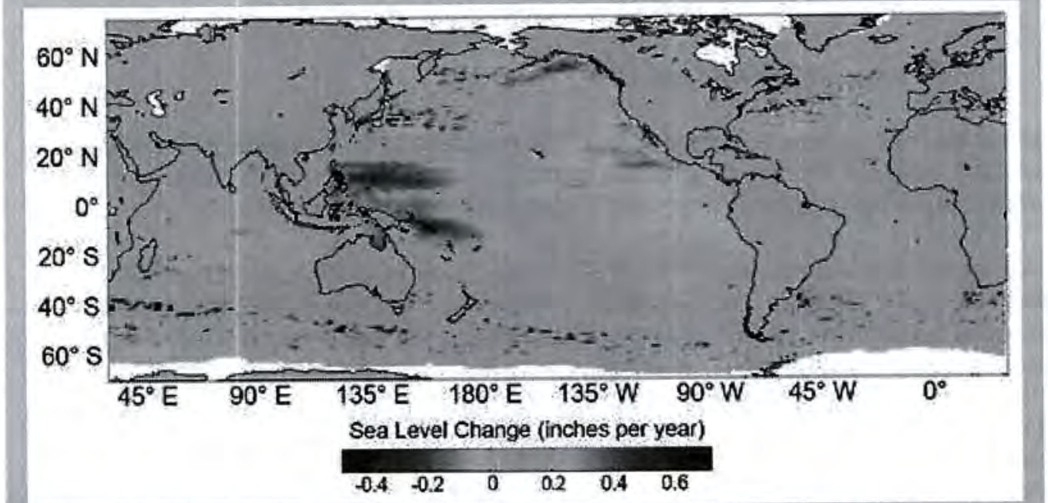

Figure 23.8. Map shows large variations across the Pacific Ocean in sea level trends for 1993-2010. The largest sea level increase has been observed in the western Pacific. (Figure source: adapted from Merrifield 2011[57] by permission of American Meteorological Society).

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

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

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

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

Adaptation Activities

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

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

23: HAWAI'I AND US AFFILIATED PACIFIC ISLANDS

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SUPPLEMENTAL MATERIAL
TRACEABLE ACCOUNTS

Process for Developing Key Messages

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

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

KEY MESSAGE #1 TRACEABLE ACCOUNT

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

Description of evidence base

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

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

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

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

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

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

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

New information and remaining uncertainties

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

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

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

Assessment of confidence based on evidence

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

Confidence Level

Very High

Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus

High

Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus

Medium

Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought

Low

Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

KEY MESSAGE #2 TRACEABLE ACCOUNT

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

Description of evidence base

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

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

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

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

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

New information and remaining uncertainties

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

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

Assessment of confidence based on evidence

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

KEY MESSAGE #3 TRACEABLE ACCOUNT

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

Description of evidence base

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

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

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

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

New information and remaining uncertainties

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

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

Climate change ecosystem response is poorly understood.[2]

Assessment of confidence based on evidence

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

KEY MESSAGE #4 TRACEABLE ACCOUNT

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

Description of evidence base

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

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

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

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

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

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

Major uncertainties

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

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

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

Assessment of confidence based on evidence

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

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

KEY MESSAGE #5 TRACEABLE ACCOUNT

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

Description of evidence base

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

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

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

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

New information and remaining uncertainties

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

Assessment of confidence based on evidence

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

Climate Change Impacts in the United States

CHAPTER 24
OCEANS AND MARINE RESOURCES

Convening Lead Authors

Scott Doney, Woods Hole Oceanographic Institution

Andrew A. Rosenberg, Union of Concerned Scientists

Lead Authors

Michael Alexander, National Oceanic and Atmospheric Administration

Francisco Chavez, Monterey Bay Aquarium Research Institute

C. Drew Harvell, Cornell University

Gretchen Hofmann, University of California Santa Barbara

Michael Orbach, Duke University

Mary Ruckelshaus, Natural Capital Project

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INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

24 OCEANS AND MARINE RESOURCES

KEY MESSAGES

1. **The rise in ocean temperature over the last century will persist into the future, with continued large impacts on climate, ocean circulation, chemistry, and ecosystems.**
2. **The ocean currently absorbs about a quarter of human-caused carbon dioxide emissions to the atmosphere, leading to ocean acidification that will alter marine ecosystems in dramatic yet uncertain ways.**
3. **Significant habitat loss will continue to occur due to climate change for many species and areas, including Arctic and coral reef ecosystems, while habitat in other areas and for other species will expand. These changes will consequently alter the distribution, abundance, and productivity of many marine species.**
4. **Rising sea surface temperatures have been linked with increasing levels and ranges of diseases in humans and marine life, including corals, abalones, oysters, fishes, and marine mammals.**
5. **Climate changes that result in conditions substantially different from recent history may significantly increase costs to businesses as well as disrupt public access and enjoyment of ocean areas.**
6. **In response to observed and projected climate impacts, some existing ocean policies, practices, and management efforts are incorporating climate change impacts. These initiatives can serve as models for other efforts and ultimately enable people and communities to adapt to changing ocean conditions.**

As a nation, we depend on the oceans for seafood, recreation and tourism, cultural heritage, transportation of goods, and, increasingly, energy and other critical resources. The U.S. Exclusive Economic Zone extends 200 nautical miles seaward from the coasts, spanning an area about 1.7 times the land area of the continental U.S. and encompassing waters along the U.S. East, West, and Gulf coasts, around Alaska and Hawai'i, and including the U.S. territories in the Pacific and Caribbean. This vast region is host to a rich diversity of marine plants and animals and a wide range of ecosystems, from tropical coral reefs to Arctic waters covered with sea ice.

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Oceans support vibrant economies and coastal communities with numerous businesses and jobs. More than 160 million people live in the coastal watershed counties of the United States, and population in this zone is expected to grow in the future. The oceans help regulate climate, absorb carbon dioxide (an important greenhouse, or heat-trapping, gas), and strongly influence weather patterns far into the continental interior. Ocean issues touch all of us in both direct and indirect ways.[1,2,3]

Changing climate conditions are already affecting these valuable marine ecosystems and the array of resources and services we derive from the sea. Some climate trends, such as rising seawater temperatures and ocean acidification, are common across much of the coastal areas and open ocean worldwide. The biological responses to climate change often vary from region to region, depending on the different combinations of species, habitats, and other attributes of local systems. Data records for the ocean are often shorter and less complete than those on land, and for many biological variables it is still difficult to discern long-term ocean trends from natural variability.[4]

Key Message 1: Rising Ocean Temperatures

The rise in ocean temperature over the last century will persist into the future, with continued large impacts on climate, ocean circulation, chemistry, and ecosystems.

Cores from corals, ocean sediments, ice records, and other indirect temperature measurements indicate the recent rapid increase of ocean temperature is the greatest that has occurred in at least the past millennium and can only be reproduced by climate models with the inclusion of human-caused sources of heat-trapping gas emissions.[5,6] The ocean is a critical reservoir for heat within Earth's climate system, and because of seawater's large heat storing capacity, small changes in ocean temperature reflect large changes in ocean heat storage. Direct measurements of ocean temperatures show warming beginning in about 1970 down to at least 2,300 feet, with stronger warming near the surface leading to increased thermal stratification (or layering) of the water column.[7,8] Sea surface temperatures in the North Atlantic and Pacific, including near U.S. coasts, have also increased since 1900.[9,10] In conjunction with a warming climate, the extent and thickness of Arctic sea ice has decreased rapidly over the past four decades.[11,12] Models that best match historical trends project seasonally ice-free northern waters by the 2030s.[13]

Climate-driven warming reduces vertical mixing of ocean water that brings nutrients up from deeper water, leading to potential impacts on biological productivity. Warming and altered ocean circulation are also expected to reduce the supply of oxygen to deeper waters, leading to future expansion of sub-surface low-oxygen zones.[15] Both reduced nutrients at the surface and reduced oxygen at depth have the potential to change ocean productivity.[14] Satellite observations indicate that warming of the upper ocean on year-to-year timescales leads to reductions in the biological productivity of tropical and subtropical (the region just outside the tropics) oceans and expansion of the area of surface waters with very low quantities of phytoplankton (microscopic marine plants) biomass.[16] Ecosystem models suggest that the same patterns of productivity change will occur over the next century as a consequence of warming during this century, perhaps also with increasing productivity near the poles.[17] These changes can affect ecosystems at multiple levels of the food web, with consequent changes for fisheries and other important human activities that depend on ocean productivity.[4,18]

Observed Ocean Warming

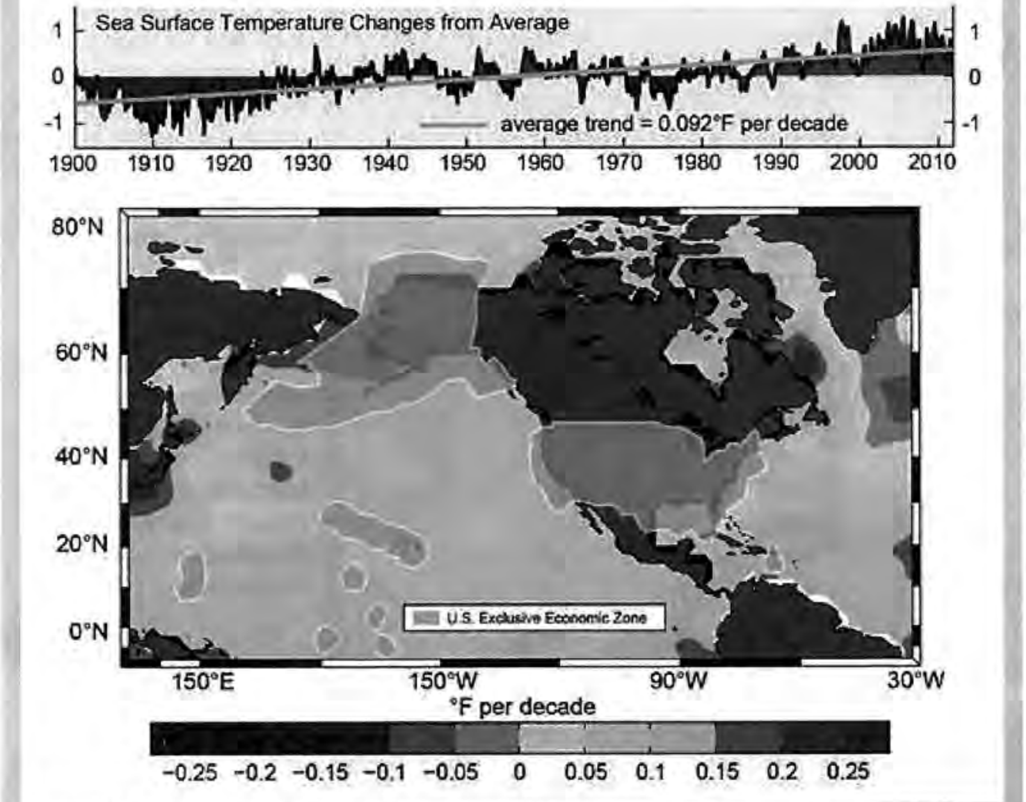


Figure 24.1. Sea surface temperatures for the ocean surrounding the U.S. and its territories have warmed by more than 0.9°F over the past century (top panel). There is significant variation from place to place, with the ocean off the coast of Alaska, for example, warming far more rapidly than other areas (bottom panel). The gray shading on the map denotes U.S. land territory and the regions where the U.S. has rights over the exploration and use of marine resources, as defined by the U.S. Exclusive Economic Zone (EEZ). (Figure source: adapted from Chavez et al. 2011[14]).

Other changes in the physical and chemical properties of the ocean are also underway due to climate change. These include rising sea level,[19] changes in upper ocean salinity (including reduced salinity of Arctic surface waters) resulting from altered inputs of freshwater and losses from evaporation, changes in wave height from changes in wind speed, and changes in oxygen content at various depths – changes that will affect marine ecosystems and human uses of the ocean in the coming years.[4]

While the long-term global pattern is clear, there is considerable variability in the effects of climate change regionally and locally because oceanographic conditions are not uniform and are strongly influenced by natural climate fluctuations. Trends during short periods of a decade or so can be dominated by natural variability.[25] For example, the high incidence of La Niña events in the last 15 years has played a role in the observed temperature trends.[26]

Analyses[27] suggest that more of the increase in heat energy during this period has been transferred to the deep ocean (see also Ch. 2: Our Changing Climate). While this might temporarily slow the rate of increase in surface air temperature, ultimately it will prolong the effects of global warming because the oceans hold heat for longer than the atmosphere does.

Interactions with processes in the atmosphere and on land, such as rainfall patterns and runoff, also vary by region and are strongly influenced by natural climate fluctuations, resulting in additional local variation in the observed effects in the ocean.

Marine ecosystems are also affected by other human-caused local and regional disturbances such as overfishing, coastal habitat loss, and pollution, and climate change impacts may exacerbate the effects of these other human factors.

Ocean Impacts of Increased Atmospheric Carbon Dioxide

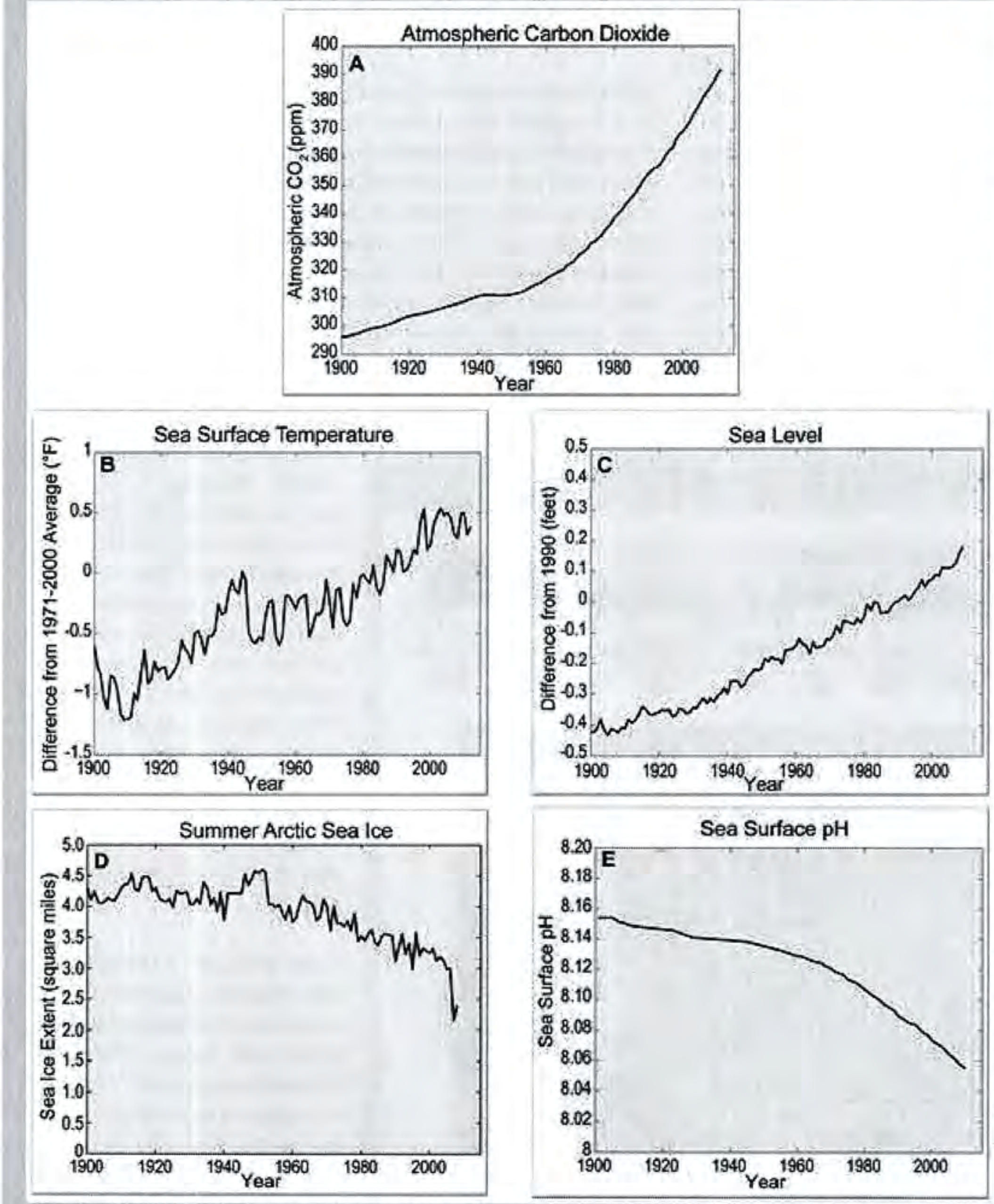


Figure 24.2. As heat-trapping gases, primarily *carbon dioxide (CO_2)* (panel A), have increased over the past decades, not only has air temperature increased worldwide, but so has the temperature of the ocean's surface (panel B). The increased ocean temperature, combined with melting of glaciers and ice sheets on land, is leading to higher sea levels (panel C). Increased air and ocean temperatures are also causing the continued, dramatic decline in Arctic sea ice during the summer (panel D). Additionally, the ocean is becoming more acidic as increased atmospheric CO_2 dissolves into it (panel E). (CO_2 data from Etheridge 2010,[20] Tans and Keeling 2012,[21] and NOAA NCDC 2012;[22] SST data from NOAA NCDC 2012[22] and Smith et al. 2008;[10] Sea level data from CSIRO 2012[23] and Church and White 2011;[19] Sea ice data from University of Illinois 2012;[24] pH data from Doney et al. 2012[4]).

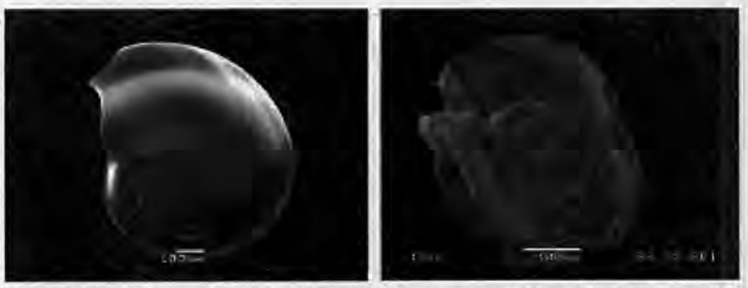
Key Message 2: Ocean Acidification Alters Marine Ecosystems

The ocean currently absorbs about a quarter of human-caused carbon dioxide emissions to the atmosphere, leading to ocean acidification that will alter marine ecosystems in dramatic yet uncertain ways.

Atmospheric carbon dioxide (CO_2) has risen by about 40% above pre-industrial levels.[21,28] The ocean absorbs about a quarter of human-caused emissions of carbon dioxide annually, thereby changing seawater chemistry and decreasing pH (making seawater more acidic) (Ch. 2: Our Changing Climate, Key Message 12).[3,29] Surface ocean pH has declined by 0.1 units, equivalent to a 30% increase in ocean acidity, since pre-industrial times.[30] Ocean acidification will continue in the future due to the interaction of atmospheric carbon dioxide and ocean water. Regional differences in ocean pH occur as a result of variability in regional or local conditions, such as upwelling that brings subsurface waters up to the surface.[31] Locally, coastal waters and estuaries can also exhibit acidification as the result of pollution and excess nutrient inputs.

More acidic waters create repercussions along the marine food chain. For example, calcium carbonate is a skeletal component of a wide variety of organisms in the oceans, including corals. The chemical changes caused by the uptake of CO_2 make it more difficult for these living things to form and maintain calcium carbonate shells and skeletal components and increases erosion of coral reefs,[32] resulting in alterations in marine ecosystems that will become more severe as present-day trends in acidification continue or accelerate (Ch. 22: Alaska; Ch. 23: Hawai'i and Pacific Islands).[33,34,35] Tropical corals are particularly susceptible to the combination of ocean acidification and ocean warming, which would threaten the rich and biologically diverse coral reef habitats.

Over 90% of seafood consumed in the U.S. is imported, and more than half of the imported seafood comes from aquaculture (fish and shellfish farming).[1] While only 1% of U.S. seafood comes from domestic shellfish farming, the industry is locally important. In addition, shellfish have historically been an important cultural and food resource for indigenous peoples along our coasts (Ch. 12: Indigenous Peoples, Key Message 1). Increased ocean acidification, low-oxygen events, and rising temperatures are already affecting shellfish aquaculture operations. Higher temperatures are predicted to increase aquaculture potential in poleward regions, but decrease it in the tropics.[37] Acidification, however, will likely reduce growth and survival of shellfish stocks in all regions.[34]



Pteropods, or "sea butterflies," are eaten by a variety of marine species ranging from tiny krill to salmon to whales. The photos show what happens to a pteropod's shell in seawater that is too acidic. On the left is a shell from a live pteropod from a region in the Southern Ocean where acidity is not too high. The shell on the right is from a pteropod in a region where the water is more acidic. (Photo credits: (left) Bednaršek et al. 2012;[105] (right) Nina Bednaršek).

Ocean Acidification Reduces Size of Clams

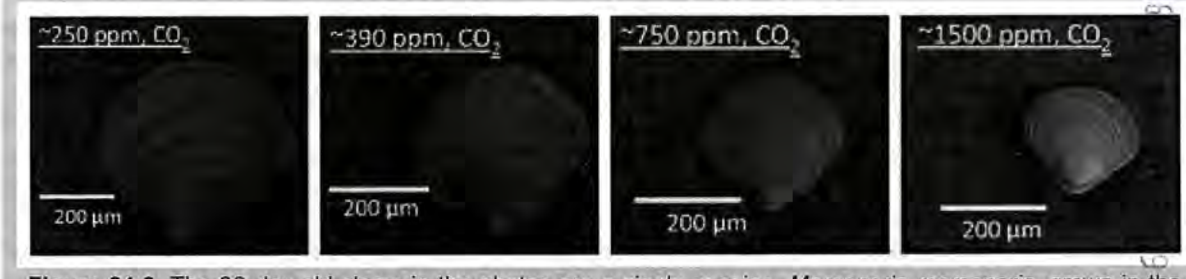


Figure 24.3. The 36-day-old clams in the photos are a single species, *Mercenaria mercenaria*, grown in the laboratory under varying levels of carbon dioxide (CO_2) in the air. CO_2 is absorbed from the air by ocean water, acidifying the water and thus reducing the ability of juvenile clams to grow their shells. As seen in the photos, where CO_2 levels rise progressively from left to right, 36-day-old clams (measured in microns) grown under elevated CO_2 levels are smaller than those grown under lower CO_2 levels. The highest CO_2 level, about 1500 parts per million (ppm; far right), is higher than most projections for the end of this century but could occur locally in some estuaries. (Figure source: Talmage and Gobler 2010[36]).

THE IMPACTS OF OCEAN ACIDIFICATION ON WEST COAST AQUACULTURE

Ocean acidification has already changed the way shellfish farmers on the West Coast conduct business. For oyster growers, the practical effect of the lowering pH of ocean water has not only been to make the water more acidic, but also more corrosive to young shellfish raised in aquaculture facilities. Growers at Whiskey Creek Hatchery, in Oregon's Netarts Bay, found that low pH seawater during spawning reduced growth in mid-stage larval (juvenile) Pacific oysters.[38] Hatcheries in Washington State have also experienced losses of spat (oyster larvae that have attached to a surface and begun to develop a shell) due to water quality issues that include other human-caused effects like dredging and pollution.[39] Facilities like the Taylor Shellfish Farms hatchery on Hood Canal have changed their production techniques to respond to increasing acidification in Puget Sound.

