Climate Change Impacts in the United States

CHAPTER 25
COASTAL ZONE DEVELOPMENT AND ECOSYSTEMS

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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.**

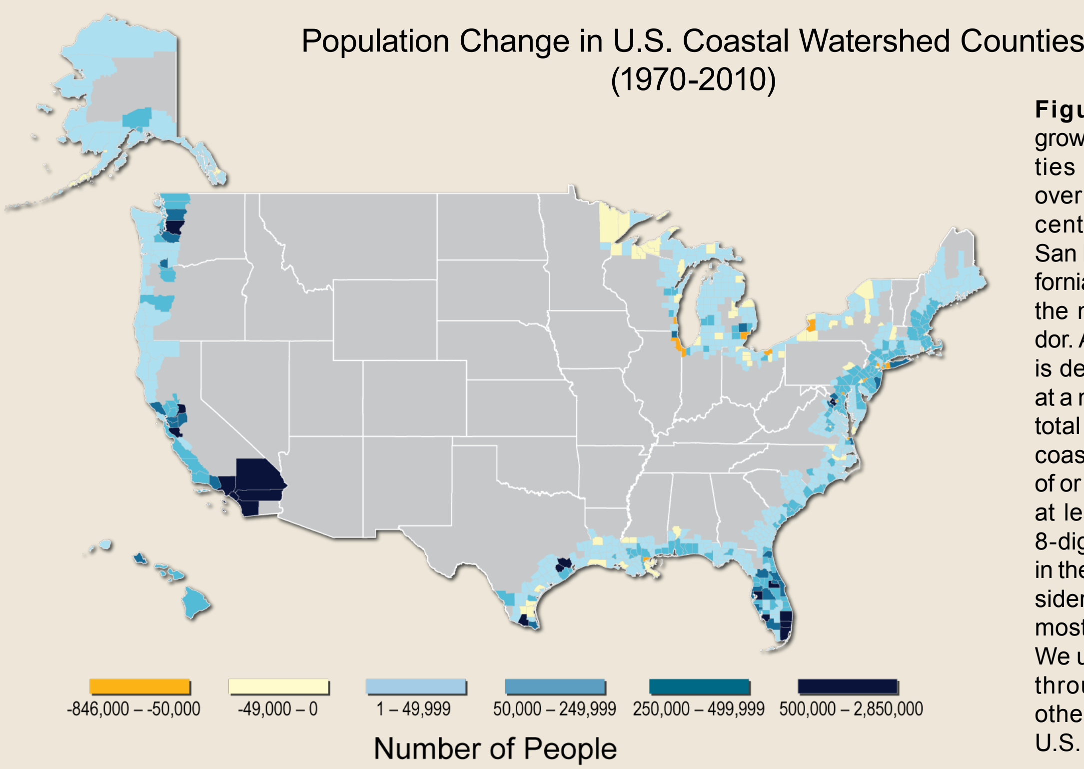


Figure 25.1. U.S. population growth in coastal watershed counties has been most significant over the past 40 years in urban centers such as Puget Sound, San Francisco Bay, southern California, Houston, South Florida and the northeast metropolitan corridor. A coastal watershed county is defined as one 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]