These impacts bring to light a potential challenge: existing natural variation may interact with human-caused changes to produce unanticipated results for shell-forming marine life, especially in coastal regions.[40] As a result, there is an increasing need for information about water chemistry conditions, such as data obtained through the use of sensor networks. In the case of Whiskey Creek, instruments installed in collaboration with ocean scientists created an "early warning" system that allows oyster growers to choose the time they take water into the hatchery from the coastal ocean. This allows them to avoid the lower-pH water related to upwelling and the commensurate loss of productivity in the hatchery.

From a biological perspective, these kinds of preventative measures can help produce higher-quality oysters. Studies on native Olympia oysters (*Ostrea lurida*) show that there is a "carry-over" effect of acidified water – oysters exposed to acidic conditions while in the juvenile stage continue to grow slower in later life stages.[41] Research on some oyster species such as Pacific oyster (*Crassostrea gigas*), the commercially important species in U.S. west coast aquaculture, shows that specially selected strains can be more resistant to acidification.[42]

Overall, economically important species such as oysters, mussels, and sea urchins are highly vulnerable to changes in ocean conditions brought on by climate change and rising atmospheric CO_2 levels. Sea temperature and acidification are expected to increase; the acidity of surface seawater is projected to nearly double by the end of this century. Some important cultured species may be influenced in larval and juvenile developing stages, during fertilization, and as adults,[43] resulting in lower productivity. Action groups, such as the California Current Acidification Network (C-CAN), are working to address the needs of the shellfish industry – both wild and aquaculture-based fisheries – in the face of ocean change. These efforts bring scientists from across disciplines together with aquaculturists, fishermen, the oceanographic community, and state and federal decision-makers to ensure a concerted, standardized, and cost-effective approach to gaining new understanding of the impact of acidification on ecosystems and the economy.[44]

Key Message 3: Habitat Loss Affects Marine Life

Significant habitat loss will continue to occur due to climate change for many species and areas, including Arctic and coral reef ecosystems, while habitat in other areas and for other species will expand. These changes will consequently alter the distribution, abundance, and productivity of many marine species.

Species have responded to climate change in part by shifting where they live.[45] Such range shifts result in ecosystem changes, including the relationships between species and their connection to habitat, because different species respond to changing conditions in different ways. This means that ocean ecosystems are changing in complex ways, with accompanying changes in ecosystem functions (such as nutrient cycling, productivity of species, and predator-prey relationships). Overall habitat extent is expected to change as well, though the degree of range migration will depend upon the life history of particular species. For example, reductions in seasonal sea-ice cover and higher surface temperatures may open up new habitats in polar regions for some important fish species, such as cod, herring, and pollock.[46] However, the continuing presence of cold bottom-water temperatures on the Alaskan Continental shelf could limit northward migration into the northern Bering Sea and Chukchi Sea.[47] In addition, warming may cause reductions in the abundance of some species, such as pollock, in their current ranges in the Bering Sea.[48] For other ice-dependent species, including several marine mammals such as polar bears, walruses, and many seal species, the loss of their critically important habitat will result in population declines.[49] Additionally, climate extremes can facilitate biological invasions by a variety of mechanisms such as increased movement or transport of invasive species, and decreased resilience of native species, so that climate change could increase existing impacts from human transport.[50] These changes will result in changing interactions among species with consequences that are difficult to predict. Tropical species and ecosystems may encounter similar difficulties in migrating poleward as success of some key species such as corals may be limited by adequate bottom substrate, water clarity, and light availability.[51]

Climate change impacts such as increasing ocean temperatures can profoundly affect production of natural stocks of fish by changing growth, reproduction, survival, and other critical characteristics of fish stocks and ecosystems. For species that migrate to freshwater from the sea, like salmon, some published studies indicate earlier start of spawning migration, warming stream temperatures, and extirpation in southern extent of range, all of which can affect productivity.[4,52] To remain within their normal temperature range, some fish stocks are moving poleward and to deeper water.[53,54] Fishery productivity is predicted to decline in the lower 48 states, but increase in parts of Alaska.[55] However, projections based only on temperature may neglect important food web effects. Fishing costs are predicted to increase as fisheries transition to new species and as processing plants and fishing jobs shift poleward.[18] The cumulative impact of such changes will be highly variable on regional scales because of the combination of factors – some acting in opposite directions. Some areas will benefit from range expansions of valuable species or increases in productivity, while others will suffer as species move away from previously productive areas.

CORAL REEF ECOSYSTEM COLLAPSE

Recent research indicates that 75% of the world's coral reefs are threatened due to the interactive effects of climate change and local sources of stress, such as overfishing, nutrient pollution, and disease.[56,57] In Florida, all reefs are rated as threatened, with significant impacts on valuable ecosystem services they provide.[58] Caribbean coral cover has decreased 80% in less than three decades.[59] These declines have in turn led to a flattening of the three dimensional structure of coral reefs and hence a decrease in the capacity of coral reefs to provide shelter and other resources for other reef-dependent ocean life.[60]

The relationship between coral and zooxanthellae (algae vital for reef-building corals) is disrupted by higher than usual temperatures and results in a condition where the coral is still alive, but devoid of all its color (bleaching). Bleached corals can later die or become infected with disease.[61,62] Thus, high temperature events alone can kill large stretches of coral reef, although cold water and poor water quality can also cause localized bleaching and death. Evidence suggests that relatively pristine reefs, with fewer human impacts and with intact fish and associated invertebrate communities, are more resilient to coral bleaching and disease.[63]

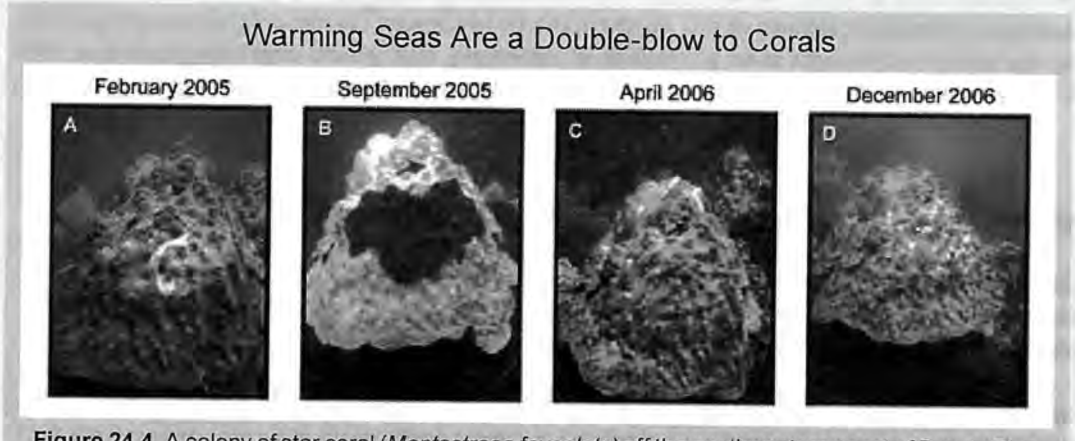


Figure 24.4. A colony of star coral (*Montastraea faveolata*) off the southwestern coast of Puerto Rico (estimated to be about 500 years old) exemplifies the effect of rising water temperatures. Increasing disease due to warming waters killed the central portion of the colony (yellow portion in A), followed by such high temperatures that bleaching - or loss of symbiotic algae from coral - occurred from the surrounding tissue (white area in B). The coral then experienced more disease in the bleached area on the periphery (C) that ultimately killed the colony (D). (Photo credit: Ernesto Weil).

Key Message 4: Rising Temperatures Linked to Diseases

Rising sea surface temperatures have been linked with increasing levels and ranges of diseases in humans and in marine life, including corals, abalones, oysters, fishes, and marine mammals.

There has been a significant increase in reported incidences of disease in corals, urchins, mollusks, marine mammals, turtles, and echinoderms (a group of some 70,000 marine species including sea stars, sea urchins, and sand dollars) over the last several decades.[64,65,66,67] Increasing disease outbreaks in the ocean affecting ecologically important species, which provide critically important habitat for other species such as corals,[65,68] algae,[69] and eelgrass,[70] have been linked with rising temperatures. Disease increases mortality and can reduce abundance for affected populations as well as fundamentally change ecosystems by changing habitat or species relationships. For example, loss of eelgrass beds due to disease can reduce critical nursery habitat for several species of commercially important fish.[70,71]

The complexity of the host/environment/pathogen interaction makes it challenging to separate climate warming from the myriad of other causes facilitating increased disease outbreaks in the ocean. However, three categories of disease-causing pathogens are unequivocally related to warming oceans. Firstly, warmer winters due to climate change can increase the overwinter survival and growth rates of pathogens.[67] A disease-causing parasite in oysters that proliferates at high water temperatures and high salinities spread northward up the eastern seaboard as water temperatures warmed during the 1990s.[72] Growth rates of coral disease lesions increased with winter and summer warming from 1996 to 2006.[62] Winter warming in the Arctic is resulting in increased incidence of a salmon disease in the Bering Sea and is now thought to be a cause of a 57% decline of Yukon Chinook salmon.[73]

Secondly, increasing disease outbreaks in ecologically important species like coral, eelgrass, and abalone have been linked with temperatures that are higher than the long-term averages. The spectacular biodiversity of tropical coral reefs is particularly vulnerable to warming because the corals that form the foundational reef structure live very near the upper temperature limit at which they thrive. The increasing frequency of record hot temperatures has caused widespread coral bleaching[66] and disease outbreaks[65] and is a principal factor contributing to the International Union for the Conservation of Nature listing a third of the reef-building corals as vulnerable, endangered, or critically endangered [74] and the National Oceanic and Atmospheric Administration proposing to list 66 species of corals under the Endangered Species Act.[75,76] In the Chesapeake Bay, eelgrass died out almost completely during the record-hot summers of 2005 and 2010,[77] and the California black abalone has been driven to the edge of extinction by a combination of warming water and bacterial disease.[78]

Thirdly, there is evidence that increased water temperature is responsible for the enhanced survival and growth of certain marine bacteria that make humans sick.[78] Increases in growth of *Vibrio parahaemolyticus* (a pathogenic bacterial species) during the warm season are responsible for human illnesses associated with oysters harvested from the Gulf of Mexico[79] and northern Europe.[80] *Vibrio vulnificus*, which is responsible for the overwhelming majority of reported seafood-related deaths in the United States,[81] is also a significant and growing source of potentially fatal wound infections associated with recreational swimming, fishing-related cuts, and seafood handling, and is most frequently found in water with a temperature above 68°F.[79,81,82]

Key Message 5: Economic Impacts of Marine-related Climate Change

Climate changes that result in conditions substantially different from recent history may significantly increase costs to businesses as well as disrupt public access and enjoyment of ocean areas.

Altered environmental conditions due to climate change will affect, in both positive and negative ways, human uses of the ocean, including transportation, resource use and extraction, leisure and tourism activities and industries, in the nearshore and offshore areas. Climate change will also affect maritime security and governance. Arctic-related national security concerns and threats to national sovereignty have also been a recent focus of attention for some researchers.[83,84] With sea ice receding in the Arctic as a result of rising temperatures, global shipping patterns are already changing and will continue to change considerably in the decades to come.[84,85] The increase in maritime traffic could make disputes over the legal status of sea lines-of-communication and international straits more pointed, but mechanisms exist to resolve these disputes peacefully through the Law of the Sea Convention and other customary international laws.

Resource use for fisheries, aquaculture, energy production, and other activities in ocean areas will also need to adjust to changing ocean climate conditions. In addition to the shift in habitat of living resources discussed above, changing ocean and weather conditions due to human-induced climate change make any activities at sea more difficult to plan, design, and operate.

In the United States, the healthy natural services (such as fishing and recreation) and cultural resources provided by the ocean also play a large economic role in our tourism industry. Nationally in 2010, 2.8% of gross domestic product, 7.52 million jobs, and $1.11 trillion in travel and recreational total sales are supported by tourism.[86] In 2009-2010, nine of the top ten states and U.S. territories and seven of the top ten cities visited by overseas travelers were coastal, including the Great Lakes. Changes in the location and distribution of marine resources (such as fish, healthy reefs, and marine mammals) due to climate change will affect the recreational industries and all the people that depend on reliable access to these resources in predictable locales. For example, as fish species shift poleward or to deeper waters,[54,87] these fish may be less accessible to recreational fishermen. Similar issues will also affect commercial fishing.

Similarly, new weather conditions differing from the historical pattern will pose a challenge for tourism, boating, recreational fishing, diving, and snorkeling, all of which rely on highly predictable, comfortable water and air temperatures and calm waters. For example, the strength of hurricanes and the number of strong (Category 4 and 5) hurricanes are projected to increase over the North Atlantic (Ch. 2: Our Changing Climate). Changes in wind patterns[88] and wave heights have been observed[89] and are projected to continue to change in the future.[90] This means that the public will not be able to rely on recent experience in planning leisure and tourism activities.[91,92] As weather patterns change and air and sea surface temperatures rise, preferred locations for recreation and tourism also may change. In addition, infrastructure such as marinas, marine supply stores, boardwalks, hotels, and restaurants that support leisure activities and tourism will be negatively affected by sea level rise. They may also be affected by increased storm intensity and changing wave heights,[92] as well as elevated storm surge due to sea level rise and other expected effects of a changing climate; these impacts will vary significantly by region.[93]

Key Message 6: Initiatives Serve as a Model

In response to observed and projected climate impacts, some existing ocean policies, practices, and management efforts are incorporating climate change impacts. These initiatives can serve as models for other efforts and ultimately enable people and communities to adapt to changing ocean conditions.

Climate considerations can be integrated into planning, restoration, design of marine protected areas, fisheries management, and aquaculture practices to enhance ocean resilience and adaptive capacity. Many existing sustainable-use strategies, such as ending overfishing, establishing protected areas, and conserving habitat, are known to increase resilience. Analyses of fishery management and climate scenarios suggest that adjustments to harvest regimes (especially reducing harvest rates of over-exploited species) can improve catch stability under changing climate conditions. These actions could have a greater effect on biological and economic performance in fisheries than impacts due to warming over the next 25 years.[94] The stability of international ocean and fisheries treaties, particularly those covering commercially exploited and critical species, might be threatened as the ocean changes.[95]

The fact that the climate is changing is beginning to be incorporated into existing management strategies. New five-year strategies for addressing flooding, shoreline erosion, and coastal storms have been developed by most coastal states under their Coastal Zone Management Act programs.[3] Many of these plans are explicitly taking into account future climate scenarios as part of their adaptation initiatives. The North Pacific Fishery Management Council and NOAA have declared a moratorium on most commercial fisheries in the U.S. Arctic pending sufficient understanding of the changing productivity of these fishing grounds as they become increasingly ice-free. Private shellfish aquaculture operations are changing their business plans to adapt to ocean acidification.[38,39] These changes include monitoring and altering the timing of spat settlement dependent on climate change induced conditions, as well as seeking alternative, acid-resistant strains for culturing. Marine protected areas in the National Marine Sanctuary (NMS) System are gradually preparing climate impact reports and climate adaptation action plans under their Climate Smart Sanctuary Initiative.[96]

Additionally, there is promise in restoring key habitats to provide a broad suite of benefits that can reduce climate impacts with relatively little ongoing maintenance costs (see Ch. 25: Coasts; Ch. 28: Adaptation). For example, if in addition to sea level rise, an oyster reef or mangrove restoration strategy also included fish habitat benefits for commercial and recreational uses and coastal protection services, the benefits to surrounding communities could multiply quickly. Coral-reef-based tourism can be more resilient to climate change impacts through protection and restoration, as well as reductions of pollution and other habitat-destroying activities. Developing alternative livelihood options as part of adaptation strategies for marine food-producing sectors can help reduce economic and social impacts of a changing climate.

CLIMATE IMPACTS ON NEW ENGLAND FISHERIES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Fishing in New England has been associated with bottom-dwelling fish for more than 400 years, and is a central part of the region's cultural identity and social fabric. Atlantic halibut, cod, haddock, flounders, hakes, pollock, plaice, and soles are included under the term "groundfish." The fishery is pursued by both small boats (less than 50 feet long) that are typically at sea for less than a day, and by large boats (longer than 50 feet) that fish for a day to a week at a time. These vessels use home ports in more than 100 coastal communities from Maine to New Jersey, and the landed value from fisheries in New England and the Mid-Atlantic in 2010 was nearly \$1.2 billion.[76] Captains and crew are often second- or third-generation fishermen who have learned the trade from their families.

From 1982 to 2006, sea surface temperature in the coastal waters of the Northeast warmed by close to twice the global rate of warming over this period.[97] Long-term monitoring of bottom-dwelling fish communities in New England revealed that the abundance of warm-water species increased, while cool-water species decreased.[54,98] A recent study suggests that many species in this community have shifted their geographic distributions northward by up to 200 miles since 1968, though substantial variability among species also exists.[54] The northward shifts of these species are reflected in the fishery as well: landings and landed value of these species have shifted towards northern states such as Massachusetts and Maine, while southern states have seen declines (see Figure 24.5).

The economic and social impacts of these changes depend in large part on the response of the fishing communities in the region.[99] Communities have a range of strategies for coping with the inherent uncertainty and variability of fishing, including diversification among species and livelihoods, but climate change imposes both increased variability and sustained change that may push these fishermen beyond their ability to cope.[100] Larger fishing boats can follow the fish to a certain extent as they shift northward, while smaller inshore boats will be more likely to leave fishing or switch to new species.[100] Long-term viability of fisheries in the region may ultimately depend on a transition to new species that have shifted from regions farther south.[18]

Fisheries Shifting North

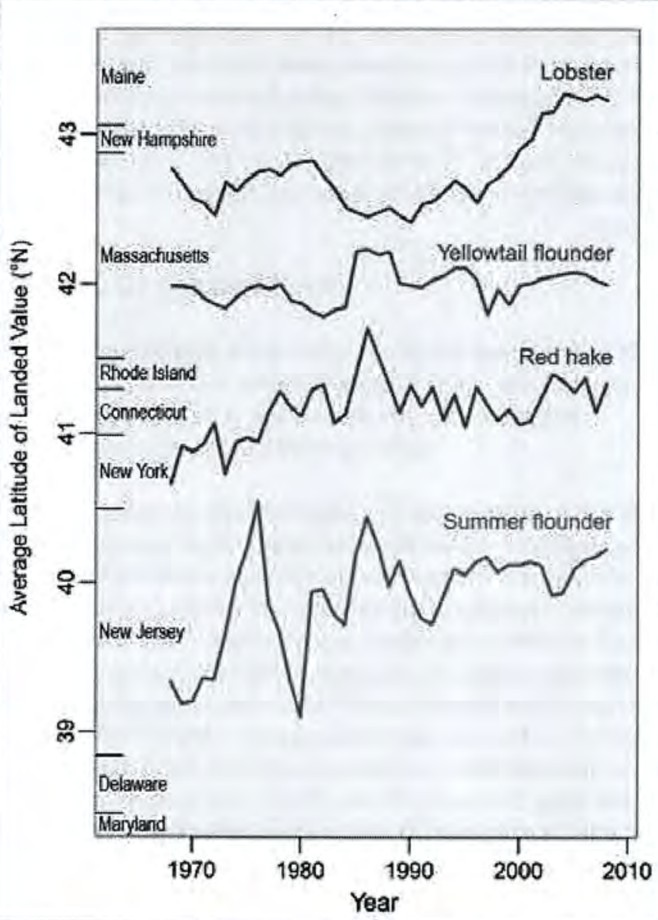

Figure 24.5. Ocean species are shifting northward along U.S. coastlines as ocean temperatures rise. As a result, over the past 40 years, more northern ports have gradually increased their landings of four marine species compared to the earlier pattern of landed value. While some species move northward out of an area, other species move in from the south. This kind of information can inform decisions about how to adapt to climate change. Such adaptations take time and have costs, as local knowledge and equipment are geared to the species that have long been present in an area. (Figure source: adapted from Pinsky and Fogerty 2012[101]).

24: OCEANS AND MARINE RESOURCES

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SUPPLEMENTAL MATERIAL

TRACEABLE ACCOUNTS

TRACEABLE ACCOUNTS

Process for Developing Key Messages:
A central component of the assessment process was the Oceans and Marine Resources Climate assessment workshop that was held January 23-24, 2012, at the National Oceanographic and Atmospheric Administration (NOAA) in Silver Spring, MD, and simultaneously, via web teleconference, at NOAA in Seattle, WA. In the workshop, nearly 30 participants took part in a series of scoping presentations and breakout sessions that began the process leading to a foundational Technical Input Report (TIR) entitled "Oceans and Marine Resources in a Changing Climate: Technical Input to the 2013 National Climate Assessment."[102] The report, consisting of nearly 220 pages of text organized into 7 sections with numerous subsections and more than 1200 references, was assembled by 122 authors representing governmental agencies, non-governmental organizations, tribes, and other entities.

The chapter author team engaged in multiple technical discussions via teleconferences that permitted a careful review of the foundational TIR[102] and of approximately 25 additional technical inputs provided by the public, as well as the other published literature, and professional judgment. The chapter author team met at Conservation International in Arlington, VA on 3-4 May 2012 for expert deliberation of draft key messages by the authors, wherein each message was defended before the entire author team before the key message was selected for inclusion in the report. These discussions were supported by targeted consultation with additional experts by the lead author of each message to help define "key vulnerabilities."

KEY MESSAGE #1 TRACEABLE ACCOUNT

The rise in ocean temperature over the last century will persist into the future, with continued large impacts on climate, ocean circulation, chemistry, and ecosystems.

Description of evidence base
The key message is supported by extensive evidence documented in Sections 2 and 3 of the Oceans Technical Input Report[102] and in the additional technical inputs received as part of the Federal Register Notice solicitation for public input, as well as stakeholder engagement leading up to drafting the chapter.

Relevant and recent peer-reviewed publications,[5,7,8] including many others that are cited therein, describe evidence that ocean temperature has risen over the past century. This evidence base includes direct and indirect temperature measurements, paleoclimate records, and modeling results.

There are also many relevant and recent peer-reviewed publications describing changes in physical and chemical ocean properties that are underway due to climate change.[11,14]

New information and remaining uncertainties
Important new information since the last National Climate Assessment[103] includes the latest update to a data set of ocean temperatures.[7]

There is accumulating new information on all of these points with regard to physical and chemical changes in the ocean and resultant impacts on marine ecosystems. Both measurements and model results are continuing to sharpen the picture.

A significant area of uncertainty remains with regard to the region-by-region impacts of warming, acidification, and associated changes in the oceans. Regional and local conditions mean that impacts will not be uniform around the U.S. coasts or internationally. Forecasting of regional changes is still an area of very active research, though the overall patterns for some features are now clear.

Large-scale and recurring climate phenomena (such as the El Niño Southern Oscillation, the Pacific Decadal Oscillation, and the Atlantic Multidecadal Oscillation) cause dramatic changes in biological productivity and ecosystem structure and make it difficult to discern climate-driven trends.

Current time series of biological productivity are restricted to a handful of sites around the globe and to a few decades, and global, comprehensive satellite time series of ocean color are even shorter, beginning in 1997. Based on an analysis of different in situ datasets, one research group suggested a decline of 1% per year over the past century, but these findings may be an artifact of limited data and have been widely debated.[14,104] However, the few in situ time series mostly indicate increases in biological productivity over the past 20 years, but with clear links to regional changes in climate.[14]

Assessment of confidence based on evidence

Confidence that the ocean is warming and acidifying, and that sea level is rising is **very high**. Changes in other physical and chemical properties such as ocean circulation, wave heights, oxygen minimums, and salinity are of **medium** confidence. For ecosystem changes, there is **high** confidence that these are occurring and will persist and likely grow in the future, though the details of these changes are highly geographically variable.

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

KEY MESSAGE #2 TRACEABLE ACCOUNT

The ocean currently absorbs about a quarter of human-caused carbon dioxide emissions to the atmosphere, leading to ocean acidification that will alter marine ecosystems in dramatic yet uncertain ways.

Description of evidence base

The key message is supported by extensive evidence documented in the Oceans Technical Input Report[102] and additional technical inputs received as part of the Federal Register Notice solicitation for public input, as well as stakeholder engagement leading up to drafting the chapter.

Numerous references provide evidence for the increasing acidity (lower pH) of oceans around the world (Ch. 2: Our Changing Climate, Key Message 12).[3,31]

There is a rapid growth in peer-reviewed publications describing how ocean acidification will impact ecosystems,[33,34] but to date evidence is largely based on studies of calcification rather than growth, reproduction, and survival of organisms. For these latter effects, available evidence is from laboratory studies in low pH conditions, rather than in situ observations.[35]

New information and remaining uncertainties

The interplay of environmental stressors may result in "surprises" where the synergistic impacts may be more deleterious or more beneficial than expected. Such synergistic effects create complexities in predicting the outcome of the interplay of stressors on marine ecosystems. Many, but not all, calcifying species are affected by increased acidity in laboratory studies. How those responses will cascade through ecosystems and food webs is still uncertain. Although studies are underway to expand understanding of ocean acidification on all aspects of organismal physiology, much remains to be learned.

Assessment of confidence based on evidence

Confidence is **very high** that carbon dioxide emissions to the atmosphere are causing ocean acidification, and **high** that this will alter marine ecosystems. The nature of those alterations is unclear, however, and predictions of most specific ecosystem changes have **low** confidence at present, but with **medium** confidence for coral reefs.

KEY MESSAGE #3 TRACEABLE ACCOUNT

Significant habitat loss will continue to occur due to climate change for many species and areas, including Arctic and coral reef ecosystems, while habitat in other areas and for other species will expand. These changes will consequently alter the distribution, abundance, and productivity of many marine species.

Description of evidence base

The key message is supported by extensive evidence documented in the Oceans Technical Input Report[102] and additional technical inputs received as part of the Federal Register Notice solicitation for public input, as well as stakeholder engagement leading up to drafting the chapter.

Many peer-reviewed publications[56,70] describe threats to coral reefs induced by global change.

There are also many relevant and recent peer-reviewed publications[53,54,87] that discuss impacts on marine species and resources of habitat change that is induced by climate change.

New information and remaining uncertainties

Regional and local variation is, again, a major component of the remaining uncertainties. Different areas, habitats, and species are responding differently and have very different adaptive capacities. Those species that are motile will certainly respond differently, or at least at a different rate, by changing distribution and migration patterns, compared to species that do not move, such as corals.

Although it is clear that some fish stocks are moving poleward and to deeper water, how far they will move and whether most species will move remains unclear. A key uncertainty is the extent to which various areas will benefit from range expansions of valuable species or increases in productivity, while other areas will suffer as species move away from previously productive areas. The loss of critically important habitat due to climate change will result in changes in species interactions that are difficult to predict.

Assessment of confidence based on evidence

There is **very high** confidence that habitat and ecosystems are changing due to climate change, but that change is not unidirectional by any means. Distribution, abundance, and productivity changes are species and location dependent and may be increasing or decreasing in a complex pattern.

Key message #4 Traceable Account

Rising sea surface temperatures have been linked with increasing levels and ranges of diseases in humans and in marine life, including corals, abalones, oysters, fishes, and marine mammals.

Description of evidence base

The key message is supported by extensive evidence in the Oceans Technical Input Report[102] and additional technical inputs received as part of the Federal Register Notice solicitation for public input, as well as stakeholder engagement leading up to drafting the chapter.

As noted in the chapter, the references document increased levels and ranges of disease coincident with rising temperatures.[64,65,66,67]

New information and remaining uncertainties

The interactions among host, environment, and pathogen are complex, which makes it challenging to separate warming due to climate change from other causes of disease outbreaks in the ocean.

Assessment of confidence based on evidence

There is **high** confidence that disease outbreaks and levels are increasing, and that this increase is linked to increasing temperatures. Again, there is substantial local to regional variation but the overall pattern seems consistent.

Key message #5 Traceable Account

Climate changes that result in conditions substantially different from recent history may significantly increase costs to businesses as well as disrupt public access and enjoyment of ocean areas.

Description of evidence base

The key message is supported by extensive evidence documented in the Oceans Technical Input Report[102] and additional technical inputs received as part of the Federal Register Notice solicitation for public input, as well as stakeholder engagement leading up to drafting the chapter.

Many peer-reviewed publications describe the predicted impacts of climate change on tourism and recreation industries and their associated infrastructure.[91,92]

New information and remaining uncertainties

Given the complexity of transportation, resource use and extraction, and leisure and tourism activities, there are large uncertainties in impacts in specific locales or for individual activities. Some businesses and communities may be able to adapt rapidly, others less so. Infrastructure impacts of climate change will also be an important part of the ability of businesses, communities, and the public to adapt.

Assessment of confidence based on evidence

As with many other impacts of climate change, the evidence that change is occurring is very strong but the resultant impacts are still uncertain. For all of these human uses, and the associated costs and disruption, the evidence is suggestive and confidence **medium** on the effects of the ongoing changes in ocean conditions.

Key message #6 Traceable Account

In response to observed and projected climate impacts, some existing ocean policies, practices, and management efforts are incorporating climate change impacts. These initiatives can serve as models for other efforts and ultimately enable people and communities to adapt to changing ocean conditions.

Description of evidence base

The key message is supported by extensive evidence documented in the Oceans Technical Input Report[102] and additional technical inputs reports received as part of the Federal Register Notice solicitation for public input, as well as stakeholder engagement leading up to drafting the chapter.

Scenarios suggest that adjustments to fish harvest regimes can improve catch stability under increased climate variability. These actions could have a greater effect on biological and economic performance in fisheries than impacts due to warming over the next 25 years.[94]

New information and remaining uncertainties

Efforts are underway to enhance the development and deployment of science in support of adaptation, to improve understanding and awareness of climate-related risks, and to enhance analytic capacity to translate understanding into planning and management activities. While critical knowledge gaps exist, there is a wealth of climate- and ocean-related science pertinent to adaptation.102

Assessment of confidence based on evidence

There is **high** confidence that adaptation planning will help mitigate the impacts of changing ocean conditions. But there is much work to be done to craft local solutions to the set of emerging issues in ocean and coastal areas.

Climate Change Impacts in the United States

CHAPTER 25
COASTAL ZONE DEVELOPMENT AND ECOSYSTEMS

Convening Lead Authors

Susanne C. Moser, Susanne Moser Research & Consulting, Stanford University

Margaret A. Davidson, National Oceanic and Atmospheric Administration

Lead Authors

Paul Kirshen, University of New Hampshire

Peter Mulvaney, Skidmore, Owings & Merrill LLP

James F. Murley, South Florida Regional Planning Council

James E. Neumann, Industrial Economics, Inc.

Laura Petes, National Oceanic and Atmospheric Administration

Denise Reed, The Water Institute of the Gulf

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On the Web: http://nca2014.globalchange.gov/report/regions/coasts

INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

25 COASTAL ZONE
DEVELOPMENT AND ECOSYSTEMS

KEY MESSAGES

1. **Coastal lifelines, such as water supply and energy infrastructure and evacuation routes, are increasingly vulnerable to higher sea levels and storm surges, inland flooding, erosion, and other climate-related changes.**
2. **Nationally important assets, such as ports, tourism and fishing sites, in already-vulnerable coastal locations, are increasingly exposed to sea level rise and related hazards. This threatens to disrupt economic activity within coastal areas and the regions they serve and results in significant costs from protecting or moving these assets.**
3. **Socioeconomic disparities create uneven exposures and sensitivities to growing coastal risks and limit adaptation options for some coastal communities, resulting in the displacement of the most vulnerable people from coastal areas.**
4. **Coastal ecosystems are particularly vulnerable to climate change because many have already been dramatically altered by human stresses; climate change will result in further reduction or loss of the services that these ecosystems provide, including potentially irreversible impacts.**
5. **Leaders and residents of coastal regions are increasingly aware of the high vulnerability of coasts to climate change and are developing plans to prepare for potential impacts on citizens, businesses, and environmental assets. Significant institutional, political, social, and economic obstacles to implementing adaptation actions remain.**

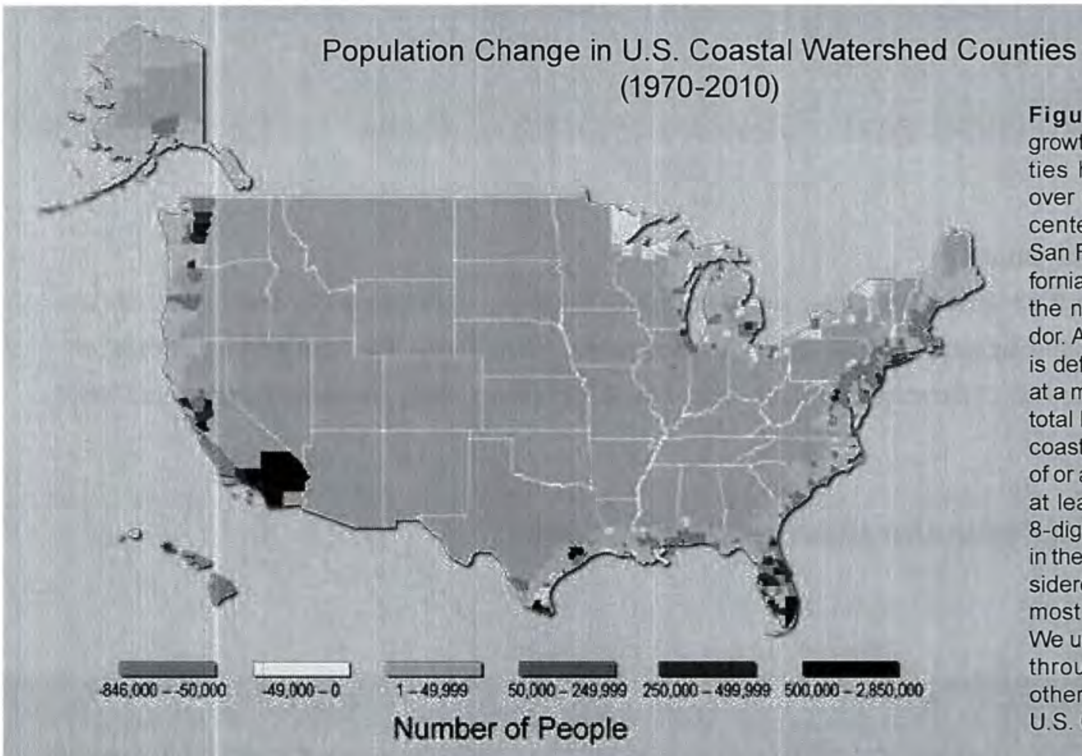


Figure 25.1. U.S. population growth in coastal watershed counties has been most significant over the past 40 years in urban centers such as Puget Sound, San Francisco Bay, southern California, Houston, South Florida and the northeast metropolitan corridor. A coastal watershed county is defined as one where either 1) at a minimum, 15% of the county's total land area is located within a coastal watershed, or 2) a portion of or an entire county accounts for at least 15% of a coastal USGS 8-digit cataloging unit.[1] Residents in these coastal areas can be considered "the U.S. population that most directly affects the coast."[1] We use this definition of "coastal" throughout the chapter unless otherwise specified. (Data from U.S. Census Bureau).

Each year, more than 1.2 million people move to the coast, collectively adding the equivalent of nearly one San Diego, or more than three Miami's, to the Great Lakes or open-ocean coastal watershed counties and parishes of the United States. As a result, 164 million Americans – more than 50% of the population – now live in these mostly densely populated areas[1,2] (Figure 25.1) and help generate 58% of the national gross domestic product (GDP).[3] People come – and stay – for the diverse and growing employment opportunities in recreation and tourism, commerce, energy and mineral production, vibrant urban centers, and the irresistible beauty of our coasts.[4] Residents, combined with the more than 180 million tourists that flock to the coasts each year,[5,6] place heavy demands on the unique natural systems and resources that make coastal areas so attractive and productive.[7]

Meanwhile, public agencies and officials are charged with balancing the needs of economic vitality and public safety, while sustaining the built and natural environments in the face of risks from well-known natural hazards such as storms, flooding, and erosion.[8] Although these risks play out in different ways along the United States' more than 94,000 miles of coastline,[9] all coasts share one simple fact: no other region concentrates so many people and so much economic activity on so little land, while also being so relentlessly affected by the sometimes violent interactions of land, sea, and air.

Humans have heavily altered the coastal environment through development, changes in land use, and overexploitation of resources. Now, the changing climate is imposing additional stresses,[10] making life on the coast more challenging (Figure 25.2). The consequences will ripple through the entire nation, which depends on the productivity and vitality of coastal regions.

COASTAL RESILIENCE DEFINED

Resilience means different things to different disciplines and fields of practice. In this chapter, resilience generally refers to an ecological, human, or physical system's ability to persist in the face of disturbance or change and continue to perform certain functions.[11] Natural or physical systems do so through absorbing shocks, reorganizing after disturbance, and adapting;[12] social systems can also consciously learn.[13]

Events like Superstorm Sandy in 2012 have illustrated that public safety and human well-being become jeopardized by the disruption of crucial lifelines, such as water, energy, and evacuation routes. As climate continues to change, repeated disruption of lives, infrastructure functions, and nationally and internationally important economic activities will pose intolerable burdens on people who are already most vulnerable and aggravate existing impacts on valuable and irreplaceable natural systems. Planning long-term for these changes, while balancing different and often competing demands, are vexing challenges for decision-makers (Ch. 26: Decision Support).

Flooding During High Tides

Figure 25.2. Sea level rise is not just a problem of the future, but is already affecting coastal communities such as Charleston, South Carolina, and Olympia in South Puget Sound through flooding during high tides. (Photo credits: (left) NOAA Coastal Services Center; (right) Ray Garrido, January 6, 2010, reprinted with permission by the Washington Department of Ecology).

Climate-related Drivers of Coastal Change

The primary climatic forces affecting the coasts are changes in temperature, sea and water levels, precipitation, storminess, ocean acidity, and ocean circulation.[7]

- Sea surface temperatures are rising[14] and are expected to rise faster over the next few decades,[15] with significant regional variation, and with the possibility for more intense hurricanes as oceans warm (Ch. 2: Our Changing Climate).

- Global average sea level is rising and has been doing so for more than 100 years (Ch.2: Our Changing Climate), and greater rates of sea level rise are expected in the future.[16] Higher sea levels cause more coastal erosion, changes in sediment transport and tidal flows, more frequent flooding from higher storm surges, landward migration of barrier shorelines, fragmentation of islands, and saltwater intrusion into aquifers and estuaries.[7,17,18,19]

- Rates of sea level rise are not uniform along U.S. coasts[20,21] and can be exacerbated locally by land subsidence or reduced by uplift.[22,23] Along the shorelines of the Great Lakes, lake level changes are uncertain (Ch. 18: Midwest), but erosion and sediment migration will be exacerbated by increased lakeside storm events, tributary flooding, and increased wave action due to loss of ice cover.[24]

- Patterns of precipitation change are affecting coastal areas in complex ways (Ch. 2: Our Changing Climate). In regions where precipitation increases, coastal areas will see heavier runoff from inland areas, with the already observed trend toward more intense rainfall events continuing to increase the risk of extreme runoff and flooding. Where precipitation is expected to decline and droughts to increase, freshwater inflows to the coast will be reduced (Ch. 3: Water).

- There has been an overall increase in storm activity near the Northeast and Northwest coastlines since about 1980.[25] Winter storms have increased slightly in frequency and intensity and their storm tracks have shifted northward.[26] The most intense tropical storms have increased in intensity in the last few decades.[27] Future projections suggest increases in hurricane rainfall and intensity (with a greater number of the strongest – Category 4 and 5 – hurricanes), a slight decrease in the frequency of tropical cyclones, and possible shifts in storm tracks, though the details remain uncertain (Ch. 2: Our Changing Climate).

- Marine ecosystems are being threatened by climate change and ocean acidification. The oceans are absorbing more carbon dioxide as the concentration in the atmosphere increases, resulting in ocean acidification, which threatens coral reefs and shellfish.[28,29,30] Coastal fisheries are also affected by rising water temperatures[31] and climate-related changes in oceanic circulation (Ch. 24: Oceans).[32,33] Wetlands and other coastal habitats are threatened by sea level rise, especially in areas of limited sediment supply or where barriers prevent onshore migration.[34] The combined effects of saltwater intrusion, reduced precipitation, and increased evapotranspiration will elevate soil salinities and lead to an increase in salt-tolerant vegetation[35,36] and the dieback of coastal swamp forests.[37]

None of these changes operate in isolation. The combined effects of climate changes with other human-induced stresses makes predicting the effects of climate change on coastal systems challenging. However, it is certain that these factors will create increasing hazards to the coasts' densely populated areas.[38,39,40]

Jacques Descloitres, MODIS Rapid Response Team, NASA/GSFC

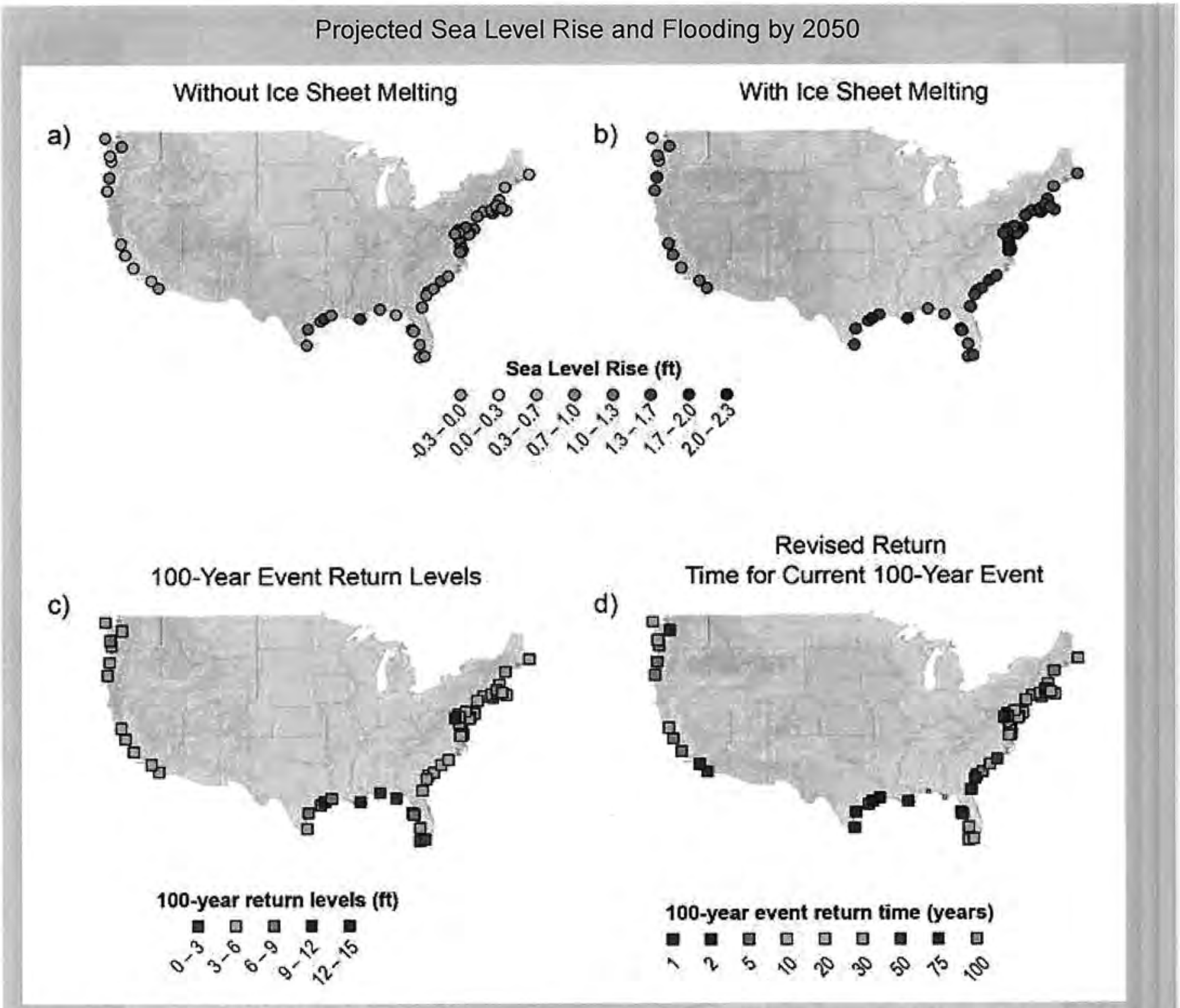


Figure 25.3. The amount of sea level rise (SLR) by 2050 will vary along different stretches of the U.S. coastline and under different SLR scenarios, mostly due to land subsidence or uplift (Ch.2: Our Changing Climate).[16] The panels show feet of sea level above 1992 levels at different tide gauge stations based on a) an 8 inch SLR and b) a 1.24 foot SLR by 2050. The flood level that has a 1% chance of occurring in any given year ("return level") is similarly projected to differ by region as a result of varying storm surge risk. Panel c) shows return levels for a 1.05 foot SLR above mean high tide by 2050. Finally, panel d) shows how a 1.05 foot SLR by 2050 could cause the level of flooding that occurs during today's 100-year storm to occur more frequently by mid-century, in some regions as often as once a decade or even annually. (Figure source: replicated Tebaldi et al. 2012[23] analysis with NCA sea level rise scenarios[16] for panels a) and b); data/ensemble SLR projections used for panels c) and d) from Tebaldi et al. 2012[23]; all estimates include the effect of land subsidence).