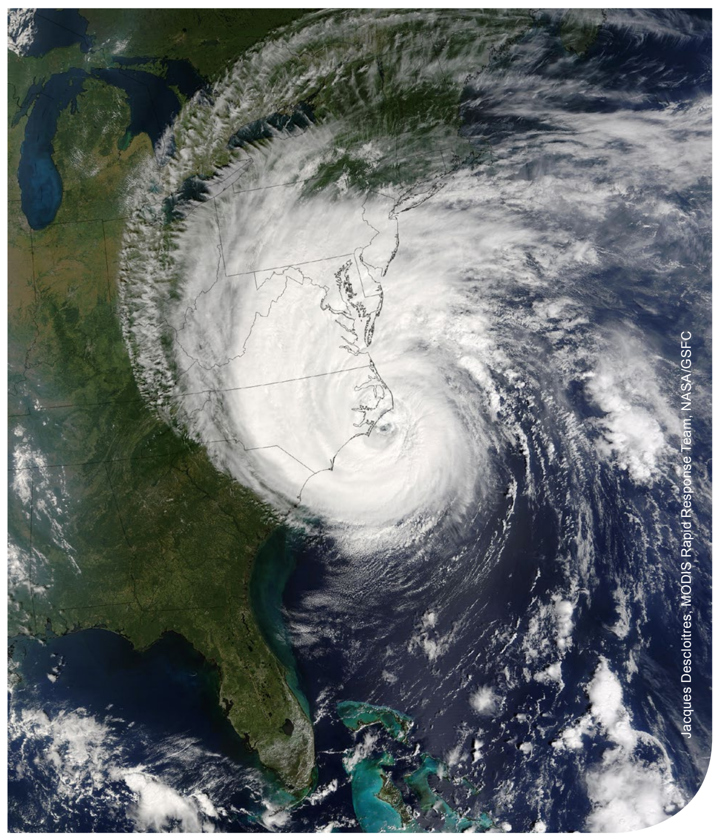
- Rates of sea level rise are not uniform along U.S. coasts[20,21] and can be exacerbated locally by land subsidence or reduced by uplift.[22,23] Along the shorelines of the Great Lakes, lake level changes are uncertain (Ch. 18: Midwest), but erosion and sediment migration will be exacerbated by increased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



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Projected Sea Level Rise and Flooding by 2050