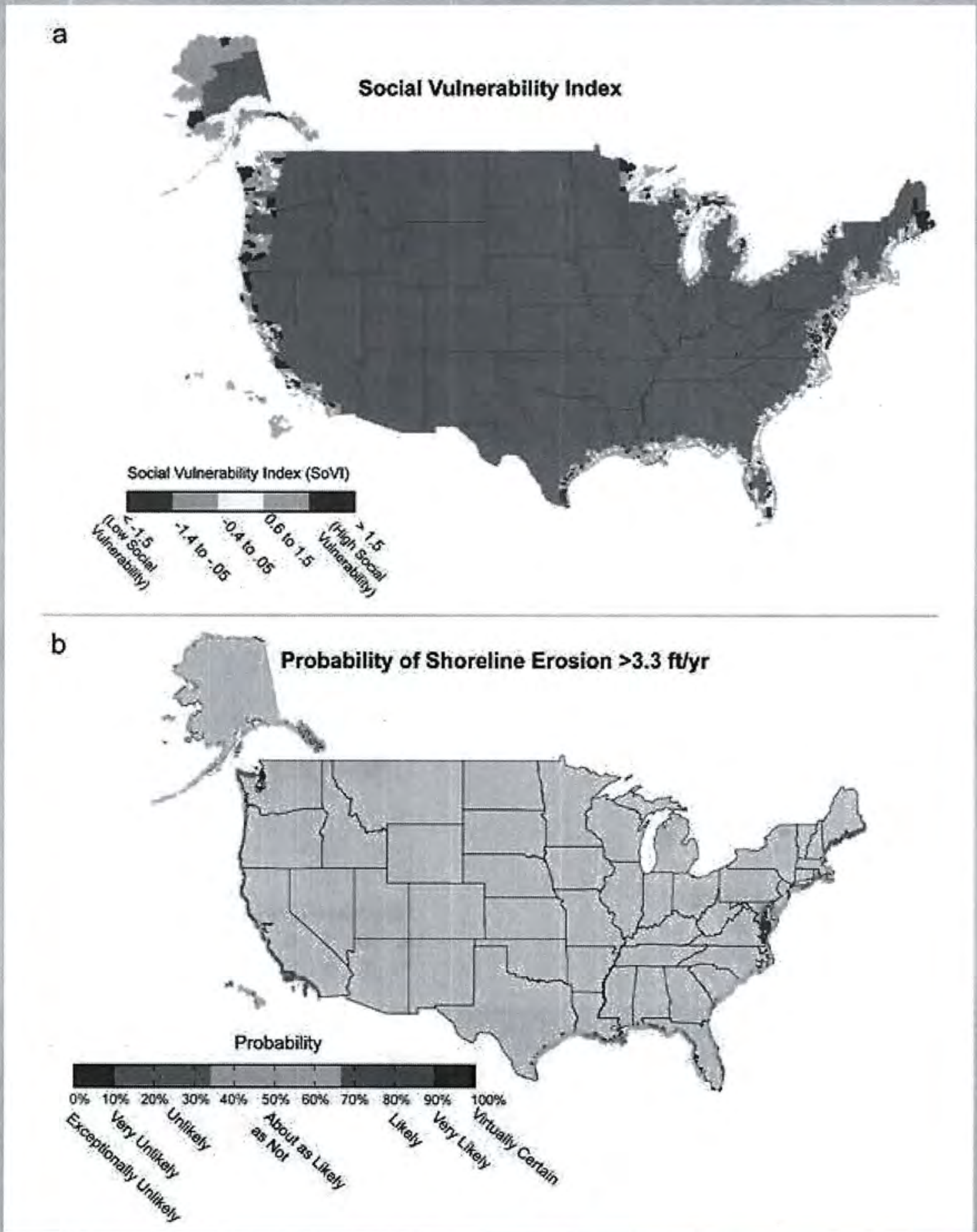
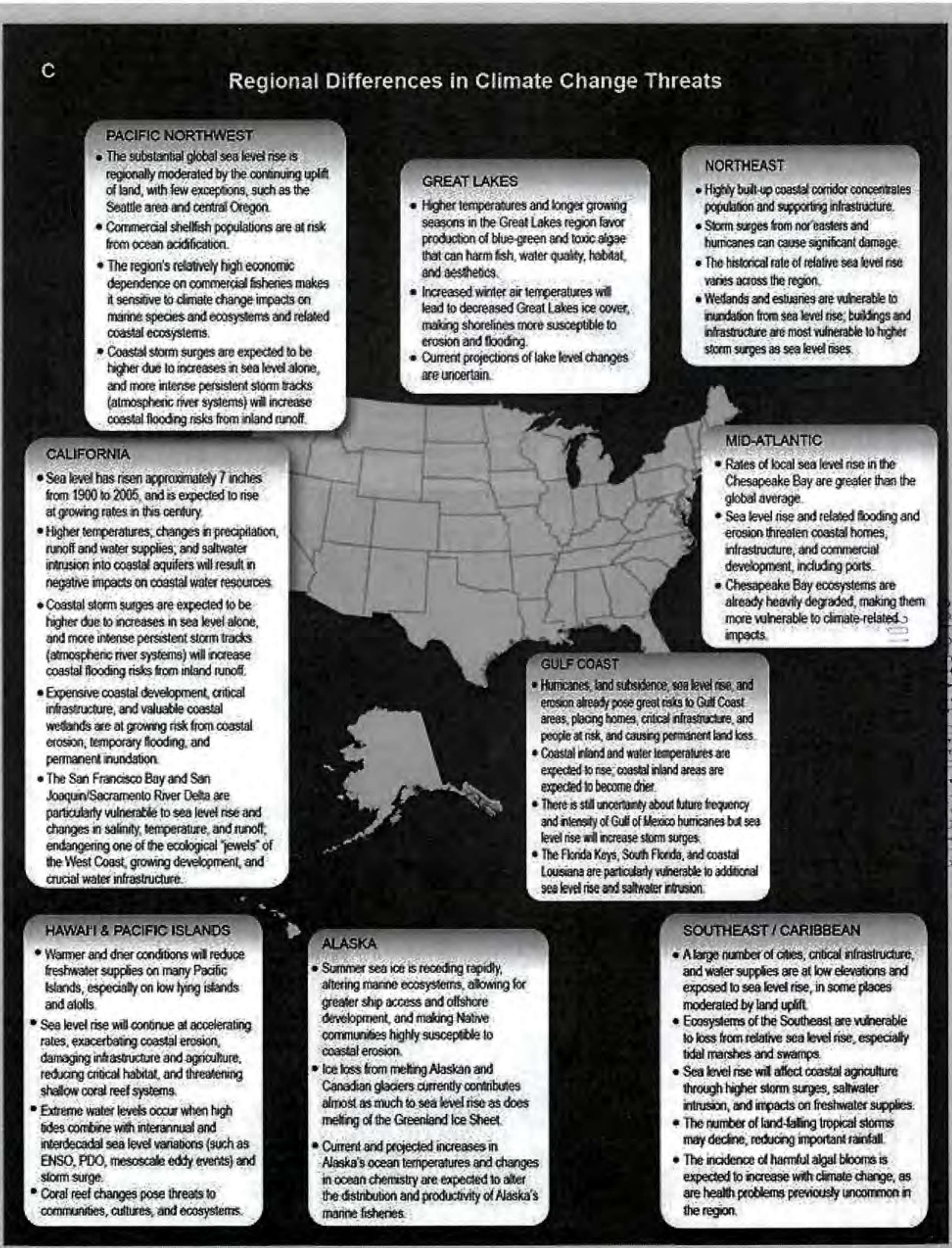


Figure 25.4. (a) Social Vulnerability, (b) Probability of Shoreline Erosion

(a) Social Vulnerabilty Index (SoVI) at the Census tract level for counties along the coast. The Social Vulnerability Index provides a quantitative, integrative measure for comparing the degree of vulnerability of human populations across the nation. A high SoVI (dark pink) typically indicates some combination of high exposure and high sensitivity to the effects of climate change and low capacity to deal with them. Specific index components and weighting are unique to each region (North Atlantic, South Atlantic, Gulf, Pacific, Great Lakes, Alaska, and Hawai'i). All index components are constructed from readily available Census data and include measures of poverty, age, family structure, location (rural versus urban), foreign-born status, wealth, gender, Native American status, and occupation.[41,42]

(b) Probability of Shoreline Erosion greater than 3.3 feet per year for counties along the coast. Probability is based on historical conditions only and does not reflect the possibility of acceleration due to increasing rates of sea level rise.[43]



Regional Differences in Climate Change Threats

PACIFIC NORTHWEST

- The substantial global sea level rise is regionally moderated by the continuing uplift of land, with few exceptions, such as the Seattle area and central Oregon.
- Commercial shellfish populations are at risk from ocean acidification.
- The region's relatively high economic dependence on commercial fisheries makes it sensitive to climate change impacts on marine species and ecosystems and related coastal ecosystems.
- Coastal storm surges are expected to be higher due to increases in sea level alone, and more intense persistent storm tracks (atmospheric river systems) will increase coastal flooding risks from inland runoff.

GREAT LAKES

- Higher temperatures and longer growing seasons in the Great Lakes region favor production of blue-green and toxic algae that can harm fish, water quality, habitat, and aesthetics.
- Increased winter air temperatures will lead to decreased Great Lakes ice cover, making shorelines more susceptible to erosion and flooding.
- Current projections of lake level changes are uncertain.

NORTHEAST

- Highly built-up coastal corridor concentrates population and supporting infrastructure.
- Storm surges from nor'easters and hurricanes can cause significant damage.
- The historical rate of relative sea level rise varies across the region.
- Wetlands and estuaries are vulnerable to inundation from sea level rise; buildings and infrastructure are most vulnerable to higher storm surges as sea level rises.

CALIFORNIA

- Sea level has risen approximately 7 inches from 1900 to 2005, and is expected to rise at growing rates in this century.
- Higher temperatures; changes in precipitation, runoff and water supplies; and saltwater intrusion into coastal aquifers will result in negative impacts on coastal water resources.
- Coastal storm surges are expected to be higher due to increases in sea level alone, and more intense persistent storm tracks (atmospheric river systems) will increase coastal flooding risks from inland runoff.
- Expensive coastal development, critical infrastructure, and valuable coastal wetlands are at growing risk from coastal erosion, temporary flooding, and permanent inundation.
- The San Francisco Bay and San Joaquin/Sacramento River Delta are particularly vulnerable to sea level rise and changes in salinity, temperature, and runoff, endangering one of the ecological "jewels" of the West Coast, growing development, and crucial water infrastructure.

MID-ATLANTIC

- Rates of local sea level rise in the Chesapeake Bay are greater than the global average.
- Sea level rise and related flooding and erosion threaten coastal homes, infrastructure, and commercial development, including ports.
- Chesapeake Bay ecosystems are already heavily degraded, making them more vulnerable to climate-related impacts.

GULF COAST

- Hurricanes, land subsidence, sea level rise, and erosion already pose great risks to Gulf Coast areas, placing homes, critical infrastructure, and people at risk, and causing permanent land loss.
- Coastal inland and water temperatures are expected to rise; coastal inland areas are expected to become drier.
- There is still uncertainty about future frequency and intensity of Gulf of Mexico hurricanes but sea level rise will increase storm surges.
- The Florida Keys, South Florida, and coastal Louisiana are particularly vulnerable to additional sea level rise and saltwater intrusion.

HAWAI'I & PACIFIC ISLANDS

- Warmer and drier conditions will reduce freshwater supplies on many Pacific Islands, especially on low lying islands and atolls.
- Sea level rise will continue at accelerating rates, exacerbating coastal erosion, damaging infrastructure and agriculture, reducing critical habitat, and threatening shallow coral reef systems.
- Extreme water levels occur when high tides combine with interannual and interdecadal sea level variations (such as ENSO, PDO, mesoscale eddy events) and storm surge.
- Coral reef changes pose threats to communities, cultures, and ecosystems.

ALASKA

- Summer sea ice is receding rapidly, altering marine ecosystems, allowing for greater ship access and offshore development, and making Native communities highly susceptible to coastal erosion.
- Ice loss from melting Alaskan and Canadian glaciers currently contributes almost as much to sea level rise as does melting of the Greenland Ice Sheet.
- Current and projected increases in Alaska's ocean temperatures and changes in ocean chemistry are expected to alter the distribution and productivity of Alaska's marine fisheries.

SOUTHEAST / CARIBBEAN

- A large number of cities, critical infrastructure, and water supplies are at low elevations and exposed to sea level rise, in some places moderated by land uplift.
- Ecosystems of the Southeast are vulnerable to loss from relative sea level rise, especially tidal marshes and swamps.
- Sea level rise will affect coastal agriculture through higher storm surges, saltwater intrusion, and impacts on freshwater supplies.
- The number of land-falling tropical storms may decline, reducing important rainfall.
- The incidence of harmful algal blooms is expected to increase with climate change, as are health problems previously uncommon in the region.

Figure 25.4. (c) Climate-Related Threats

(c) Regional Threats from Climate Change are compiled from technical input reports, the regional chapters in this report, and from scientific literature. For related information, see http://data.globalchange.gov/report/regional-differences-2012

ALASKA

- Newtok, AK, is relocating away from the eroding shoreline.

NORTHEAST

- Portland, ME, is assessing costs for retrofitting its wastewater infrastructure.
- New Hampshire's Coastal Adaptation Workgroup is providing education, guidance, and networking for local planners.
- City of Boston considers adaptation and mitigation equal priorities, and sea level rise is a top concern.
- Connecticut State Assembly amended the state's Coastal Management Act to promote adaptation to sea level rise.

GREAT LAKES

- Wisconsin's state adaptation plan includes emphasis on lake shorefront areas.
- Bay-Lake Regional Planning Commission updated hazard mitigation plans.
- Ohio's Lake Erie Commission is in the process of developing model shoreline development legislation.

PACIFIC NORTHWEST

- Swinomish Tribe's Climate Change Initiative highlights special challenges of coastal tribes.
- Oregon Sea Grant surveyed its coastal professionals on preparedness for local climate change impacts.

MID-ATLANTIC

- Delaware launched a multi-faceted effort to prepare coastal communities for sea level rise
- Maryland's Comprehensive Strategy for Reducing Vulnerability to Climate Change has a strong initial focus on sea level rise and coastal hazards.
- The Hampton Roads area, including the City of Norfolk, Virgina, is working to reduce recurrent flooding and impacts on coastal infrastructrure.

CALIFORNIA

- San Diego Bay engaged in a multi-sector, multi-level stakeholder process to develop a first adaptation plan.
- California Ocean Protection Council developed sea level rise guidance for state and local governments.
- Bay Conservation and Development Commission passed Bay Plan Amendment.

GULF COAST

- Mississippi – Coastal Improvements Program includes buy-outs and relocation.
- 2012 Lousiana Coastal Master Plan ambitiously aims to protect and restore low-lying land.
- Entergy, America's Wetland Foundation, and Oxfam champion joint adaptation planning for America's Energy Coast.
- Texas requires rolling easements.

SOUTHEAST / CARIBBEAN

- NC Department of Transportation is raising the road bed of US Highway 64 to account for future sea level rise.
- The City of Charleston upgraded stormwater pumps and sewer systems to reduce tidal flooding.
- Charlotte Harbor National Estuary Program and City of Punta Gorda, FL, involved community stakeholders in its adaptation planning process.
- Southeast Florida Regional Climate Change Compact designated Adaptation Action Areas.

HAWAI'I & PACIFIC ISLANDS

- Researchers map sea level rise in Honolulu to help communities assess risks.
- USGS helps monitor saltwater intrusion on Majuro Atoll, Marshall Islands.

Figure 25.4. (d) Adaptation Activities

(d) Examples of Adaptation Activities in Coastal Areas of the U.S. and Affiliated Island States are compiled from technical input reports, the regional chapters in this report, and scientific literature. For related information, see http://data.globalchange.gov/report/coastal-adaptation-examples-2012

Key Message 1: Coastal Lifelines at Risk

Coastal lifelines, such as water supply and energy infrastructure and evacuation routes, are increasingly vulnerable to higher sea levels and storm surges, inland flooding, erosion, and other climate-related changes.

Key coastal vulnerabilities arise from complex interactions among climate change and other physical, human, and ecological factors. These vulnerabilities have the potential to fundamentally alter life at the coast and disrupt coast-dependent economic activities.

Coastal infrastructure is exposed to climate change impacts from both the landward and ocean sides.[44,45,46,47,48] Some unique characteristics increase the vulnerability of coastal infrastructure to climate change (Ch. 11: Urban).[7,49] For instance, many coastal regions were settled long ago, making much of the infrastructure older than in other locations.[50] Also, inflexibility of some coastal, water-dependent infrastructure, such as onshore gas and oil facilities, port facilities, thermal power plants, and some bridges, makes landward relocation difficult (Figure 25.5), and build-up of urban and industrial areas inland from the shoreline can inhibit landward relocation.[7]

Adapting Coastal Infrastructure to Sea Level Rise and Land Loss

Figure 25.5. This "mock-up" shows the existing Highway LA-1 and Leeville Bridge in coastal Louisiana (on the right) with a planned new, elevated bridge that would retain functionality under future, higher sea level conditions (center left). (Current sea level and sinking bridge are shown here.) A 7-mile portion of the planned bridge has been completed and opened to traffic in December 2011. (Figure source: Greater Lafourche Port Commission, reprinted with permission).

Infrastructure is built to certain site-specific design standards (such as the once-in-10-year, 24-hour rainstorm or the once-in-100-year flood) that take account of historical variability in climate, coastal, and hydrologic conditions. Impacts exceeding these standards can shorten the expected lifetime, increase maintenance costs, and decrease services. In general, higher sea levels, especially when combined with inland changes from flooding and erosion, will result in accelerated infrastructure impairment, with associated indirect effects on regional economies and a need for infrastructure upgrades, redesign, or relocation.[7,44,45,46,51]

The more than 60,000 miles of coastal roads[52] are essential for human activities in coastal areas (Ch. 5: Transportation), especially in case of evacuations during coastal emergencies.[53,54] Population growth to date and expected additional growth place increasing demands on these roads, and climate change will decrease their functionality unless adaptation measures are taken.[55,56] Already, many coastal roads are affected during storm events[57] and extreme high tides.[58] Moreover, as coastal bridges, tunnels, and roads are built or redesigned, engineers must account for inland and coastal changes, including drainage flooding, thawing permafrost, higher groundwater levels, erosion, and increasing saturation of roadway bases.[59] During Hurricane Katrina, many bridges failed because they had only been designed for river flooding but were also unexpectedly exposed to storm surges.[55,60]

Wastewater management and drainage systems constitute critical infrastructure for coastal businesses and residents (Ch. 3: Water). Wastewater treatment plants are typically located at low elevations to take advantage of gravity-fed sewage collection. Increased inland and coastal flooding make such plants more vulnerable to disruption, while increased inflows will reduce treatment efficiency.[47,61,62] Drainage systems – designed using mid-1900s rainfall records – will become overwhelmed in the future with increased rainfall intensity over more impervious surfaces, such as asphalt and concrete.[27,63,64,65] Sea level rise will increase pumping requirements for coastal wastewater treatment plants, reduce outlet capacities for drainage systems, and increasingly infiltrate sewer lines, while salt water intrusion into coastal aquifers will affect coastal water supplies and salt fronts will advance farther up into coastal rivers, affecting water supply intakes (Ch. 3: Water).[19,66] Together, these impacts increase the risks of urban flooding, combined sewer overflows, deteriorating coastal water quality, and human health impacts (Ch. 11: Urban; Ch. 9: Human Health).[67,68,69]

Coastal water infrastructure adaptation options include (but are not limited to):

- integrating both natural landscape features and human-engineered, built infrastructure to reduce stormwater runoff and wave attack, including, where feasible, creative use of dredge material from nearby coastal locations in the build-up of wetlands and berms (Figure 25.6);
- constructing seawalls around wastewater treatment plants and pump stations;
- pumping effluent to higher elevations to keep up with sea level rise;
- pumping freshwater into coastal aquifers to reduce infiltration of saltwater; and
- reusing water after treatment to replace diminished water supplies due to sea level rise.[70]

Technical and financial feasibility may limit how well and how long coastal infrastructure can be protected in place before it needs to be moved or abandoned. One group estimated that nationwide adaptation costs to utilities for wastewater systems alone could range between $123 billion and $252 billion by 2050 and, while not specific to coastal systems, gives a sense of the magnitude of necessary expenditures to avert climate change impacts.[71]

Ecosystem Restoration

Figure 25.6. A coastal ecosystem restoration project in New York City integrates revegetation (a form of green infrastructure) with bulkheads and riprap (gray or built infrastructure). Investments in coastal ecosystem conservation and restoration can protect coastal waterfronts and infrastructure, while providing additional benefits, such as habitat for commercial and recreational fish, birds, and other animal and plant species, that are not offered by built infrastructure. (Photo credit: Department of City Planning, New York City, reprinted with permission).

The nation's energy infrastructure, such as power plants, oil and gas refineries, storage tanks, transformers, and electricity transmission lines, are often located directly in the coastal floodplain.[48,72] Roughly two-thirds of imported oil enters the U.S. through Gulf of Mexico ports,[55] where it is refined and then transported inland. Unless adaptive measures are taken, storm-related flooding, erosion, and permanent inundation from sea level rise will disrupt these refineries (and related underground infrastructure) and, in turn, will constrain the supply of refined products to the rest of the nation (Ch. 4: Energy; Ch. 10: Energy, Water, and Land) (Figure 25.5).[73]

Coastal communities have a variety of options to protect, replace, and redesign existing infrastructure, including flood proofing and flood protection through dikes, berms, pumps, integration of natural landscape features, elevation, more frequent upgrades, or relocation.[74] Relocation of large coastal infrastructure away from the coastline can be very expensive and, for some facilities such as port installations, impossible due to the need for direct access to the shoreline. In most instances, the addition of new flood-proofed infrastructure in high-hazard zones has been viewed as a more cost-effective near-term option than relocation.[75] In these cases, significantly higher removal costs may be incurred later when sea level is higher or if the facility needs to be abandoned altogether in the future. This suggests that adaptation options are best assessed in a site-specific context, comprehensively weighing social, economic, and ecological considerations over multiple timeframes. A combination of gray and green infrastructure is increasingly recognized as a potentially cost-effective approach[67,76] to reducing risks to communities and economies while preserving or restoring essential ecosystems and thus their benefits to human welfare (Figure 25.6).[7,77]

ASSESSING FLOOD EXPOSURE OF CRITICAL FACILITIES AND ROADS

NOAA's Critical Facilities Flood Exposure Tool provides an initial assessment of the risk to a community's critical facilities and roads within the "100-year" flood zone established by the Federal Emergency Management Agency (FEMA) (the 100-year flood zone is the areal extent of a flood that has a 1% chance of occurring or being exceeded in any given year). The tool helps coastal managers quickly learn which facilities may be at risk – providing information that can be used to increase flood risk awareness and to inform a more detailed analysis and ultimately flood risk reduction measures. The critical facilities tool was initially created to assist Mississippi/Alabama Sea Grant in conducting its "Coastal Resiliency Index: A Community Self-Assessment" workshops and is now available for communities nationwide. For additional information see: http://www.csc.noaa.gov/digitalcoast/tools/criticalfacilities.

Key Message 2: Economic Disruption

Nationally important assets, such as ports, tourism, and fishing sites, in already-vulnerable coastal locations, are increasingly exposed to sea level rise and related hazards. This threatens to disrupt economic activity within coastal areas and the regions they serve and results in significant costs from protecting or moving these assets.

In 2010, economic activity in shoreline counties accounted for approximately 66 million jobs and $3.4 trillion in wages[78] through diverse industries and commerce. In many instances, economic activity is fundamentally dependent on the physical and ecological characteristics of the coast. These features provide the template for coastal economic activities, including natural protection from waves, access to beaches, flat land for port development and container storage, and wetlands that support fisheries and provide flood protection.

More than 5,790 square miles and more than $1 trillion of property and structures are at risk of inundation from sea level rise of two feet above current sea level – an elevation which could be reached by 2050 under a high rate of sea level rise of approximately 6.6 feet by 2100,[16] 20 years later assuming a lower rate of rise (4 feet by 2100) (Ch. 2: Our Changing Climate), and sooner in areas of rapid land subsidence.[79,80] Roughly half of the vulnerable property value is located in Florida, and the most vulnerable port cities are Miami, Greater New York, New Orleans, Tampa-St. Petersburg, and Virginia Beach.[38,45,79,81]

Although comprehensive national estimates are not yet available, regional studies are indicative of the potential risk: the incremental annual damage of climate change to capital assets in the Gulf region alone could be $2.7 to $4.6 billion by 2030, and $8.3 to $13.2 billion by 2050; about 20% of these at-risk assets are in the oil and gas industry.[82] Investing approximately $50 billion for adaptation over the next 20 years could lead to approximately $135 billion in averted losses over the lifetime of adaptive measures.[82,83]

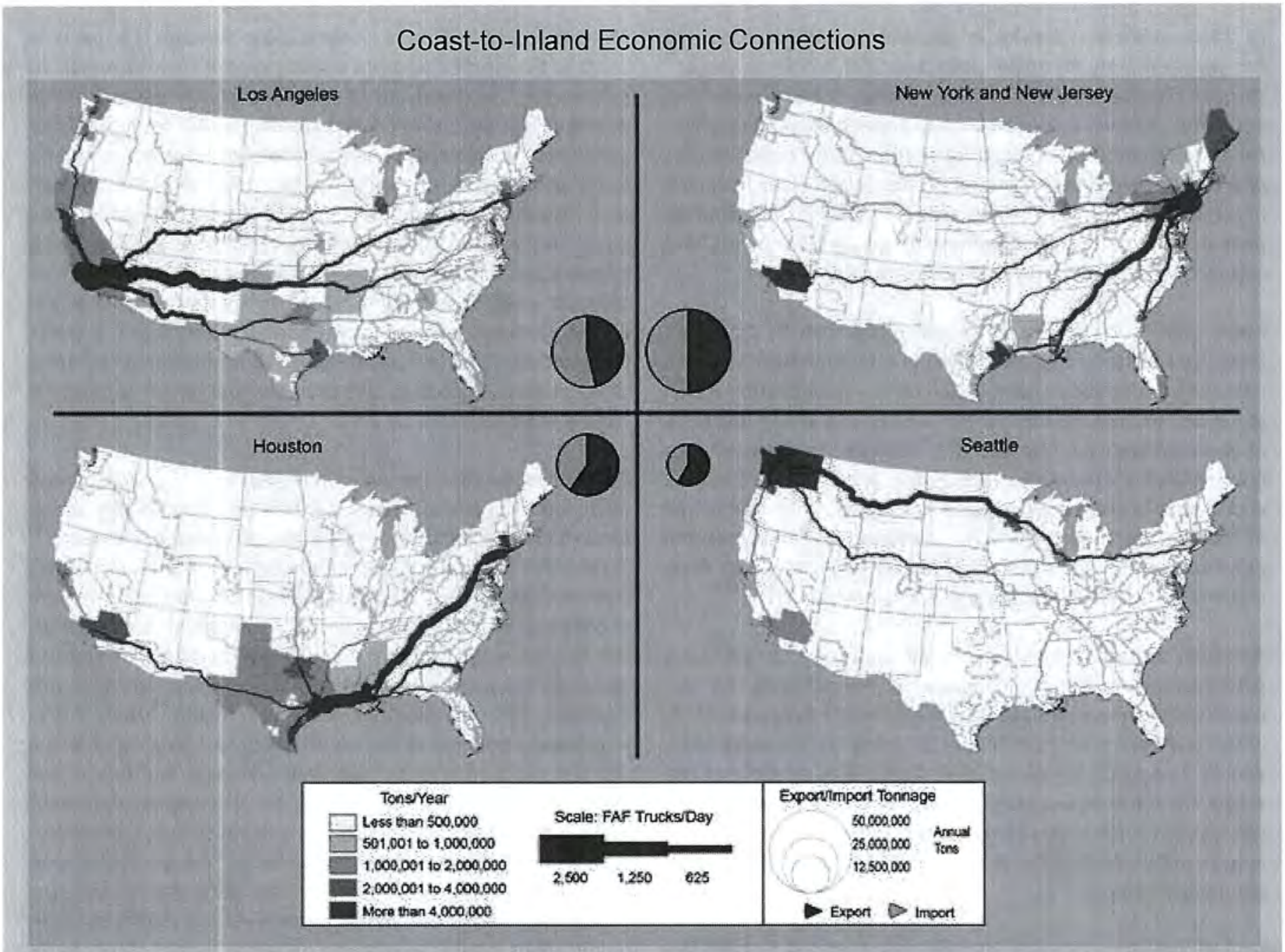

©Boston Globe via Getty Images

More than $1.9 trillion in imports came through U.S. ports in 2010, with commercial ports directly supporting more than 13 million jobs[78] and providing 90% of consumer goods.[84] Ports damaged during major coastal storms can be temporarily or permanently replaced by other modes of freight movement, but at greater cost (Ch. 5: Transportation). The stakes are high and resources exist for ports to take proactive adaptation steps, such as elevating and interconnecting port- and land-based infrastructure or developing offsite storage capability (off-dock intermodal yards) for goods and related emergency response procedures.[85] However, a recent survey showed that most U.S. ports have not yet taken actions to adapt their operations to rising seas, increased flooding, and the potential for more extreme coastal storms.[86]

Coastal recreation and tourism comprises the largest and fastest-growing sector of the U.S. service industry, accounting for 85% of the $700 billion annual tourism-related revenues,[5,88] making this sector particularly vulnerable to increased impacts from climate change.[89] Historically, development of immediate shoreline areas with hotels, vacation rentals, and other tourism-related establishments has frequently occurred without adequate regard for coastal hazards, shoreline dynamics (for example, inlet migration), or ecosystem health.[90] Hard shoreline protection against the encroaching sea (like building sea walls or riprap) generally aggravates erosion and beach loss and causes negative effects on coastal ecosystems, undermining the attractiveness of beach tourism. Thus, "soft protection," such as beach replenishment or conservation and restoration of sand dunes and wetlands, is increasingly preferred to "hard protection" measures. Increased sea level rise means sand replenishment would need to be undertaken more frequently, and thus at growing expense.[34,91,92,93]

Natural shoreline protection features have some capacity to adapt to sea level rise and storms (Figure 25.6) and can also provide an array of ecosystem services benefits[94] that may offset some maintenance costs. A challenge ahead is the need to integrate climate considerations (for example, temperature change and sea level rise) into coastal ecosystem restoration and conservation efforts,[95] such as those underway in the Gulf of Mexico, Chesapeake Bay, and Sacramento-San Joaquin Delta, to ensure that these projects have long-term effectiveness.

U.S. oceanic and Great Lakes coasts are important centers for commercial and recreational fishing due to the high productivity of coastal ecosystems. In 2009, the U.S. seafood industry supported approximately 1 million full- and part-time jobs and generated $116 billion in sales and $32 billion in income.[96] Recreational fishing also contributes to the economic engine of the coasts, with some 74 million saltwater fishing trips along U.S. coasts in 2009 generating $50 billion in sales and supporting over 327,000 jobs.[96] Climate change threatens to disrupt fishing operations through direct and indirect impacts to fish stocks (for example, temperature-related shifts in species ranges, changes in prey availability, and loss of coastal nursery habitat) as well as storm-related disruptions of harbor installations (Ch. 24: Oceans).



Coast-to-Inland Economic Connections

Figure 25.7. Ports are deeply interconnected with inland areas through the goods imported and exported each year. Climate change impacts on ports can thus have far-reaching implications for the nation's economy. These maps show the exports and imports in 2010 (in tons/year) and freight flows (in trucks per day) from four major U.S. ports to other U.S. areas designated in the U.S. Department of Transportation's Freight Analysis Framework (FAF): Los Angeles, Houston, New York/New Jersey, and Seattle. Note: Highway Link Flow less than 5 FAF Trucks/Day are not shown. (Figure source: U.S. Department of Transportation, Federal Highway Administration, Office of Freight Management and Operations, Freight Analysis Framework, version 3.4, 2012).[87]

Key Message 3: Uneven Social Vulnerability

Socioeconomic disparities create uneven exposures and sensitivities to growing coastal risks and limit adaptation options for some coastal communities, resulting in the displacement of the most vulnerable people from coastal areas.

In 2010, almost 2.8% of the U.S. population, or more than 8.6 million Americans, lived within the area subject to coastal floods that have at least a 1% chance of occurring in any one year.[97,98] More than 120 million Americans live in counties that border the open ocean or Great Lakes coasts and/or have a 100-year coastal floodplain within them.[98] Two trends will place even more people at risk in the future: 1) the expansion of the floodplain as sea level rises, and 2) the continuing immigration of people to coastal areas.

By 2100, the fraction of the U.S. population living in coastal counties is expected to increase by 50% (46.2 million) to 144% (131.2 million) depending on alternative projections of future housing.[99] While specific population projections for future 100-year flood zones are only available for some locations,[100] many of these new arrivals can be expected to locate in high-hazard areas. Thus, coastal population densities, along with increasing economic development, will continue to be an important factor in the overall exposure to climate change.[3,7,39,101]

Despite persistent beliefs that living on the coast is reserved for the wealthy,[79,102] there are large social disparities in coastal areas that vary regionally.[41,103] Full understanding of risk for coastal communities requires consideration of social vulnerability factors limiting people's ability to adapt. These factors include lower income; minority status; low educational achievement; advanced age; income dependencies; employment in low-paying service, retail, and other sectors, as well as being often place-bound; less economically and socially mobile; and much less likely to be insured than wealthy property owners (see panel (a) in Figure 25.4).[104]

For example, in California, an estimated 260,000 people are currently exposed to a 100-year flood; this number could increase to 480,000 by 2100 as a result of a 4.6 foot sea level rise alone (roughly equivalent to the high end of the 1 to 4 foot range of sea level rise projections, Ch.2: Our Changing Climate).[38] Approximately 18% of those exposed to high flood risk by the end of this century also are those who currently fall into the "high social vulnerability" category.[81] This means that while many coastal property owners at the shorefront tend to be less socially vulnerable, adjacent populations just inland are often highly vulnerable.

The range of adaptation options for highly socially vulnerable populations is limited.[81] Native communities in Alaska, Louisiana, and other coastal locations already face this challenge today (see "Unique Challenges for Coastal Tribes" and Ch. 12: Indigenous Peoples).[105,106] As sea level rises faster and coastal storms, erosion, and inundation cause more frequent or widespread threats, relocation (also called (un)managed retreat or realignment), while not a new strategy in dynamic coastal environments, may become a more pressing option. In some instances relocation may become unavoidable, and for poorer populations sooner than for the wealthy. Up to 50% of the areas with high social vulnerability face the prospect of unplanned displacement under the 1 to 4 foot range of projected sea level rise (Ch.2: Our Changing Climate), for several key reasons: they cannot afford expensive protection measures themselves, public expense is not financially justified (often because social, cultural, and ecological factors are not considered), or there is little social and political support for a more orderly retreat process. By contrast, only 5% to 10% of the low social vulnerability areas are expected to face relocation.[41] This suggests that climate change could displace many socially vulnerable individuals and lead to significant social disruptions in some coastal areas.[107,108,109]

UNIQUE CHALLENGES FOR COASTAL TRIBES

Coastal Native American and Native Alaskan people, with their traditional dependencies upon natural resources and specific land areas, exhibit unique vulnerabilities. Tribal adaptation options can be limited because tribal land boundaries are typically bordered by non-reservation lands, and climate change could force tribes to abandon traditionally important locations, certain cultural practices, and natural resources on which they depend (Ch. 12: Indigenous Peoples).[110] Coastal food sources are also threatened, including salmon and shellfish. Climate change could affect other food species as well, worsening already existing health problems such as obesity, diabetes, and cancer.

Tribes pride themselves, however, for their experience and persistence in adapting to challenging situations. Some tribes are exploring unique adaptation approaches. In Louisiana's Isle de Jean Charles, for example, the Biloxi-Chitimacha-Choctaw Indian community partnered with a local academic center and a religious congregation to work toward relocating scattered tribal members with those seeking a communal safe haven, while working to save their ancestral land – aiming for community and cultural restoration and for the redevelopment of traditional livelihoods.[108,111]

Key Message 4: Vulnerable Ecosystems

Coastal ecosystems are particularly vulnerable to climate change because many have already been dramatically altered by human stresses; climate change will result in further reduction or loss of the services that these ecosystems provide, including potentially irreversible impacts.

Coastal ecosystems provide a suite of valuable benefits (ecosystem services) on which humans depend, including reducing the impacts from floods, buffering from storm surge and waves, and providing nursery habitat for important fish and other species, water filtration, carbon storage, and opportunities for recreation and enjoyment (Figure 25.8).[95,112,113]

However, many of these ecosystems and the services they provide are rapidly being degraded by human impacts, including pollution, habitat destruction, and the spread of invasive species. For example, 75% of U.S. coral reefs in the Atlantic, Caribbean, and Gulf of Mexico are already in "poor" or "fair" condition;[114,115] all Florida reefs are currently rated as "threatened."[116] Coastal barrier ecosystems continue to be degraded by human development, even in cases where development has slowed (for example, Crawford et al. 2013; Feagin et al. 2010b [117]). Coastal wetlands are being lost at high rates in southeastern Louisiana (Figure 25.9).[118] In addition, the incidence of low-oxygen "dead zones" in coastal waters has increased 30-fold in the U.S. since 1960, with over 300 coastal water bodies now experiencing stressful or lethal oxygen levels (Ch. 8: Ecosystems).[119]

These existing stresses on coastal ecosystems will be exacerbated by climate change effects, such as increased ocean temperatures that lead to coral bleaching,[30] altered river flows affecting the health of estuaries,[121] and acidified waters threatening shellfish.[122] Climate change affects the survival, reproduction, and health of coastal plants and animals in different ways. For example, changes in the timing of seasonal events (such as breeding and migration), shifts in species distributions and ranges, changes in species interactions, and declines in biodiversity all combine to produce fundamental changes in ecosystem character, distribution, and functioning.[28] Species with narrow physiological tolerance to change, low genetic diversity, specialized resource requirements, and poor competitive abilities are particularly vulnerable.[123,124] Where the rate of climate change exceeds the pace at which plants and animals can acclimate or adapt, impacts on coastal ecosystems will be profound.[35,125,126] For example, high death rates of East Coast intertidal mussels at their southern range boundary have occurred because of rising temperatures between 1956 and 2007.[127] The presence of physical barriers (for example, hardened shorelines or reduced sediment availability) and other non-climatic stressors (such as pollution, habitat destruction, and invasive species) will further exacerbate the ecological impacts of climate change and limit the ability of these ecosystems to adapt.[128,129,130] Onshore migration of coastal marshes as sea level rises is often limited by bulkheads or roads (a phenomenon often called "coastal squeeze"), ultimately resulting in a reduction in wetland area.[35,126,128,131,132,133]

Of particular concern is the potential for coastal ecosystems to cross thresholds of rapid change ("tipping points"), beyond which they exist in a dramatically altered state or are lost entirely from the area; in some cases, these changes will be irreversible.[134] These unique, "no-analog" environments present serious challenges to resource managers, who are confronted with conditions never seen before.[135,136,137] The ecosystems most susceptible to crossing such tipping points are those that have already lost some of their resilience due to degradation or depletion by non-climatic stressors.[138] Certain coastal ecosystems are already rapidly changing as a result of interactions between climatic and non-climatic factors, and others have already crossed tipping points. Eelgrass in the Chesapeake Bay died out almost completely during the record-hot summer of 2005, when temperatures exceeded the species' tolerance threshold of 86°F,[139] and subsequent recovery has been poor.[140] Severe low-oxygen events have emerged as a new phenomenon in the Pacific Northwest due to changes in the timing and duration of coastal upwelling.[32,141] These have led to high mortality of Dungeness crabs[33] and the temporary disappearance of rockfish,[32] with consequences for local fisheries. Reducing non-climatic stressors at the local scale can potentially prevent crossing some of these tipping points.[142]

Coastal Ecosystem Services

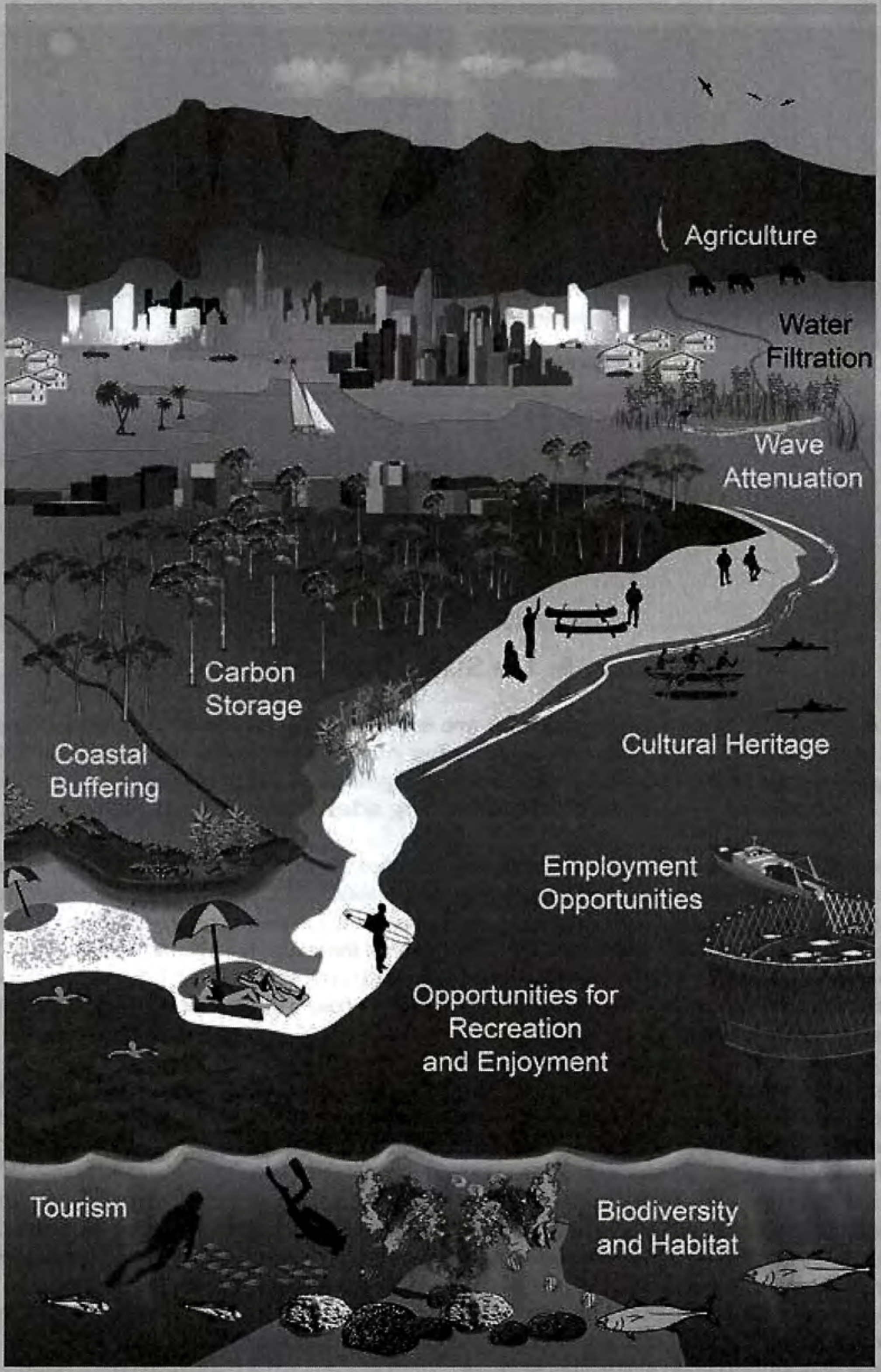


Figure 25.8. Coastal ecosystems provide a suite of valuable benefits (ecosystem services) on which humans depend for food, economic activities, inspiration, and enjoyment. This schematic illustrates many of these services situated in a Pacific or Caribbean island setting, but many of them can also be found along mainland coastlines.

Projected Land Loss from Sea Level Rise in Coastal Louisiana

Figure 25.9. These maps show expected future land change in coastal Louisiana under two different sea level rise scenarios without protection or restoration actions. Red indicates a transition from land (either wetlands or barrier islands) to open water. Green indicates new land built over previously open water. Land loss is influenced by factors other than sea level rise, including subsidence, river discharge and sediment load, and precipitation patterns. However, all these factors except sea level rise were held constant for this analysis. The panel on the left shows land change with a sea level rise of 10.6 inches between 2010 and 2060, while the one on the right assumes 31.5 inches of sea level rise for the same period. These amounts of sea level rise are within the projected ranges for this time period (Ch. 2: Our Changing Climate). (Figure source: State of Louisiana, reprinted with permission[120]).

Key Message 5: The State of Coastal Adaptation

Leaders and residents of coastal regions are increasingly aware of the high vulnerability of coasts to climate change and are developing plans to prepare for potential impacts on citizens, businesses, and environmental assets. Significant institutional, political, social, and economic obstacles to implementing adaptation actions remain.

Considerable progress has been made since the last National Climate Assessment in both coastal adaptation science and practice (Figure 25.4, panel (d)), though significant gaps in understanding, planning, and implementation remain.[20,143,144,145] U.S. coastal managers pay increasing attention to adaptation, but are mostly still at an early stage of building their capacities for adaptation rather than implementing structural or policy changes (Ch. 28: Adaptation).[20,146,147] Although many non-structural (land-use planning, fiscal, legal, and educational) and structural adaptation tools are available through the Coastal Zone Management Act, Coastal Barriers Resources Act, and other frameworks, and while coastal managers are well familiar with these historical approaches to shoreline protection, they are less familiar with some of the more innovative approaches to coastal adaptation, such as rolling easements, ecosystem-based adaptation, or managed realignment.[109,131,144,148] Federal, state, and local management approaches have also been found to be at odds at times,[149] making successful integration of adaptation more difficult.[145] There is only limited evidence of more substantial ("transformational") adaptation occurring, that is, of adaptations that are "adopted at a much larger scale, that are truly new to a particular region or resource system, and that transform places and shift locations,"[150] such as relocation of communities in coastal Alaska and Louisiana (Ch. 22: Alaska).[83,109,150,151] Although more research is needed, reasons for the limited transformational adaptation to date may include the relatively early stage of recognizing climate change and sea level rise risks, the perception that impacts are not yet severe enough, and the fact that social objectives can still be met.[152]

Coastal leaders and populations, however, are increasingly concerned about climate-related impacts and support the development of adaptation plans,[153,154,155] but support for development restrictions or managed retreat is limited.[156,157,158] Economic interests and population trends tend to favor continued (re)development and in-fill in near-shore locations. Current disaster recovery practices frequently promote rapid rebuilding on-site with limited consideration for future conditions[159] despite clear evidence that more appropriate siting and construction can substantially reduce future losses.[160,161]

Enacting measures that increase resilience in the face of current hazards, while reducing long-term risks due to climate change, continues to be challenging.[162,163,164] This is particularly difficult in coastal flood zones that are subject to a 1%

or greater chance of flooding in any given year, including those areas that experience additional hazards from wave action. According to FEMA and policy/property data maintained by the National Flood Insurance Program's (NFIP) Bureau and Statistical Agent, nearly half of the NFIP's repetitive flood losses occur in those areas.[165,166] A robust finding is that the cost of inaction is 4 to 10 times greater than the cost associated with preventive hazard mitigation.[79,160] Even so, prioritizing expenditures now whose benefits accrue far in the future is difficult.[167] Moreover, cumulative costs to the economy of responding to sea level rise and flooding events alone could be as high as $325 billion by 2100 for 4 feet of sea level rise, with $130 billion expected to be incurred in Florida and $88 billion in the North Atlantic region.[80] The projected costs associated with one foot of sea level rise by 2100 are roughly $200 billion. These figures only cover costs of beach nourishment, hard protective structures, and losses of inundated land and property where protection is not warranted, but exclude losses of valuable ecosystem services, as well as indirect losses from business disruption, lost economic activity, impacts on economic growth, or other non-market losses.[80,168,169] Such indirect losses, even in regions generally well prepared for disaster events, can be substantial (in the case of Superstorm Sandy, followed by a nor'easter, in fall 2012, insured losses and wider economic damages added up to at least $65 billion).[170] Sequences of extreme events that occur over a short period not only reduce the time available for natural and social systems to recover and for adaptation measures to be implemented, but also increase the cumulative effect of back-to-back extremes compared to the same events occurring over a longer period.[164,171] The cost of managed retreat requires further assessment.