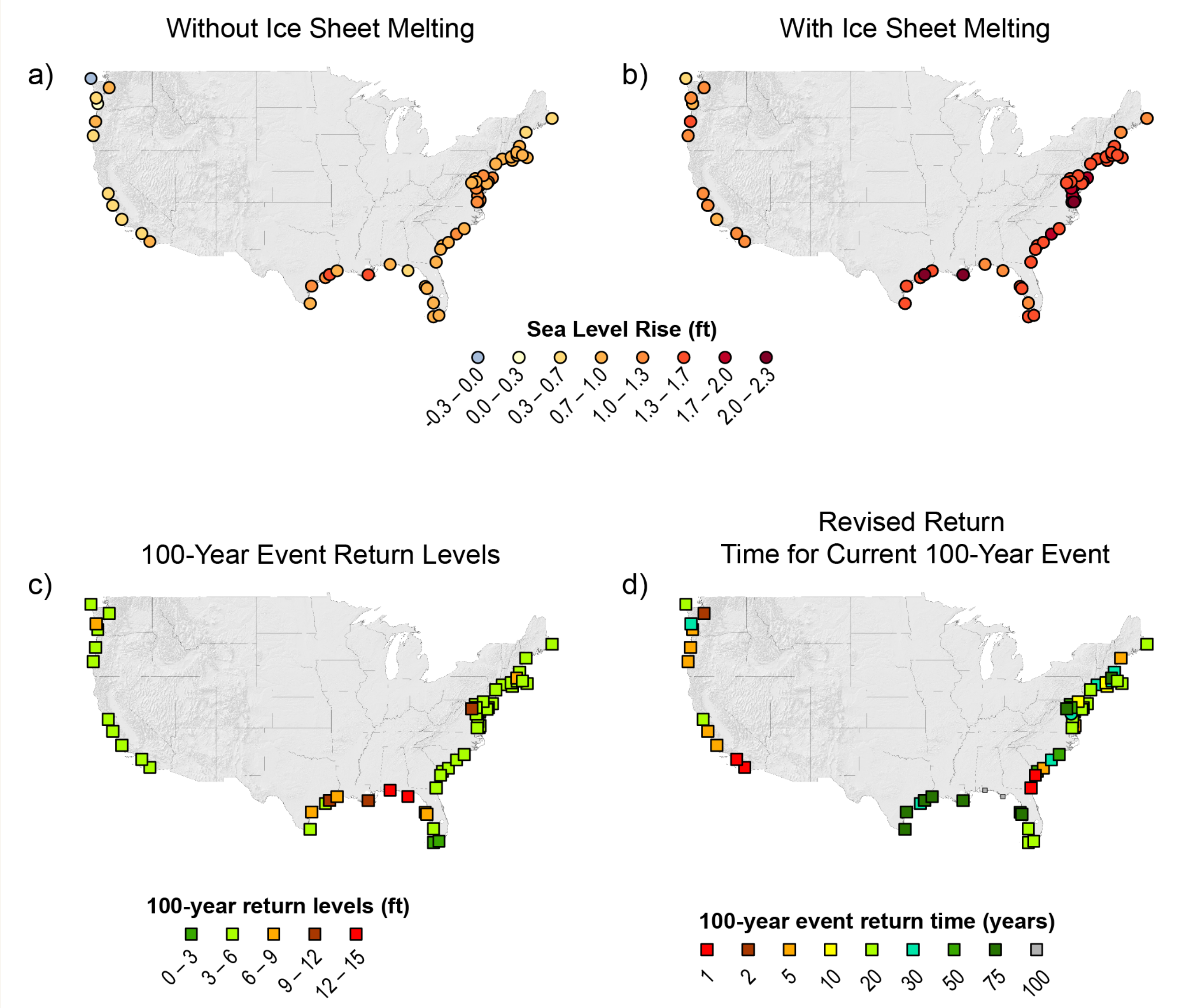

Figure 25.3. The amount of sea level rise (SLR) by 2050 will vary along different stretches of the U.S. coastline and under different SLR scenarios, mostly due to land subsidence or uplift (Ch.2: Our Changing Climate).[16] The panels show feet of sea level above 1992 levels at different tide gauge stations 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).