Property insurance can serve as an important mode of financial adaptation to climate risks,[172] but the full potential of leveraging insurance rates and availability has not yet been realized.[7,173,174] The Government Accountability Office (GAO) listed the National Flood Insurance Program as a "high-risk area" for the first time in 2006, indicating its significance in terms of federal fiscal exposure (nearly $1.3 trillion in 2012).[175] In the context of identifying climate change as a high risk to federal operations, the GAO in 2013 singled out the NFIP again, recognizing growing risks and liabilities due to climate change and sea level rise and the increase in erosion and flooding they entail.[176] While insured assets in coastal areas represent only a portion of this total liability, taxpayers are responsible, via the NFIP, for more than $510 billion of insured assets in the coastal Special Flood Hazard Area (SFHA) alone.[53,177] A number of reforms in the NFIP have been enacted in 2012 to ensure that the program is more fiscally sound and hazard mitigation is improved, though various challenges remain.[178]

Climate adaptation efforts that integrate hazard mitigation, natural resource conservation, and restoration of coastal ecosystems can enhance ecological resilience and reduce the exposure of property, infrastructure, and economic activities to climate change impacts (Figure 25.6).[113,179] Yet, the integration and translation of scientific understanding of the benefits provided by ecosystems into engineering design and hazard management remains challenging.[180] Moreover, interdependencies among functioning infrastructure types and coastal uses require an integrated approach across scientific disciplines and levels of government, but disconnected scientific efforts and fragmented governance at the managerial, financial, and regulatory levels, and narrow professional training, job descriptions, and agency missions pose significant barriers (Ch. 11: Urban; Ch. 28: Adaptation).[145,181,182] Adaptation efforts to date that have begun to connect across jurisdictional and departmental boundaries and create innovative solutions are thus extremely encouraging.[7,145,183,184]

25: COASTAL ZONE DEVELOPMENT AND ECOSYSTEMS

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PHOTO CREDITS

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SUPPLEMENTAL MATERIAL

TRACEABLE ACCOUNTS

Process for Developing Key Messages

A central component of the assessment process was a Chapter Lead Authors meeting held in St. Louis, Missouri in April 2012. The key messages were initially developed at this meeting. Key vulnerabilities were operationally defined as those challenges that can fundamentally undermine the functioning of human and natural coastal systems. They arise when these systems are highly exposed and sensitive to climate change and (given present or potential future adaptive capacities) insufficiently prepared or able to respond. The vulnerabilities that the team decided to focus on were informed by ongoing interactions of the author team with coastal managers, planners, and stakeholders, as well as a review of the existing literature. In addition, the author team conducted a thorough review of the technical input reports (TIR) and associated literature, including the coastal zone foundational TIR prepared for the National Climate Assessment (NCA).[7] Chapter development was supported by numerous chapter author technical discussions via teleconference from April to June 2012.

KEY MESSAGE #1 TRACEABLE ACCOUNT

Coastal lifelines, such as water supply and energy infrastructure and evacuation routes, are increasingly vulnerable to higher sea levels and storm surges, inland flooding, erosion, and other climate-related changes.

Description of evidence base

Coastal infrastructure is defined here to include buildings, roads, railroads, airports, port facilities, subways, tunnels, bridges, water supply systems, wells, sewer lines, pump stations, wastewater treatment plants, water storage and drainage systems, port facilities, energy production and transmission facilities on land and offshore, flood protection systems such as levees and seawalls, and telecommunication equipment. Lifelines are understood in the common usage of that term in hazards management.

The key message and supporting text summarize extensive evidence documented in the coastal zone technical input report[7] as well as a technical input report on infrastructure.[48] Technical input reports (68) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input, along with the extant scientific literature. Additional evidence is provided in other chapters on hurricanes (Ch. 2: Our Changing Climate, Key Message 8), global sea level rise (Ch. 2: Our Changing Climate, Key Message 10), water supply vulnerabilities (Ch. 3: Water); key coastal transportation vulnerabilities (Ch. 5: Transportation), and energy-related infrastructure (Ch. 4: Energy). This key message focuses mainly on water supply and energy infrastructure and evacuation routes, as these constitute critical lifelines.

The evidence base for exposure, sensitivity, and adaptive capacity to higher sea levels and storm surges is very strong, both from empirical observation and historical experience and from studies projecting future impacts on critical coastal infrastructure. There are numerous publications concerning the effects of sea level rise and storm surges on roadways, coastal bridges, and supply of refined products.[7,38,40,64,93,147,162] The information on roadways came from various reports (for example, DOT 2012; Transportation Research Board 2011; NPCC 2009, 2010[55,56,184]) and other publications (for example, State of Louisiana 2012[83]). The impact on coastal bridges is documented in U.S. Department of Transportation reports.[55,59] A number of publications explored the impacts on supply of refined oil-based products such as gasoline.[73]

The evidence base is moderate for the interaction of inland and coastal flooding. There are many and recent publications concerning impacts to wastewater treatment plants[47,61] and drainage systems.[18,27,64,65,70] These impacts lead to increased risk of urban flooding and disruption of essential services to urban residents.

New information and remaining uncertainties

The projected rate of sea level rise (SLR) is fully accounted for through the use of common scenarios. We note, however, that there is currently limited impacts literature yet that uses the lowest or highest 2100 scenario and none that specifically use the broader range of SLR (0.2 to 2 meters, or 0.7 to 6.6 feet, by 2100) [16] and NCA land-use scenarios (60% to 164% increase in urban and suburban land area).[185]

The severity and frequency of storm damage in any given location cannot yet be fully accounted for due to uncertainties in projecting future extratropical and tropical storm frequency, intensity, and changes in storm tracks for different regions (Ch. 2: Our Changing Climate).[7]

The timely implementation and efficacy of adaptation measures, including planned retreat, in mitigating damages is accounted for in the underlying literature (for example, by varying assumptions about the timing of implementation of adaptation measures and the type of adaptation measures) such as hard protection, elevation, relocation, or protection through wetlands and dunes in front of the infrastructure in question) (for example, Aerts and Botzen 2012; Biging et al. 2012; Bloetscher et al. 2011; Heberger et al. 2009; Irish et al. 2010; Kirshen et al. 2011[18,38,44,45,47]). However, such studies can only test the sensitivity of conclusions to these assumptions; they do not allow statements about what is occurring on the ground.

Additional uncertainties arise from the confluence of climate change impacts from the inland and ocean side, which have yet to be studied in an integrated fashion across different coastal regions of the United States.

Assessment of confidence based on evidence

Given the evidence base, the large quantity of infrastructure (water-related infrastructure, energy infrastructure, and the 60,000 miles of coastal roads) in the U.S. coastal zone, and the directional trend at least of sea level rise and runoff associated with heavy precipitation events, we have **very high** confidence that these types of infrastructure in the coastal zone are increasingly vulnerable.

Confidence Level

Very High

Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus

High

Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus

Medium

Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought

Low

Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

KEY MESSAGE #2 TRACEABLE ACCOUNT

Nationally important assets, such as ports, tourism and fishing sites, in already-vulnerable coastal locations, are increasingly exposed to sea level rise and related hazards. This threatens to disrupt economic activity within coastal areas and the regions they serve and results in significant costs from protecting or moving these assets.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the coastal zone technical input report.[7] Technical input reports (68) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input, as well as the extant scientific literature.

The evidence base for increased exposure to assets is strong. Many publications have assessed at-risk areas (for example, Biging et al. 2012; Cooley et al. 2012; Heberger et al. 2009; Neumann et al. 2010a[38,45,79,81]). Highly reliable economic activity information is available from recurring surveys conducted by the National Oceanographic and Atmospheric Administration (NOAA) and others, and asset exposure is conclusively demonstrated by historical information (from storm and erosion damage), elevation data (in Geographic Information System (GIS)-based, LIDAR, and other forms), and numerous vulnerability and adaptation studies of the built environment. Further evidence is provided in technical input reports and other NCA chapters on infrastructure and urban systems (Ch. 11: Urban),[48] transportation (Ch. 5: Transportation),[55] and energy (Ch. 4: Energy). A number of studies in addition to the ones cited in the text, using various economic assumptions, aim to assess the cost of protecting or relocating coastal assets and services. Many publications and reports explore the cost of replacing services offered by ports,[55,91] though one study[186] notes that few ports are implementing adaptation practices to date. The economic consequences of climate change on tourism are supported by a number of recent studies.[89,90,91,93] The threats of climate change on fishing have been explored in the coastal zone technical input report.[7]

Additional evidence comes from empirical observation: public statements by private sector representatives and public officials indicate high awareness of economic asset exposure and a determination to see those assets protected against an encroaching sea, even at high cost (New York City, Miami Dade County, San Francisco airport, etc.). The economic value of exposed assets and activities is frequently invoked when they get damaged or interrupted during storm events (for example, Hallegattee 2012[169]). Threats to economic activity are also consistently cited as important to local decision-making in the coastal context (for example, Titus et al. 2009[109]).

New information and remaining uncertainties

The projected rate of sea level rise is fully accounted for through the use of common scenarios. We note, however, that there is currently limited impacts literature that uses the lowest or highest scenario for 2100, and no studies that specifically use the broader range of SLR (0.7 to 6.6 feet,) and NCA land-use scenarios (60% to 164% increase in urban and suburban land area).[185]

The projected severity and frequency of storm damage in any given location cannot yet be fully accounted for due to uncertainties in projecting future extratropical and tropical storm frequency, intensity, and changes in storm tracks for different regions.[7]

The timely implementation and efficacy of adaptation measures, including planned retreat, in mitigating damages are accounted for in the underlying literature (for example, by varying assumptions about the timing of implementation of adaptation measures, the type of adaptation measures, and other economic assumptions such as discount rates). However, such studies can only test the sensitivity of conclusions to these assumptions; they do not allow statements about what is occurring on the ground. Well-established post-hoc assessments[160] suggest that hazard mitigation action is highly cost-effective (for every dollar spent, four dollars in damages are avoided). A more recent study suggests an even greater cost-effectiveness.[79]

Assessment of confidence based on evidence

Given the evidence base, the well-established accumulation of economic assets and activities in coastal areas, and the directional trend of sea level rise, we have **very high** confidence in the main conclusion that resources and assets that are nationally important to economic productivity are threatened by SLR and climate change.

While there is currently no indication that the highest-value assets and economic activities are being abandoned in the face of sea level rise and storm impacts, we have **very high** confidence that the cost of protecting these assets in place will be high, and that the cost will be higher the faster sea level rises relative to land.

We have **very high** confidence that adequate planning and arrangement for future financing mechanisms, timely implementation of hazard mitigation measures, and effective disaster response will keep the economic impacts and adaptation costs lower than if these actions are not taken.

We are not able to assess timing or total cost of protecting or relocating economic assets with any confidence at this time, due to uncertainties in asset-specific elevation above sea level, in the presence and efficacy of protective measures (at present and in the future), in the feasibility of relocation in any particular case, and uncertainties in future storm surge heights and storm frequencies.

KEY MESSAGE #3 TRACEABLE ACCOUNT

Socioeconomic disparities create uneven exposures and sensitivities to growing coastal risks and limit adaptation options for some coastal communities, resulting in the displacement of the most vulnerable people from coastal areas.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the coastal zone technical input report.[7] Technical input reports (68) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input, along with the extant literature.

Evidence base is moderate: assessment of the social vulnerability to coastal impacts of climate change is a comparatively new research focus in the United States, and clearly an advance since the prior NCA.[187] There are currently multiple published, peer-reviewed studies, by different author teams, using different vulnerability metrics, which all reach the same conclusion: economically and socially vulnerable individuals and communities face significant coastal risks and have a lower adaptive capacity than less socially vulnerable populations. Studies have shown that the U.S. coastal population is growing [99] and have assessed the importance of this population for climate change exposure.[39,101] The social factors that play key roles in coastal vulnerability are detailed in numerous publications.[81,104,188]

There is an additional body of evidence emerging in the literature that also supports this key message, namely the growing literature on "barriers to adaptation," particularly from studies conducted here in the United States.[7,81,105,145,189] This literature reports on the limitations poorer communities face at present in beginning adaptation planning, and on the challenges virtually all communities face in prioritizing adaptation and moving from planning to implementation of adaptation options.

There is empirical evidence for how difficult it is for small, less wealthy communities (for example, the Native communities in Alaska or southern Louisiana) to obtain federal funds to relocate from eroding shorelines.[107,108] Eligibility criteria (positive benefit-cost ratios) make it particularly difficult for low-income communities to obtain such funds; current federal budget constraints limit the available resources to support managed retreat and relocation.[166,173] The recent economic hardship has placed constraints even on the richer coastal communities in the U.S. in developing and implementing adaptation strategies, for example in California.[145] While the economic situation, funding priorities, or institutional mechanisms to provide support to socially vulnerable communities will not remain static over time, there is no reliable scientific evidence for how these factors may change in the future.

New information and remaining uncertainties

The body of research on this topic is largely new since the prior NCA in 2009.[187] Each of the peer-reviewed studies discusses data gaps and methodological limitations, as well as the particular challenge of projecting demographic variables – a notoriously difficult undertaking – forward in time. While methods for population projections are well established (typically using housing projections), those, in turn, depend on more difficult to make assumptions about fertility, migration, household size, and travel times to urban areas. The conclusion is limited by uneven coverage of in-depth vulnerability studies; although those that do exist are consistent with and confirm the conclusions of a national study.[41] This latter study was extended by applying the same approach, data sources, and methodology to regions previously not covered, thus closing important informational gaps (Hawai'i, Alaska, the Great Lakes region). Data gaps remain for most coastal locations in the Pacific Islands, Puerto Rico, and other U.S. territories.

The most important limit on understanding is the current inability to project social vulnerability forward in time. While some social variables are more easily predicted (for example, age and gender distribution) than others (for example, income distribution, ethnic composition, and linguistic abilities), the predictive capability declines the further out projections aim (beyond 2030 or 2050). Further, it is particularly difficult to project these variables in specific places subject to coastal hazards, as populations are mobile over time, and no existing model reliably predicts place-based demographics at the scale important to these analyses.

Assessment of confidence based on evidence

We have **high** confidence in this conclusion, as it is based on well-accepted techniques, replicated in several place-based case studies, and on a nationwide analysis, using reliable Census data. Consistency in insights and conclusions in these studies, and in others across regions, sectors, and nations, add to the confidence. The conclusion does involve significant projection uncertainties, however, concerning where socially vulnerable populations will be located several decades from now. Sensitivity analysis of this factor, and overall a wider research base is needed, before a higher confidence assessment can be assigned.

KEY MESSAGE #4 TRACEABLE ACCOUNT

Coastal ecosystems are particularly vulnerable to climate change because many have already been dramatically altered by human stresses; climate change will result in further reduction or loss of the services that these ecosystems provide, including potentially irreversible impacts.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the coastal zone technical input report.[7] Technical input reports (68) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input, along with the extant literature.

Evidence base is strong for this part of the key message: "Coastal ecosystems are particularly vulnerable to climate change because many have already been dramatically altered by human stresses."

The degradation and depletion of coastal systems due to human stresses (for example, pollution, habitat destruction, and overharvesting) has been widely documented throughout the U.S. and the world.[68,115,116,118,119] The degree of degradation varies based on location and level of human impact. However, evidence of degradation is available for all types of U.S. coastal ecosystems, from coral reefs to seagrasses and rocky shores. Human stresses can be direct (for example, habitat destruction due to dredging of bays) or indirect (for example, food web disruption due to overfishing). There is also consistent evidence that ecosystems degraded by human activities are less resilient to changes in climatic factors, such as water temperature, precipitation, and sea level rise (for example, Gedan et al. 2009; Glick et al. 2011; Williams and Grosholz 2008[128,129,130]).

Evidence base is strong: "climate change will result in further reduction or loss of the services that these ecosystems provide."

The impacts of changing coastal conditions (for example, changes associated with altered river inflows, higher temperatures, and the effects of high rates of relative sea level rise) on coastal ecosystems and their associated services have been extensively documented through observational and empirical studies, including recent publications.[28,121,122,123,129,133] Many models of coastal ecosystem responses to climatic factors have been well-validated with field data. Given the existing knowledge of ecosystem responses, future climate projections, and the interactions with non-climatic stressors that further exacerbate climatic impacts, evidence is strong of the potential for further reduction and/or loss of ecosystem services.

Evidence is suggestive: "including potentially irreversible impacts."

Severe impacts (for example, mass coral bleaching events and rapid species invasions) have been extensively documented for U.S. coastal ecosystems. Many experts have suggested that some of these impacts may be irreversible[134] and never before seen conditions have been documented.[136,137] Recovery may or may not be possible in different instances; this depends on factors that are not well-understood, such as the adaptive capacity of ecosystems, future projections of change that consider interactions among multiple climatic and non-climatic human alterations of systems, the dynamics and persistence of alternative states that are created after a regime shift has occurred, and whether or not the climatic and/or non-climatic stressors that lead to impacts will be ameliorated.[32,33,138,139,140,141]

New information and remaining uncertainties

Since the 2009 NCA,[187] new studies have added weight to previously established conclusions. The major advance lies in the examination of tipping points for species and entire ecosystems (for example, Barnosky et al. 2012; Folke et al. 2004; Foti et al. 2013; Hoegh-Guldberg and Bruno 2010[134,135,137,138]). Existing uncertainties and future research needs were identified through reviewing the NCA technical inputs and other peer-reviewed, published literature on these topics, as well as through our own identification and assessment of knowledge gaps.

Key uncertainties in our understanding of ecosystem impacts of climate change in coastal areas are associated with:

- the interactive effects and relative contributions of multiple climatic and non-climatic stressors on coastal organisms and ecosystems;
- how the consequences of multiple stressors for individual species combine to affect community- and ecosystem-level interactions and functions;
- the projected magnitude of coastal ecosystem change under different scenarios of temperature change, sea level rise, and land-use change, particularly given the potential for feedbacks and non-linearities in ecosystem responses;
- the potential adaptive capacity of coastal organisms and ecosystems to climate change;
- trajectories, timeframes, and magnitudes of coastal ecosystem recovery;
- the dynamics and persistence of alternative states that are created after ecosystem regime shifts have occurred; and
- the potential and likelihood for irreversible climate-related coastal ecosystem change.

In general, relatively little work to date has been conducted to project future coastal ecosystem change under integrative scenarios of temperature change, sea level rise, and changes in human uses of, and impacts to, coastal ecosystems (for example, through land-use change). Advancing understanding and knowledge associated with this key uncertainty, as well as the others included in the above list, would be fostered by additional research.

Assessment of confidence based on evidence

We have **very high** confidence that coastal ecosystems are particularly vulnerable to climate change because they have already been dramatically altered by human stresses, as documented in extensive and conclusive evidence.

We have **very high** confidence that climate change will result in further reduction or loss of the services that these ecosystems provide, as there is extensive and conclusive evidence related to this vulnerability.

We have **high** confidence that climatic change will include "potentially irreversible impacts." Site-specific evidence of potentially irreversible impacts exists in the literature. This vulnerability is frequently identified by studies of coastal ecosystems. However, methods, research, and models are still being developed for understanding, documenting, and predicting potentially irreversible impacts across all types of coastal ecosystems.

KEY MESSAGE #5 TRACEABLE ACCOUNT

Leaders and residents of coastal regions are increasingly aware of the high vulnerability of coasts to climate change, and are developing plans to prepare for potential impacts on citizens, businesses, and environmental assets. Significant institutional, political, social, and economic obstacles to implementing adaptation actions remain.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the coastal zone technical input report.[7] Technical input reports (68) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input, along with the extant literature.

Evidence base is moderate to strong: the results on which this key message relies are based on case studies, direct observation and "lessons learned" assessments from a wide range of efforts, surveys, and interview studies in ongoing adaptation efforts around the country.[154] There has been some planning for remediating climate change impacts, including recent publications[144,153,168,184] and there are publications on the lower social acceptance of certain adaptation option (for example, Finzi Hart et al. 2012; Peach 2012[144,158]) and on the many barriers that affect adaptation.[145,181,182]

In addition, there is confirming evidence of very similar findings from other locations outside the U.S. (some, from Canada, were also submitted as technical input reports to the NCA), such as the United Kingdom, continental Europe, Australia, and others.[157,181]

New information and remaining uncertainties

Adaptation is a rapidly spreading policy and planning focus across coastal America. This was not previously captured or assessed in the 2009 NCA[187] and is thus a major advance in understanding, including what adaptation activities are underway, what impedes them, and how coastal stakeholders view and respond to these emerging adaptation activities.

Given the local nature of adaptation (even though it frequently involves actors from all levels of government), it is difficult to systematically track, catalog, or assess progress being made on adaptation in coastal America. The difficulty, if not impossibility, of comprehensively tracking such progress has been previously acknowledged.[20] This conclusion is reiterated in the Adaptation chapter (Ch. 28) of this report.

While the findings and integrative key message stand on strong evidence, some uncertainties remain about U.S. coastal regions' adaptive capacity, the level of adoption of hazard mitigation and other adaptation strategies, and the extent and importance of barriers to adaptation.

Possibly the least well-understood aspect about coastal adaptation is how and when to undertake large-scale, transformational adaptation. Aside from the mentioned examples of relocation, no other examples exist at the present time, and further research is required to better understand how major institutional, structural, or social transformation might occur and what would be involved to realize such options.

Assessment of confidence based on evidence

We have **very high** confidence in this key message, as it is primarily based on studies using well-accepted social science research techniques (for example, surveys, interviews, and participant observation), replicated in several place-based case studies, and on a nationwide compilation of adaptation case studies. Consistency in insights and conclusions in these studies, and in others across regions, sectors, and nations, add to the confidence.

As described above, a comprehensive catalogue of all adaptation efforts, and of related challenges and lessons learned, is difficult if not impossible to ever obtain. Nevertheless, the emerging insights and evidence from different regions of the country provide considerable confidence that the situation is reasonably well captured in the documents relied on here. The coastal stakeholders represented among the authors of the foundational technical input report[7] confirmed the conclusions from their long-term experience in coastal management and direct involvement in adaptation efforts locally.

Moreover, evidence from other regions outside the U.S. adds weight to the conclusions drawn here.

RESPONSE STRATEGIES

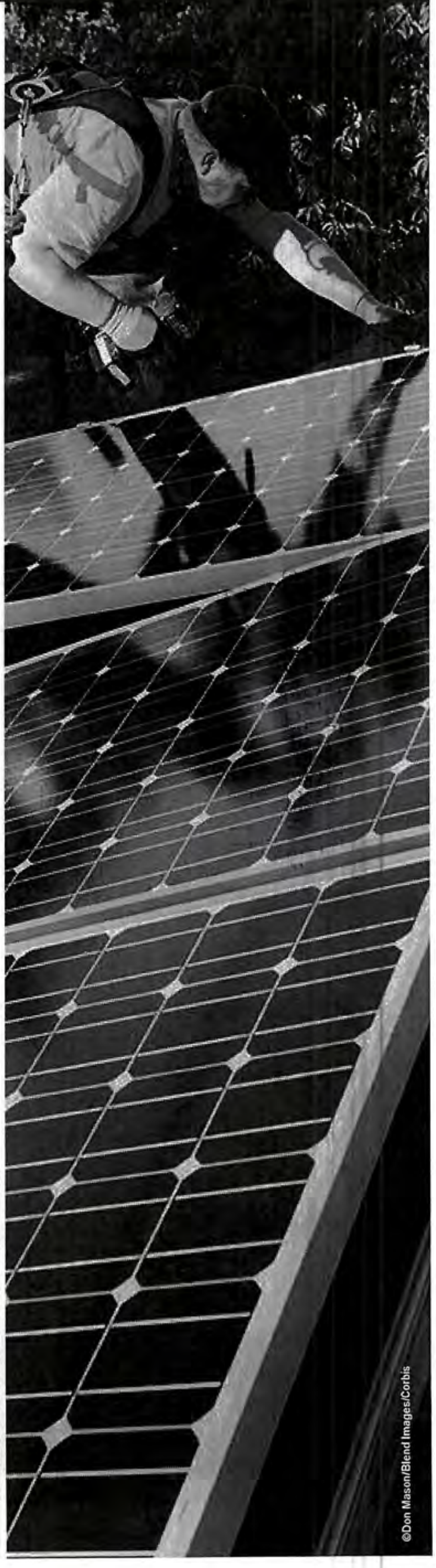
People make choices every day about risks and benefits in their lives, weighing experience, information, and judgment as they consider the impacts of their decisions on themselves and the people around them. Similarly, people make choices that alter the magnitude of impacts resulting from current and future climate change. Using science-based information to anticipate future changes can help society make better decisions about how to reduce risks and protect people, places, and ecosystems from climate change impacts. Decisions made now and in the future will influence society's resilience to impacts of future climate change.