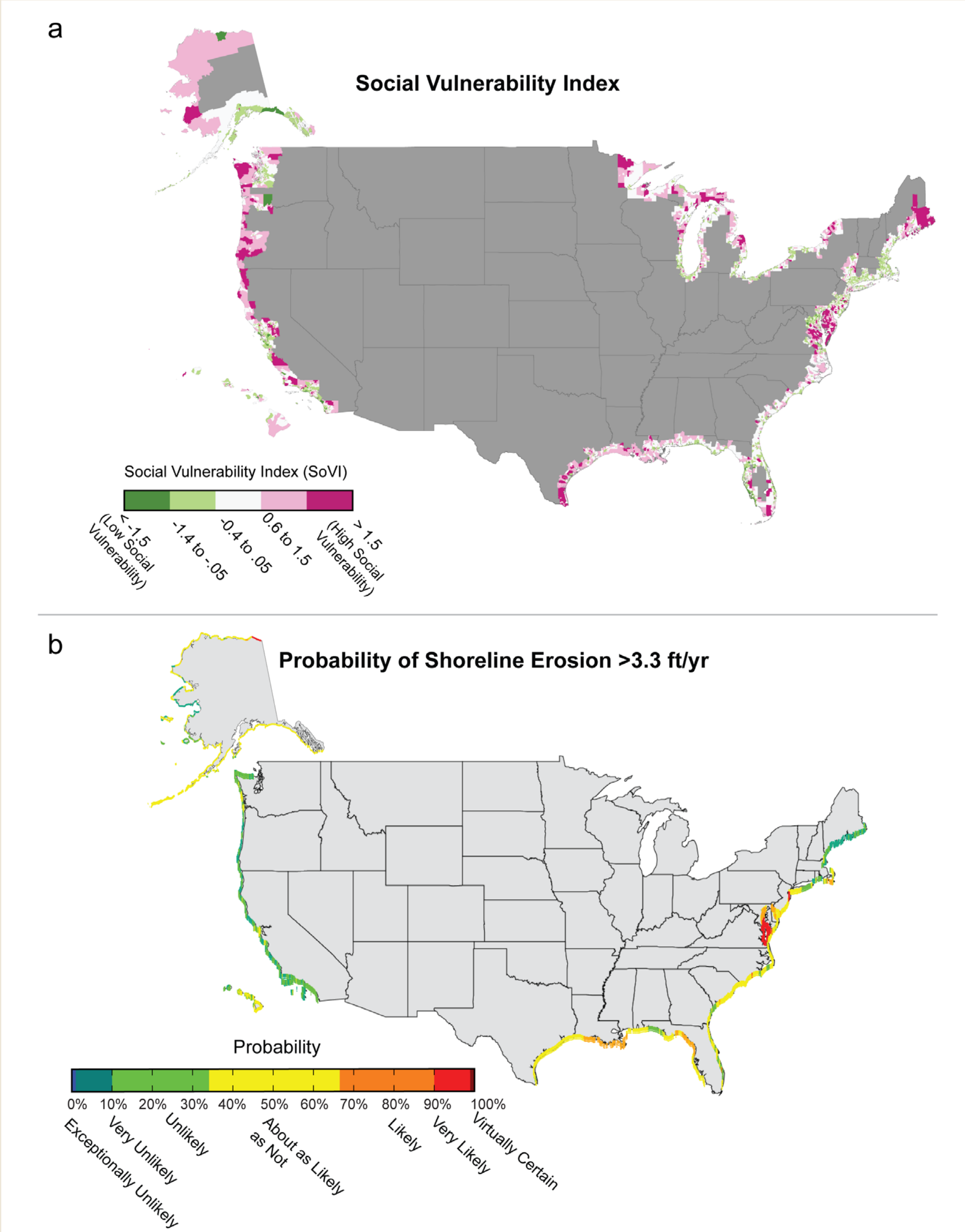

Figure 25.4. (a) Social Vulnerability, (b) Probability of Shoreline Erosion

(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]

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

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]


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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

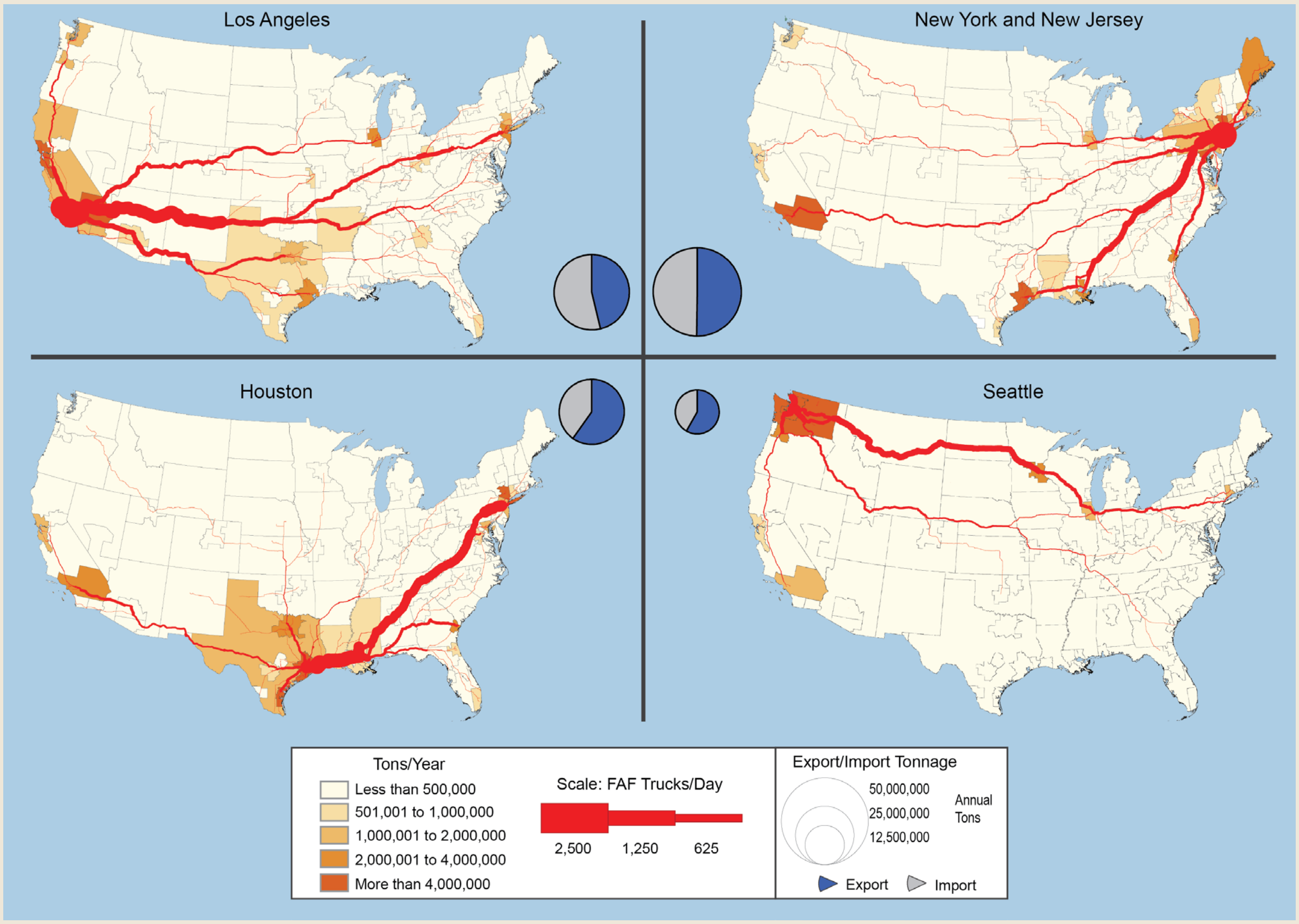

Figure 25.7. Ports are deeply interconnected with inland areas through the goods imported and exported each year. Climate change impacts on ports can thus have far-reaching implications for the nation's economy. These maps show the exports and imports in 2010 (in tons/year) and freight flows (in trucks 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