In recognition of the significance of these decisions, the National Climate Assessment presents information that is useful for a wide variety of decisions across regions and sectors, at multiple scales, and over multiple time frames. For the first time, the National Climate Assessment includes chapters on Decision Support, Mitigation, and Adaptation, in addition to identifying research needs associated with these topics.

As with other sections of this report, the linkages across and among these chapters are extremely important. There are direct connections between mitigation decisions (about whether and how to manage emissions of heat-trapping gases) and how much climate will change in the future. The amount of change that occurs will in turn dictate the amount of adaptation that will be required.

In the Decision Support chapter, a variety of approaches to bridge the gap between scientific understanding and decision-making are discussed, leading to the conclusion that there are many opportunities to help scientists understand the needs of decision-makers, and also to help decision-makers use available tools and information to reduce the risks of climate change. The Mitigation chapter describes emissions trajectories and assesses the state of mitigation activities. Policies already enacted and other factors lowered U.S. emissions in recent years, but achievement of a global emissions path consistent with the lower scenario (B1) analyzed in this assessment will require strenuous action by all major emitters. The Adaptation chapter assesses current adaptation activities across the United States in the public and private sectors, and concludes that although a lot of adaptation planning is being done, implementation lags significantly behind the scale of anticipated changes.

This report concludes with chapters on Research Needs to improve future climate and global change assessments and on the Sustained Assessment Process, which describes the rationale for ongoing assessment activity to achieve greater efficiency and better scientific and societal outcomes.



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Climate Change Impacts in the United States

CHAPTER 26
DECISION SUPPORT
CONNECTING SCIENCE, RISK PERCEPTION, AND DECISIONS

Convening Lead Authors

Richard Moss, Joint Global Change Research Institute, Pacific Northwest National Laboratory, University of Maryland
P. Lynn Scarlett, The Nature Conservancy

Lead Authors

Melissa A. Kenney, University of Maryland
Howard Kunreuther, University of Pennsylvania
Robert Lempert, RAND Corporation
Jay Manning, Cascadia Law Group
B. Ken Williams, The Wildlife Society

Contributing Authors

James W. Boyd, Resources for the Future
Emily T. Cloyd, University Corporation for Atmospheric Research
Laurna Kaatz, Denver Water
Lindene Patton, Zurich North America

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On the Web: http://nca2014.globalchange.gov/report/response-strategies/decision-support

INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

26 DECISION SUPPORT:

CONNECTING SCIENCE, RISK PERCEPTION, AND DECISIONS

KEY MESSAGES

1. **Decisions about how to address climate change can be complex, and responses will require a combination of adaptation and mitigation actions. Decision-makers – whether individuals, public officials, or others – may need help integrating scientific information into adaptation and mitigation decisions.**
2. **To be effective, decision support processes need to take account of the values and goals of the key stakeholders, evolving scientific information, and the perceptions of risk.**
3. **Many decision support processes and tools are available. They can enable decision-makers to identify and assess response options, apply complex and uncertain information, clarify tradeoffs, strengthen transparency, and generate information on the costs and benefits of different choices.**
4. **Ongoing assessment processes should incorporate evaluation of decision support tools, their accessibility to decision-makers, and their application in decision processes in different sectors and regions.**
5. **Steps to improve collaborative decision processes include developing new decision support tools and building human capacity to bridge science and decision-making.**

After a long period of relative stability in the climate system, climate conditions are changing and are projected to continue to change (Ch. 2: Our Changing Climate). As a result, historically successful strategies for managing climate-sensitive resources and infrastructure will become less effective over time. Although decision-makers routinely make complex decisions under uncertain conditions, decision-making in the context of climate change can be especially challenging due to a number of factors. These include the rapid pace of changes in some physical and human systems, long time lags between human activities and response of the climate system, the high economic and political stakes, the number and diversity of potentially affected stakeholders, the need to incorporate uncertain scientific information of varying confidence levels, and the values of stakeholders and decision-makers.[1,2,3] The social, economic, psychological, and political dimensions of these decisions underscore the need for ways to improve communication of scientific information and uncertainties and to help decision-makers assess risks and opportunities.

Extensive literature and practical experience offer means to help improve decision-making in the context of climate variability and change. The decision-support literature includes topics such as decision-making frameworks, decision support tools, and decision support processes. These approaches can help evaluate the costs and benefits of alternative actions, communicate relative amounts of risk associated with different options, and consider the role of alternative institutions and governance structures. In particular, iterative decision processes that incorporate improving scientific information and learning though periodic reviews of decisions over time are helpful in the context of rapid changes in environmental conditions.[3,4] Some of the approaches described in this chapter can also help overcome barriers to the use of existing tools and improve communications among scientists, decision-makers, and the public.[5,6]

FOCUS OF THIS CHAPTER

This chapter introduces decision-making frameworks that are useful for considering choices about climate change responses through the complementary strategies of adaptation and mitigation. It also includes numerous examples in which decision support tools are being employed in making adaptation and mitigation decisions. It focuses on the processes that promote sustained interaction between decision-makers and the scientific/technical community. This chapter reviews the state of knowledge and practice in the context of managing risk. Extensive literature makes clear that in many cases, decisions aided by the types of approaches described here prove more successful than unaided decisions.[3,7] Because of space limitations, the chapter describes some general classes of tools but does not assess specific decision support tools.

What are the decisions and who are the decision-makers?

Decisions about climate change adaptation and mitigation are being made in many settings (Table 26.1). For example:

- The Federal Government is engaged in decisions that affect climate policy at the national and international level; makes regulatory decisions (for example, setting efficiency standards for vehicles); and makes decisions about infrastructure and technologies that may reduce risks associated with climate change for its own facilities and activities.
- State, tribal, and local governments are involved in setting policy about both emissions and adaptation activities in a variety of applications, including land use, renewable portfolio and energy efficiency standards, and investments in infrastructure and technologies that increase resilience to extreme weather events.
- Private-sector companies have initiated strategies to respond both to the risks to their investments and the business opportunities associated with preparing for a changing climate.
- Non-governmental organizations have been active in supporting decisions that integrate both adaptation and mitigation considerations, often in the context of promoting sustainability within economic sectors, communities, and ecosystems.

Individuals make decisions on a daily basis that affect their contributions to greenhouse gas emissions, their preparedness for extreme events, and the health and welfare of their families.[8]

Many decisions involve decision-makers and stakeholders at multiple scales and in various sectors. Effective decision support must link and facilitate interactions across different decision networks.[9]

Table 26.1. Examples of Decisions at Different Scales

Individuals ↓ ↓	A farmer decides whether to adopt no-till agricultural practices.
Organizations	A private firm decides whether to invest in solar or wind energy.
↓ ↓	A city develops a plan to increase resiliency to coastal floods in light of projections for sea level rise.
Communities ↓	A government agency plans incentives for renewable energy to meet greenhouse gas reduction goals.
↓ ↓ National Governments ↓	A national government develops its positions for international climate negotiations, including what commitments the government should make with respect to reducing greenhouse gas emissions.
↓ ↓ International Institutions	A United Nations agency designs a long-term strategy to manage increased flows of refugees who are migrating in part due to desertification related to climate change.

What is decision support?

Decision support refers to "organized efforts to produce, disseminate, and facilitate the use of data and information" to improve decision-making.[3] It includes processes, decision support tools, and services. Some examples include methods for assessing tradeoffs among options, scenarios of the future used for exploring the impacts of alternative decisions, vulnerability and impacts assessments, maps of projected climate impacts, and tools that help users locate, organize, and display data in new ways. Outcomes of effective decision support processes include building relationships and trust that can support longer-term problem-solving capacity between knowledge producers and users; providing information that users regard as credible, useful, and actionable; and enhancing the quality of decisions.[3] Decision support activities that facilitate well-structured decision processes can result in consensus about defining the problems to be addressed, objectives and options for consideration, criteria for evaluation, potential opportunities and consequences, and tradeoffs (Figure 26.1).

Decision-Making Elements and Outcomes

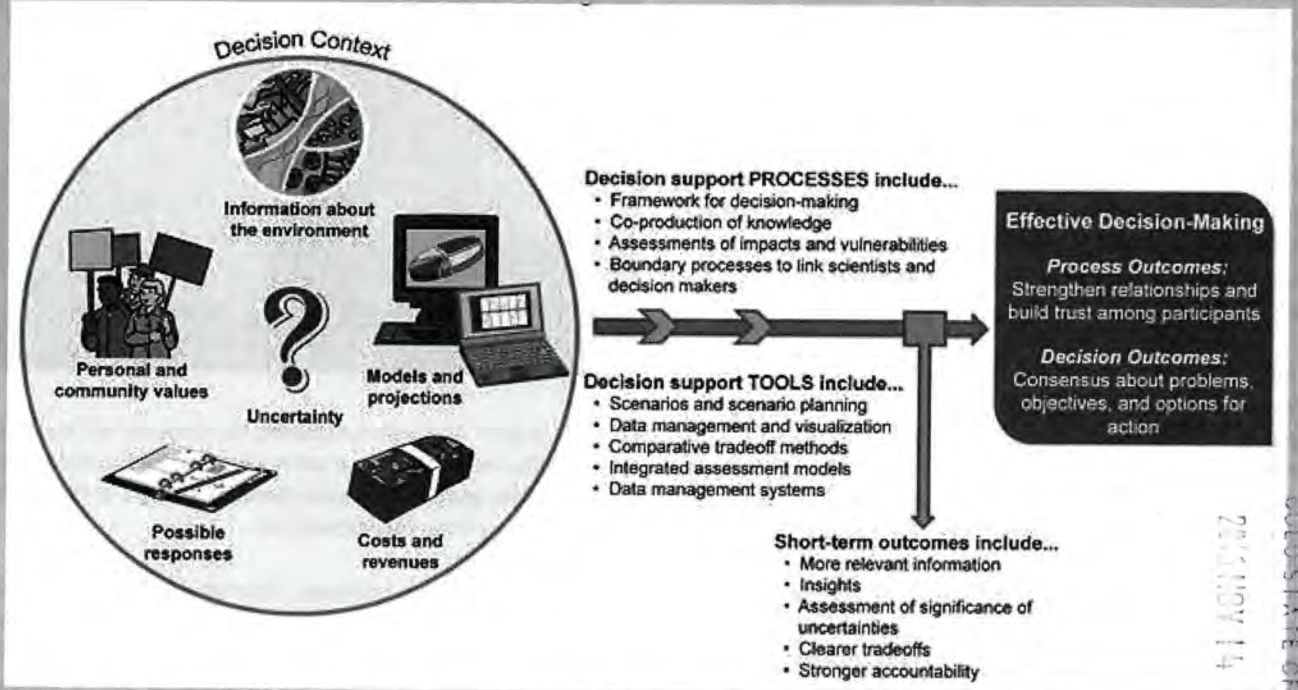

Figure 26.1. Decisions take place within a complex context. Decision support processes and tools can help structure decision-making, organize and analyze information, and build consensus around options for action.

Boundary Processes: Collaboration among Decision-Makers, Scientists, and Stakeholders

Incorporating the implications of climate change in decision-making requires consideration of scientific insights as well as cultural and social considerations, such as the values of those affected and cultural and organizational characteristics. Chapter 28 (Adaptation) addresses how some of these factors might be addressed in the context of adaptation. The importance of both scientific information and societal considerations suggests the need for the public, technical experts, and decision-makers to engage in mutual shared learning and shared production of relevant knowledge.[3,10] A major challenge in these engagements is communicating scientific information about the risks and uncertainties of potential changes in climate.[11]

Boundary Processes Linking Decision-Makers and Scientific/Technical Experts

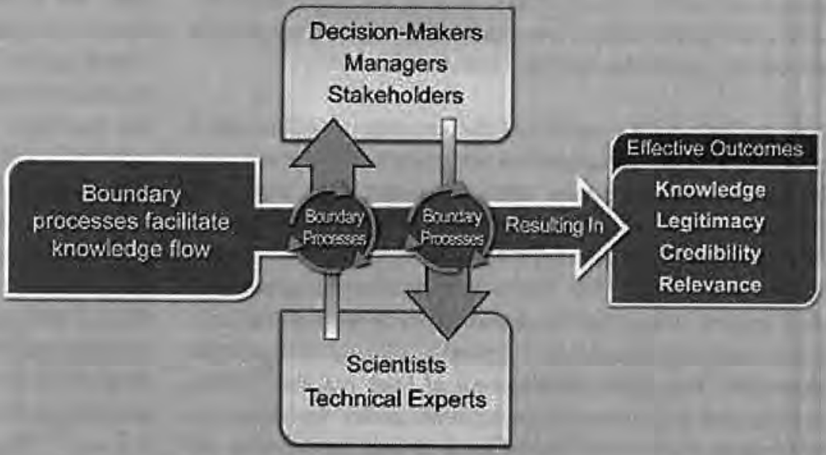

Figure 26.2. Boundary processes facilitate the flow of information and sharing of knowledge between decision-makers and scientists/technical experts. Processes that bring these groups together and help translate between different areas of expertise can provide substantial benefits.

Efforts to facilitate interactions among technical experts and members of the public and decision-makers are often referred to as "boundary processes" (Figure 26.2). Boundary processes and associated tools include, for example, joint fact finding, structured decision-making, collaborative adaptive management, and computer-aided collaborative simulation, each of which engages scientists, stakeholders, and decision-makers in ongoing dialog about understanding the policy problem and identifying what information and analyses are necessary to evaluate decision options.[12,13,14] The use of these kinds of processes is increasing in decision settings involving complex scientific information and multiple – sometimes competing – societal values and goals. Well-designed boundary processes improve the match between the availability of scientific information and capacity to use it and result in scientific information that is perceived as useful and applicable.

Though boundary processes developed to support climate-related decisions vary in their design, they all involve bringing together scientists, decision-makers, and citizens to collaborate in the scoping, conduct, and employment of technical and scientific studies to improve decision-making. Boundary processes can involve establishing specialized institutions, sometimes referred to as boundary organizations, to provide a forum for interaction amongst scientists and decision-makers.[15] One such boundary activity is the National Oceanic and Atmospheric Administration's (NOAA) Regional Integrated Science and Assessment (RISA) Program. Interdisciplinary RISA teams are largely based at universities and engage regional, state, and local governments, non-governmental organizations, and private sector organizations to address issues of concern to decision-makers and planners at the regional level. RISA teams help to build bridges across the scientist, decision-maker, and stakeholder divide.[16] Effective engagement may also occur through less formal approaches by incorporating boundary processes that bring scientists, stakeholders, and decision-makers together within a specific decision-making setting rather than relying on an independent boundary organization. Sustained conversations among scientists, decision-makers, and stakeholders are often necessary to frame issues and identify, generate, and use relevant information.[17]

Some analysts have emphasized the importance of boundary processes that are collaborative and iterative.[18] In one example, federal, state, and local agencies, water users, and other stakeholders are using a collaborative process to manage the Platte River to meet species protection goals and the needs of other water users. The Platte River Recovery Implementation Program brings together participants on an ongoing basis to help set goals, choose management options, and generate information about the effectiveness of their actions.[19] Scientists engaged in the process do not make policy decisions, but they engage directly with participants to help them frame scientific questions relevant to management choices, understand available information, design monitoring systems to assess outcomes of management actions, and generate new knowledge tailored to addressing key decision-maker questions. The process has helped participants move beyond disagreements about the water-flow needs of the endangered species and move to action. Through monitoring, participants will evaluate whether the water flows and other management practices are achieving the goals for species recovery set out in the Platte River Recovery Implementation Plan.

Courtesy of Lynn Laws, Iowa State University 2013

In a number of other examples, boundary processes involve the use of computer simulation models.[14] Scientists, stakeholders, and decision-makers develop a shared understanding of the problem and potential solutions by jointly designing models that reflect their values, interests, and analytical needs. The U.S. Army Corps of Engineers has developed this type of boundary process in their "shared vision planning."[20] A comprehensive website provides a history of the process, demonstrations and case studies, and tools and techniques for implementing the process.[21]

Recently, the International Joint Commission used the shared vision planning process in decisions about how to regulate water levels in both the Lake Ontario-St. Lawrence River system[22] and in the Upper Great Lakes.[23,24] Both studies engaged hundreds of participants from the United States and Canada in discussions about water level management options and the impacts of those options on ecosystems; recreational boating and tourism; hydropower; commercial navigation; municipal, industrial, and domestic water use; and the coastal zone. The models used in the studies incorporated information about ecosystem responses, shoreline dynamics, economics, and lake hydrology, and the potential operating plans were tested using multiple climate change scenarios. Although the shared vision planning process did not ultimately lead to consensus on a single recommended plan in the Lake Ontario-St. Lawrence River Study, the process did help improve participants' understanding of the system and develop a shared vision of possible futures.[22,25] Building on lessons from the Lake Ontario-St. Lawrence River Study, the Upper Great Lakes Study's use of shared vision planning did result in a single recommended plan.[24]

Using a Decision-Making Framework

The term "adaptive management" is used here to refer to a specific approach in which decisions are adjusted over time to reflect new scientific information and decision-makers learn from experience. The National Research Council (NRC) contrasts the processes of "adaptive management" and "deliberation with analysis."[3] Both can be used as part of an "iterative adaptive risk management framework" that is useful for decisions about adaptation and ways to reduce future climate change, especially given uncertainties and ongoing advances in scientific understanding.[8,26] Iterative adaptive risk management emphasizes learning by doing and continued adaptation to improve outcomes. It is especially useful when the likelihood of potential outcomes is very uncertain.

An idealized iterative adaptive risk management process includes clearly defining the issue, establishing decision criteria, identifying and incorporating relevant information, evaluating options, and monitoring and revisiting effectiveness (Figure 26.3). The process can be used in situations of varying complexity, and while it can be more difficult for complex decisions,[27] the incorporation of an iterative approach makes it possible to adjust decisions as information improves. Iterative adaptive risk management can be undertaken through collaborative processes that facilitate incorporation of stakeholder values in goal-setting and review of decision options.[28] Examples of the process and decision support tools that are helpful at its different stages are included in subsequent sections of this chapter.

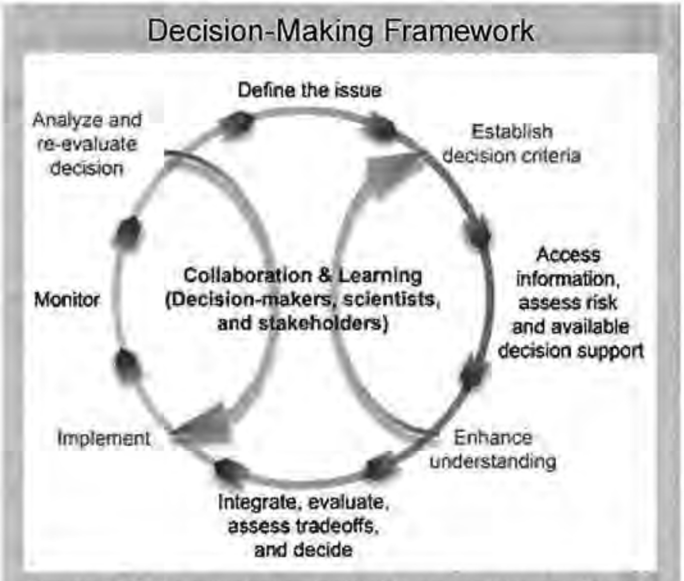

Figure 26.3. This illustration highlights several stages of a well-structured decision-making process. (Figure source: adapted from NRC 2010[8] and Willows and Connell 2003[26]).

Defining the Issue and Establishing Decision Criteria

An initial step in a well-structured decision process is to identify the context of the decision and factors that will affect choices – making sure that the questions are posed properly from scientific, decision-maker, and stakeholder (or public) perspectives (corresponding to the first two steps in Figure 26.3). An important challenge is identifying the stakeholders and how to engage them in decision-making processes. There are often many categories of stakeholders, including those directly and indirectly affected by, or interested in, the outcomes of decisions, as well as the decision-makers, scientists, and elected officials.[29] Other important considerations often overlooked but critical to defining the issue are:

- understanding the goals and values of the participants in the decision process;
- identifying risk perceptions and the sense of urgency of the parties involved in the decision;
- being clear about the time frame of the decision (short- versus long-term options relative to current and future risk levels) – and when the decision must be reached;
- acknowledging the scale and degree of controversy associated with the risks and opportunities as well as the alternatives;
- assessing the distribution of benefits or losses associated with current conditions and the alternatives being considered;
- reaching out to communities that will be affected but may lack ready access to the process (for example, considering environmental justice issues);
- recognizing the diverse interests of the participants;
- recognizing when neutral facilitators or trained science translators are needed to support the process; and
- understanding legal or institutional constraints on options.

Identifying and agreeing on decision criteria – metrics that help participants judge the outcomes of different decision options – can be extremely helpful in clarifying the basis for reaching a decision. Based on the relevant objectives, decision criteria can be established that reflect constraints and values of decision-makers and affected parties. Criteria can be quantitative (for example, obtaining a particular rate of return on investment) or qualitative (for example, maintaining a community's character or culture). If the issue identified is to reduce the risks associated with climate change, decision criteria might include minimizing long-term costs and maximizing public safety. Related sections below provide information on tools for valuing and comparing options and outcomes and provide a basis for using decision criteria.

Decision framing and establishment of decision criteria can be facilitated using various methods, including brainstorming, community meetings, focus groups, surveys, and problem mapping;[3,29] selecting among techniques requires consideration of a number of context-specific issues.[30] There are a variety of techniques for organizing, weighting information, and making tradeoffs for the goals that are important for a decision,[31,32] several of which are discussed in more detail in the section "Examples of Decision Support Tools and Methods."

Accessing Information

Developing a solid base of information to support decision-making is ideally a process of matching user needs with available information, including observations, models, and decision support tools. In some cases, needed information does not exist in the form useful to decision makers, thus requiring the capacity for synthesis of currently available information into new data products and formats. For decisions in the context of climate change and variability, it is critical to consult information that helps clarify the risks and opportunities to allow for appropriate planning and management. An example of information systems that synthesize data and products to support mitigation and adaptation decisions is the National Integrated Drought Information System (NIDIS), a federal, interagency effort to supply information about drought impacts and risks as well as decision support tools to allow sectors and communities to prepare for the effects of drought.[33] Learning from the successes of such efforts, the National Climate Assessment (NCA) is currently developing an indicator system to track climate changes as well as physical, natural, and societal impacts, vulnerabilities, and responses.[34] This effort is building on existing indicator efforts, such as the U.S. Environmental Protection Agency's (EPA) Climate Change Indicators,[35] NASA Vital Signs,[36] and NOAA indicator products,[37] as well as identifying when new data, information, and indicator products are needed.