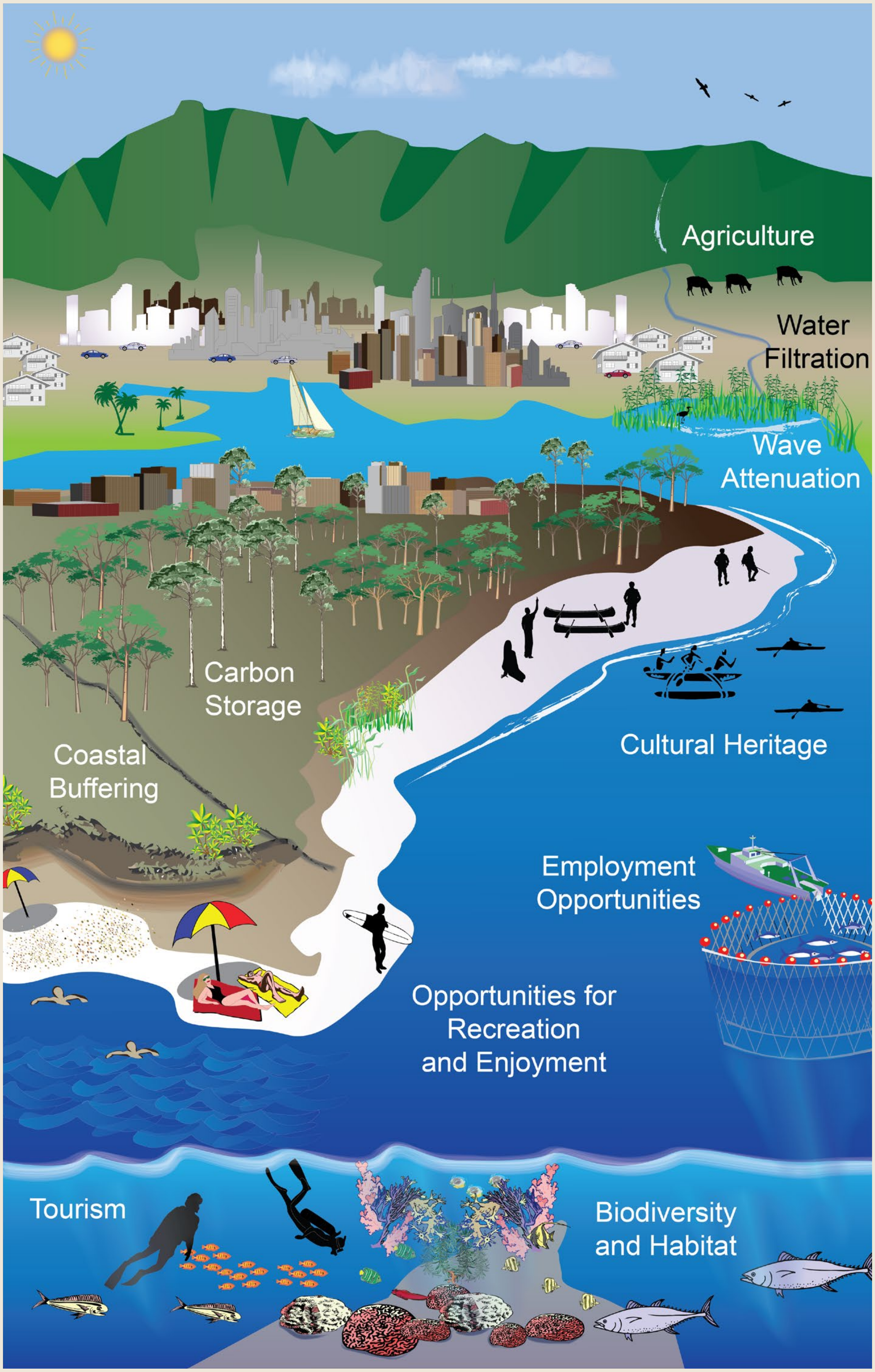

Figure 25.8. Coastal ecosystems provide a suite of valuable benefits (ecosystem services) on which humans depend for food, economic activities, inspiration, and enjoyment. This schematic illustrates many of these services situated in a Pacific or Caribbean island setting, but many of them can also be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

Projected Land Loss from Sea Level Rise in Coastal Louisiana

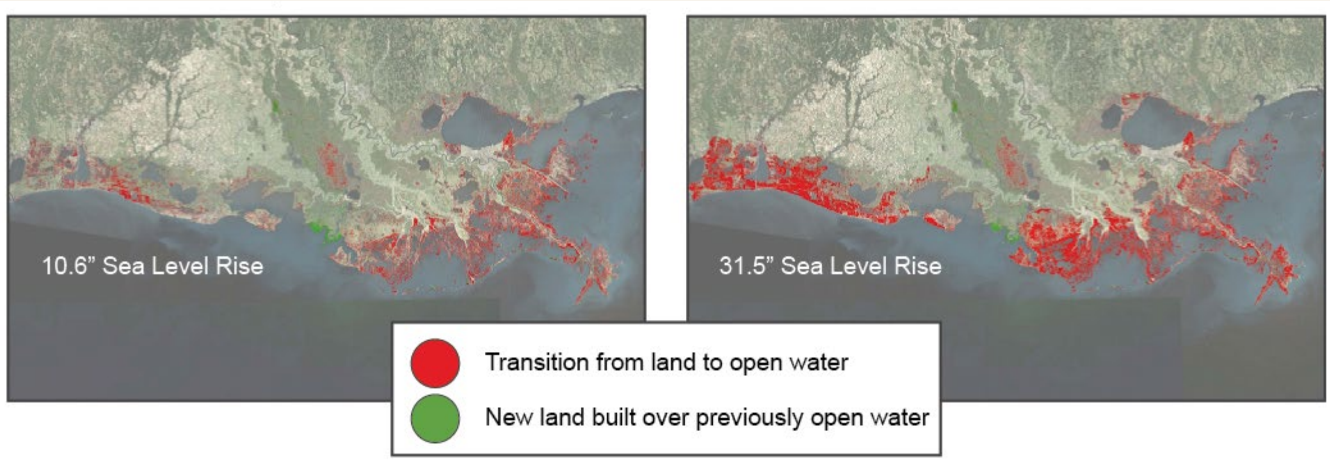

Figure 25.9. These maps show expected future land change in coastal Louisiana under two different sea level rise scenarios without protection or restoration actions. Red indicates a transition from land (either wetlands or barrier islands) to open water. Green indicates new land built over previously 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]

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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[144,153,163,164] 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.