Information technology systems and data analytics can harness vast data sources, facilitating collection, storage, access, analysis, visualization, and collaboration by scientists, analysts, and decision-makers. Such technologies allow for rapid scenario building and testing using many different variables, enhancing capacity to measure the physical impacts of climate change. These technologies are managing an increasing volume of data from satellite instruments, in situ (direct) measurement networks, and increasingly detailed and high-resolution models.[38] "Information Technology Supports Adaptation Decision-Making" below highlights use of an open platform data system that facilitated collaboration across multiple public and private sector entities in analyzing climate risk and adaptation economics along the U.S. Gulf Coast.

While progress is being made in development of data management and information systems, multiple challenges remain. Specific issues highlighted in the recent USGCRP *National Global Change Research Plan*[38] include data permanence, volume, transparency, quality control, and access. For data on socioeconomic systems – important for evaluating vulnerabilities, adaptation, and mitigation – privacy, confidentiality, and integration with broader systems of environmental data are important issues.[38] Experience with adaptation and mitigation decisions is often an excellent source of information and knowledge but is difficult to access and validate. Several organizations have been developing knowledge management systems for integrating this highly dispersed information and providing it to a network of practitioners (for example, CAKE 2012[39]). Addressing these and other challenges is essential for making progress in establishing a sustained assessment process and meeting the challenge of informing decision-making.[40]

INFORMATION TECHNOLOGY SUPPORTS ADAPTATION DECISION-MAKING

Entergy (a regional electric utility), Swiss Re (a reinsurance company), and the Economics of Climate Adaptation Working Group (a partnership between several public and private organizations) integrated natural catastrophe weather models with economic data to develop damage estimates related to climate change adaptation.[41] An extension of this work is the first comprehensive analysis of climate risks and adaptation economics along the U.S. Gulf Coast.[42] Another example is a simplified model, developed with support from EPA, to look at flooding risks associated with coastal exposure in southern Maine.[43] Use of an "open platform" system that allows multiple users to input and access data resulted in spreadsheets, graphs, and three-dimensional imagery displayed on contour maps downscaled to the city and county level for local decision-makers to access.[44]

Assessing, Perceiving, and Managing Risk

Making effective climate-related decisions requires balance among actions intended to manage, reduce, and transfer risk. Risks are threats to life, health and safety, the environment, economic well-being, and other things of value. Risks are often evaluated in terms of how likely they are to occur (probability) and the damages that would result if they did happen (consequences). As noted by the Intergovernmental Panel on Climate Change,[45] human choices affect the risks associated with climate variability and change. Such choices include how to manage our ecosystems and agriculture, where to live, and how to build resilient infrastructure. Choices regarding a portfolio of actions to address the risks associated with climate variability and change are most effective when they take into consideration the range of factors affecting human behavior, including people's perception of risk, the relative importance of those risks, and the socioeconomic context.[45,46] The process shown in Figure 26.4 is designed to help take such factors into consideration.

The next few sections describe the "integrate, evaluate, and decide" steps in Figure 26.3, which aim to help decision-makers choose *risk management* strategies. While a full quantitative risk analysis is not always possible, the concept of *risk assessment* coupled with understanding of *risk perception* provides a powerful framework for decision-makers to evaluate alternative options for managing the risks that they face today and in the future.[47] As described below, methods such as multiple criteria analysis, valuation of both risks and opportunities, and scenarios can help to combine experts' assessment of climate change risks with public perception of these risks, both influenced by the diverse values people bring to these questions[48] and in support of risk management strategies more likely to achieve both public support and their desired objectives.[46] To illustrate how this framework can be applied to resource management decisions, we use an example of coastal risk management decisions in the context of climate change.[49]

Linking Risk Assessment and Risk Perception with Risk Management of Climate Change

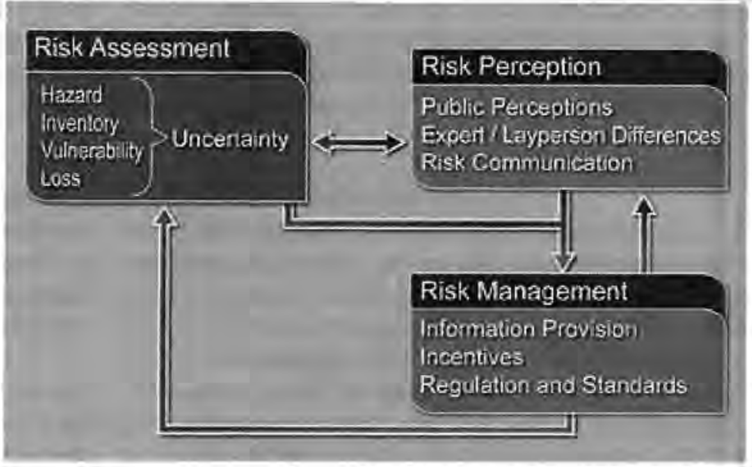

Figure 26.4. This figure highlights the importance of incorporating both experts' *assessment* of the climate change risk and general public *perceptions* of this risk in developing risk management strategies for reducing the negative impacts of climate change. As indicated by the arrows, how the public perceives risk should be considered when experts communicate data on the risks associated with climate change so the public refines its understanding of these risks. As the arrows indicate, the general public's views must also be considered in addition to experts' judgments when developing risk management strategies that achieve decision-makers' desired objectives. Climate change policies that are implemented will, in turn, affect both expert assessment and public perception of this risk in the future, as indicated by the feedback loop from risk management to these two boxes.

Risk Assessment

Risk assessment includes studies that estimate the likelihood of specific sets of events occurring and/or their potential consequences.[50] Experts often provide quantitative information regarding the nature of the climate change risk and the degree of uncertainty surrounding their estimates. Risk assessment focuses on the likelihood of negative consequences but does not exclude the possibility that there may also be beneficial consequences.

There are four basic elements for assessing risk – hazard, inventory, vulnerability, and loss.[51] This generalized approach to risk assessment is useful for a variety of types of decisions. The first element focuses on the risk of a *hazard* as a function of climate change, including interactions of climate effects with other factors. In the context of the coastal community example, the community is concerned with the likelihood of future hurricanes and the impacts that sea level rise may have on damage to the residential development from future hurricanes. There is likely to be considerable uncertainty about maximum storm surge and sea level from hurricanes during the next 50 to 70 years. The second element identifies the *inventory* of properties, people, and the environment at risk. To inventory structures, for instance, requires evaluating their location, physical dimensions, and construction quality.

Evaluating both the hazard and its impacts on the inventory often requires an appropriate treatment of uncertainty. In some cases a probabilistic treatment may prove sufficient. For instance, in the coastal community example, decision-makers may have sufficient confidence in estimates of the return frequency of extreme storms (for example, that the once-in-a-hundred-years storm is and will remain a once-in-a-hundred-years storm) to base their choices largely on these estimates. If such probabilistic estimates are not available, or if decision-makers lack sufficient confidence in those that are available, they may find it useful to consider a range of scenarios and seek risk management strategies robust across these ranges of estimates.[49,52,53]

Together, the hazard and inventory elements enable calculation of the damage *vulnerability* of the structures, people, and environment at risk. The vulnerability component enables estimation of the human, property, and environmental *losses* from different climate change scenarios by integrating biophysical information on climate change and other stressors with socioeconomic and environmental information.[54] These assessments typically involve evaluation of exposure, sensitivity, and adaptive capacity for current and projected conditions. Quantitative indicators are increasingly used to diagnose potential vulnerabilities under different scenarios of socioeconomic and environmental change[55] and to identify priorities and readiness for adaptation investments.[56] In the case of a coastal residential development, the design of the facility will influence its ability to reduce damage from hurricanes and injuries or fatalities from hurricane storm surge and sea level rise. Decisions may involve determining whether to elevate the facility so it is above ten feet, how much this adaptation measure will cost, and the reduction in the impact of future hurricanes on damage to the facility and on the residents in the building, as a function of different climate change scenarios.

Risk Perception in Climate Change Decision-Making

The concept of risk perception refers to individual, group, and public views and attitudes toward risks, where risks are understood as threats to life, health and safety, the environment, economic well-being, and other things of value. Risk perception encompasses perspectives on various dimensions of risks, including their severity, scope, incidence, timing, controllability, and origins or causes. The knowledge base regarding risk perception includes research in psychology, social psychology, sociology, decision science, and health-related disciplines (see "Factors Affecting Attitudes Toward Risk").

As noted in "Factors Affecting Attitudes Towards Risk," many factors influence risk. Social scientists and psychologists have studied people's concerns about climate change risks and found that many individuals view hazards for which they have little personal knowledge and experience as highly risky.[72] On the other hand, seeing climate change as a simple and gradual change from current to future values on variables such as average temperatures and precipitation may make it seem controllable.[73]

The effects of risk perception on decision-making have also been studied extensively and support a number of conclusions that need to be considered in decision support processes. The decision process of non-experts with respect to low-probability, high-consequence events differs from that of experts.[74] Non-experts tend to focus on short time horizons, seeking to recoup investments over a short period of time, in which case future impacts from climate change are not given much weight in actions taken today. This is a principal reason why there is a lack of interest in undertaking adaptation measures with upfront investments costs where the benefits accrue over

FACTORS AFFECTING ATTITUDES TOWARDS RISK

Extensive literature indicates that a range of factors shape risk perceptions. For example, psychological risk dimensions have been shown to influence people's perceptions of health and safety risks across numerous studies in multiple countries.[57] People also often use common "mental shortcuts," such as availability and representativeness, to organize a wide range of experiences and information.[58] How risks are framed is also important – for example, as numbers versus percentages and worst-case formulations versus more probable events.[59] Recent research has emphasized the role of emotions in the perception of risk.[60,61]

Other factors explored in the literature center on perceived characteristics of specific risks, such as whether the risks are familiar or unfamiliar; prosaic or perceived as catastrophic ("dread" risks); reversible or irreversible; and voluntarily assumed or imposed.[62] Risk perception is also influenced by the social characteristics of individuals and groups, including gender, race, and socioeconomic status.[61,63] Experiences with specific risks are also important, such as being affected by a hazard (for discussions, see Figner and Weber 2011;[64] NRC 2006;[64] Tierney et al. 2001[66]) and experiencing near misses or false alarms.[67]

Risk perceptions do not exist as isolated perceptions, but are linked to other individual and group perceptions and beliefs and to psychosocial factors, such as fatalism, locus of control (the degree to which people feel they have control over their own lives and outcomes), and religiosity,[65,66] as well as to more general worldviews. Research has also focused on people's mental models regarding the causality and effects of different risks.[68]

Still other research focuses on how risk information is mediated through organizations and institutions and how mediation processes influence individual and group risk perceptions. For example, the "social amplification of risk" framework stresses the importance of the media and other institutions in shaping risk perceptions, such as by making risks seem more or less threatening.[69] Perceptions are also related to people's trust in the institutions that manage risk; loss of trust can lead to feelings of disloyalty regarding organizations that produce risks and institutions charged with managing them, which can in turn amplify individual and public concerns.[70] Additionally, perceptions are linked to individual and group attitudes concerning sources of risk information, including official and media sources. These factors include the perceived legitimacy, credibility, believability, and consistency of information sources.[71]

a long period of time.[75] In the context of the coastal residential development, elevating the structure will reduce expected damages from hurricanes, resulting in smaller annual insurance premiums. Long-term loans that spread the costs of this action over time can make the option financially attractive, if the savings on the insurance premiums outweigh the costs of the loan payments.

There is also a tendency for decision-makers to treat a low-probability event as if it had no chance of occurring because it is below their threshold level of concern (such as a 1 in 100 chance of a damaging disaster occurring next year). As shown by empirical research, stretching the time horizon over which information is communicated can make a difference in risk perception.[76] In the case of the coastal residential development, community leaders may pay more attention to the need for adaptation measures if the likelihood of inundation by a future hurricane is presented over a 25-year or 50-year horizon (for example, the facility may flood 5 times in 25 years) rather than as a risk on annual basis (for example, there is a 20% chance of flooding in any given year).

Risk Management Strategies

In general, an effective response to the current and future risks from climate variability and change will require a portfolio of different types of actions, ranging from those intended to manage, reduce, and transfer risk to those intended to provide additional information on risks and the effectiveness of various actions for addressing it (see "Value of Information"). For instance, in the coastal community example, decision-makers might better *manage* risk through changes in building codes intended to reduce the impact of flooding on structures, might *share* risk by appropriate adjustments in flood insurance rates, and might *reduce* risk via land-use policies that shift development towards higher ground and via participating in and advocating for greenhouse gas emission reduction policies that may reduce future levels of sea level rise.

To facilitate these strategies given the uncertainty associated with the likelihood and consequences of climate change, "robust decision-making" may be a useful tool for evaluating alternative options and risk management strategies. One study reviews the application of a range of decision-making approaches to assessing options for mitigating or adapting to the impacts of climate change.[77] In the context of the coastal residential development, the choice of adaptation measures to reduce the likelihood of future water-related damage may require using such an approach. To illustrate, consider two adaptation measures, elevating a building and flood-proofing it, to reduce the chances of severe water damage from hurricane storm surge coupled with sea level rise. Measure 1 (elevation) may perform extremely well based on specific estimates of the likelihood of different climate change conditions that will affect storm surge and sea level rise, but it may perform poorly if those estimates turn out to be mistaken. Measure 2 (flood-proofing) may have a lower expected benefit than elevation but much less variance in its outcomes and thus be the preferred choice of the community.[49]

Turning to risk management strategies, public agencies, private firms, and individuals have incentives, information, and options available to adapt to emerging conditions due to climate change. These options may include ensuring continuity of service or fulfillment of agency responsibilities, addressing procurement or supply chain issues, preserving market share, or holding the line on agency or private-sector production costs. Commercially available mechanisms such as insurance can also play a role in providing protection against losses due to climate change.[78] However, insurers may be unwilling to provide coverage against such losses due to the uncertainty of the risks and lack of clarity on the liability issues associated with global climate change.[79] In these cases, public sector involvement through public education programs, economic incentives (subsidies and fines), and regulations and standards may be relevant options. Criteria for evaluating risk management strategies can include impacts on resource allocation, equity and distributional impacts, ease of implementation, and justification.

VALUE OF INFORMATION

A frequently asked question when making complex decisions is: "When does the addition of more information contribute to decision-making so that the benefit of obtaining this information exceeds the expense of collecting, processing, or waiting for it?" In a decision context, the value of information often is defined as the expected additional benefit from additional information, relative to what could be expected without that information.[80,81] Even though decision-makers often cite a lack of information as a rationale for not making timely decisions, delaying a decision to obtain more information does not always lead to different or better decisions.[82,83]

Implementation, Continued Monitoring, and Evaluation of Decisions

The implementation phase of a well-structured decision process involves an ongoing cycle of setting goals, taking action, learning from experience, and monitoring to evaluate the consequences of undertaking specific actions, as shown on the left-hand side of Figure 26.3. This cycle offers the potential for policy and outcome improvement through time. Ongoing evaluation can focus on how the system responds to the decision, leading to better future decisions, as well as on how different stakeholders respond, resulting in improvements in future decision-making processes. The need for social and technical learning to inform decision-making is likely to increase in the face of pressures on social and resource systems from climate change. However, the relative effectiveness of monitoring and assessment in producing social and technical learning depends on the nature of the problem, the amount and kind of uncertainty and risk associated with climate change, and the design of the monitoring and evaluation efforts.

Examples of Decision Support Tools and Methods

While decision frameworks vary in their details, they generally incorporate most or all of the steps outlined above. To support decision-making across these steps, various technical tools and methods, developed in both the public and private sectors, can assist stakeholders and decision-makers in meeting their objectives and clarify where there are value differences or varying tolerances for risk and uncertainty. Many of these tools and methods are applicable throughout the decision-making process, from framing through assessment of options through evaluation of outcomes. Several of the tools and methods – data management systems and scientific assessments – help to expand the relevant information and provide a means of managing large amounts of data. Three other tools described below – comparative tradeoff methods, scenario planning, and integrated assessment models – are particularly useful in assisting stakeholders and decision-makers in identifying and evaluating different options for managing risks associated with climate change. The following discussion describes these approaches; examples are provided in "Example Decision Support Tools."

EXAMPLE DECISION SUPPORT TOOLS

Many decision support tools apply climate science and other information to specific decisions and issues; several online clearinghouses describe these tools and provide case studies of their use (for example, CAKE 2012;[39] CCSP 2005;[84] NatureServe 2012[85]). Typically, these applications integrate observed or modeled data on climate and a resource or system to enable users to evaluate the potential consequences of options for management, investment, and other decisions. These tools apply to many types of decisions; examples of decisions and references for further information are provided in Table 26.2.

Table 26.2. Examples of Decisions and Tools Used

Topic	Example Decision(s)	Further Information and Case Studies
Water resources	Making water supply decisions in the context of changes in precipitation, increased temperatures, and changes in water quality, quantity, and water use	Means et al. 2010;[86] International Upper Great Lakes Study 2012;[24] State of Washington 2012;[87] "Denver Water Case Study" (below); Ch. 3: Water
Infrastructure	Designing and locating energy or transportation facilities in the coastal zone to limit the impacts of sea level rise	Ch. 11: Urban; Ch. 10: Energy, Water, and Land
Ecosystems and biodiversity	Managing carbon capture and storage, fire, invasive species, ecosystems, and ecosystem services	Byrd et al. 2011;[88] Labiosa et al. 2009;[89] USGS 2012a, 2012b, 2012c;[90,91] Figure 26.5
Human health	Providing public health warnings in response to ecosystem changes or degradation, air quality, or temperature issues	Ch. 9: Human Health
Regional climate change response planning	Develop plans to reduce emissions of greenhouse gases in multiple economic sectors within a state	"Washington State's Climate Action Team" (below)

Continued

EXAMPLE DECISION SUPPORT TOOLS (CONTINUED)

Many available and widely applied decision-making tools can be used to support management in response to climate extremes or seasonal fluctuations. Development of decision support resources focused on decadal or multi-decadal investment decisions is in a relatively early stage but is evolving rapidly and shared through the types of clearinghouses discussed above.

Land-use Planning Tool for the Upper Santa Cruz Watershed

▼ General Data
☐ Binational Features
☑ Hydrology
☑ Santa Cruz Watershed
☐ Population Density
▼ SWAT Results
○ None
● 85606 Evapotranspiration
○ 85606 Percolation
○ 85606 Sediment Yield
○ 85606 Surface Runoff
▼ Land Use/Land Cover
○ Existing ○ Future ● None
▼ Base Imagery
○ None
○ The National Map
○ The National Map Imagery

Figure 26.5. The Santa Cruz Watershed Ecosystem Portfolio Model is a regional land-use planning tool that integrates ecological, economic, and social information and values relevant to decision-makers and stakeholders. The tool is a map-based set of evaluation tools for planners and stakeholders, and is meant to help in balancing disparate interests within a regional context. Projections for climate change can be added to tools such as this one and used to simulate impacts of climate change and generate scenarios of climate change sensitivity; such an application is under development for this tool (Figure source: USGS 2012[90]).

Valuing the Effects of Different Decisions

Understanding costs and benefits of different decisions requires understanding people's preferences and developing ways to measure outcomes of those decisions relative to preferences. This "valuation" process is used to help rank alternative actions, illuminate tradeoffs, and enlighten public discourse.[31] In the context of climate change, the process of measuring the economic values or non-monetary benefits of different outcomes involves managers, scientists, and stakeholders and a set of methods to help decision-makers evaluate the consequences of climate change decisions.[92] Although values are defined differently by different individuals and groups and can involve different metrics – for example, monetary values and non-monetary benefit measures[93] – in all cases, valuation is used to assess the relative importance to the public or specific stakeholders of different impacts. Such valuation assessments can be used as inputs into iterative adaptive risk management assessments (which has advantages in a climate context because of its ability to address uncertainty) or more traditional cost-benefit analyses, if appropriate.

Some impacts ultimately are reflected in changes in the value of activities within the marketplace and in dollars[94] – for example, the impacts of increased temperatures on commercial crop yields.[95] Other evaluations use non-monetary benefit measures such as biodiversity measures[96] or soil conservation and water services.[97]

Valuation methods can provide input to a range of decisions, including cost-benefit analysis of new or existing regulations[98] or government projects;[99] assessing the implications of land-use changes;[100] transportation investments and other planning efforts;[101,102] developing metrics for ecosystem services; and stakeholder and conflict resolution processes.[103]

Comparative Tradeoff Methods

Once their consequences are valued or otherwise described, alternative options are often compared against the objectives or decision criteria. In such cases, approaches such as listing the pros and cons,[104] cost-benefit analysis,[105] multi-criteria methods,[80] or robust decision methods[106] can be useful. Multi-criteria methods provide a way to compare options by considering the positive and negative consequences for each of the objectives without having to choose a single valuation method for all the attributes important to decision-makers.[31] This approach allows for consequences to be evaluated using criteria most relevant for a given objective.[107] The options can then be compared directly by considering the relative importance of each objective for the particular decision.

Integrated Assessment Models

Integrated Assessment Models are tools for modeling interactions across climate, environmental, and socioeconomic systems.[108] In particular, integrated assessment models can be used to provide information that informs tradeoffs analyses, often by simulating the potential consequences of alternative decisions. Integrated assessment models typically include representations of climate, economics, energy, and other technology systems, as well as demographic trends and other factors that can be used in scenario development and uncertainty quantification.[109] They are useful in national and global policy decisions about emissions targets, timetables, and the implications of different technologies for emissions management.[110] These models are now being extended to additional domains such as water resources and ecosystem services to inform a broader range of tradeoff analyses and to finer resolutions to support regional decision-making.[111]

Scenarios and Scenario Planning

Scenarios are depictions of possible futures or plausible conditions given a set of assumptions; they are not predictions. Scenarios enable decision makers to consider uncertainties in future conditions and explore how alternate decisions could shape the futures or perform under uncertainty. One approach to building scenarios begins with identifying any changes over time that might occur in climate and socioeconomic factors (for example, population growth and changes in water availability), and then using these projections to help decision-makers rank the desirability of alternative decision options to respond to these changes.[112] This works well when decision-makers agree on the definition of the problem and scientific evidence.[53,113] A second approach is widely used in robust decision-making and decision-scaling approaches. It begins with a specific decision under consideration by a specific community of users and then poses questions relevant to these decisions (for example, "how can we build a vibrant economy in our community in light of uncertainty about population growth and water supply?") to organize information about future climate and socioeconomic conditions (for example, Robinson 1988[114]).

Scenario planning often combines quantitative science-based scenarios with participatory "visioning" processes used by communities and organizations to explore desired futures.[115] It can also facilitate participatory learning and development of a common understanding of problems or decisions. There are many different approaches, from a single workshop that uses primarily qualitative approaches to more complex exercises that integrate qualitative and quantitative methods with visualization and/or simulation techniques over multiple workshops or meetings. Common elements include scoping and problem definition; group development of qualitative (and, optionally, quantitative) scenarios and analyses that explore interactions of key driving forces, uncertainties, and decision options.

Scenario planning has been useful for water managers such as Denver Water, which has also used "robust decision-making" to assess policies that perform well across a wide range of future conditions, in the face of uncertainty and unknown probabilities (see "Denver Water Case Study"). Other examples of the use of scenario planning include:

- National Park Service, to consider potential climate change impacts and identify adaptation needs and priorities in several parks or regions[116]
- California State Coastal Conservancy, to plan tidal marsh restoration and planning in the San Francisco estuary in the face of climate change and sea level rise[117]
- Urban Ecology Research Lab at the University of Washington, for planning adaptation to preserve ecosystem services in the Snohomish Basin[118]
- A group of agencies and organizations considering the impacts of climate change on ecosystems in the Florida Everglades[119]

The National Climate Assessment has developed and used a number of different types of scenarios and approaches in preparation of this report (see Appendix 5: Scenarios and models).[120]