Fifth National Climate Assessment: Chapter 9

Coastal Effects

Chapter 9. Coastal Effects

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Introduction

Our Nation's coasts support industries, commerce, communities, cultures, traditions, and recreation while also providing iconic landscapes and diverse ecosystem services. Observed sea level rise (SLR) and changes in the frequency and intensity of extreme storms, coupled with changes in land use and land cover that can magnify flood risk, have a significant and demonstrable negative impact on people living and working along the coast. Impacts are expected to worsen in the coming decades as SLR continues to accelerate. Observed and projected trends vary along our Nation's coasts (KM 9.1); therefore, consideration of local and regional trends is important when evaluating impacts (KM 9.2) and adaptation (KM 9.3).[1,2]

The number of people living in coastal areas at risk of SLR inundation (permanent inundation by daily high tides) or surge- or wave-driven flooding (temporary flooding driven by storm events) is in continual flux.[3] Between 1990 and 2020, the number of people living below high tide elevations plus 3.3 feet (1 m) of SLR increased by about 14%–18% to 2.2 million, consistent with continued growth and development.[3] Human modifications to coastal landscapes, such as seawalls and levees, can exacerbate flood risks and erosion[4,5,6] and affect the ability of coastal ecosystems to naturally adapt.[7]

Weather-related disasters continue to increase across US coasts (KMs 2.2, 3.5), with SLR amplifying the flooding and impacts to coastal communities. Between 2000 and 2021, 38 tropical cyclones caused over $1 trillion in losses (in 2022 dollars) and 6,200 deaths.[8] Federal, state, and local actions to reduce these losses are underway, yet progress is slow, and substantial wealth inequities, systemically sustained gaps in resources and capacity, and past injustices continue to disparately impact frontline communities, including Tribes and Indigenous Peoples, rural communities, and lower-income populations (KM 20.1). It is difficult to disentangle the vulnerabilities and consequences associated with climate change from histories and racial inequities that shaped social–environmental systems that exist today.[9] However, climate adaptation efforts that embed equity considerations, support environmental justice, and center the local communities may have the best chance of success, using adaptation strategies that range from protection-in-place to planned relocation.[10,11,12]

Increasing weather-related disasters and SLR also increase impacts on coastal ecosystems and natural shorelines, resulting in gradual (e.g., inland migration of wetlands) to abrupt (e.g., storm erosion of dunes and bluffs) changes that increase flood risks and damages to coastal communities and major infrastructure (e.g., highways, railroads, ports, airports, and other critical infrastructure; KM 12.2). The combined impacts will require fundamental reimagining of the coast. Protection structures can reduce risks on an interim basis; however, many communities and the infrastructure they depend on will need gradual relocation to higher ground, which can provide space for coastal ecosystems to adapt (KM 8.1). In some locations, coordinated and deliberate coastal relocation, implemented equitably, will be essential to reduce future risk to lives and livelihoods (KM 31.1).[13,14,15]

Key Message 9.1

Coastal Hazards Are Increasing Due to Accelerating Sea Level Rise and Changing Storm Patterns

The severity and risks of coastal hazards across the Nation are increasing (*very likely*, *high confidence*), driven by accelerating sea level rise and changing storm patterns, resulting in increased flooding, erosion, and rising groundwater tables. Over the next 30 years (2020–2050), coastal sea levels along the contiguous US coasts are expected to rise about 11 inches (28 cm), or as much as the observed rise over the last 100 years (*likely*, *high confidence*). In response, coastal flooding will occur 5–10 times more often by 2050 than 2020 in most locations, with damaging flooding occurring as often as disruptive "high tide flooding" does now if action is not taken (*very likely*, *high confidence*).

Accelerating Sea Level Rise

Global mean sea level is rising at an accelerated rate, with the average rate of about 0.05 ± 0.01 inches per year (1.2 ± 0.2 mm per year) over the pre-satellite era (1901–1990)[16] nearly tripling to 0.13 ± 0.02 inches per year (3.4 ± 0.4 mm per year) during the 30-year satellite era (1993–2022)[17] due to thermal expansion from warming waters and the growing contribution from melting glaciers and ice sheets.[18] Global SLR rates further accelerated to 0.17 inches per year (4.4 mm per year) over the last decade (2013–2022), although this acceleration may include components of natural variability due to the short time period.[19]

To help communities plan for an uncertain future, the US Interagency Sea Level Rise Task Force established five future SLR scenarios that span the range of plausible SLR amounts by 2100 using the latest scientific consensus from the Intergovernmental Panel on Climate Change (IPCC) and other scientific bodies.[2] The five SLR scenarios represent the range on a global scale, with projected SLR amounts in 2100 and scenarios defined as follows:

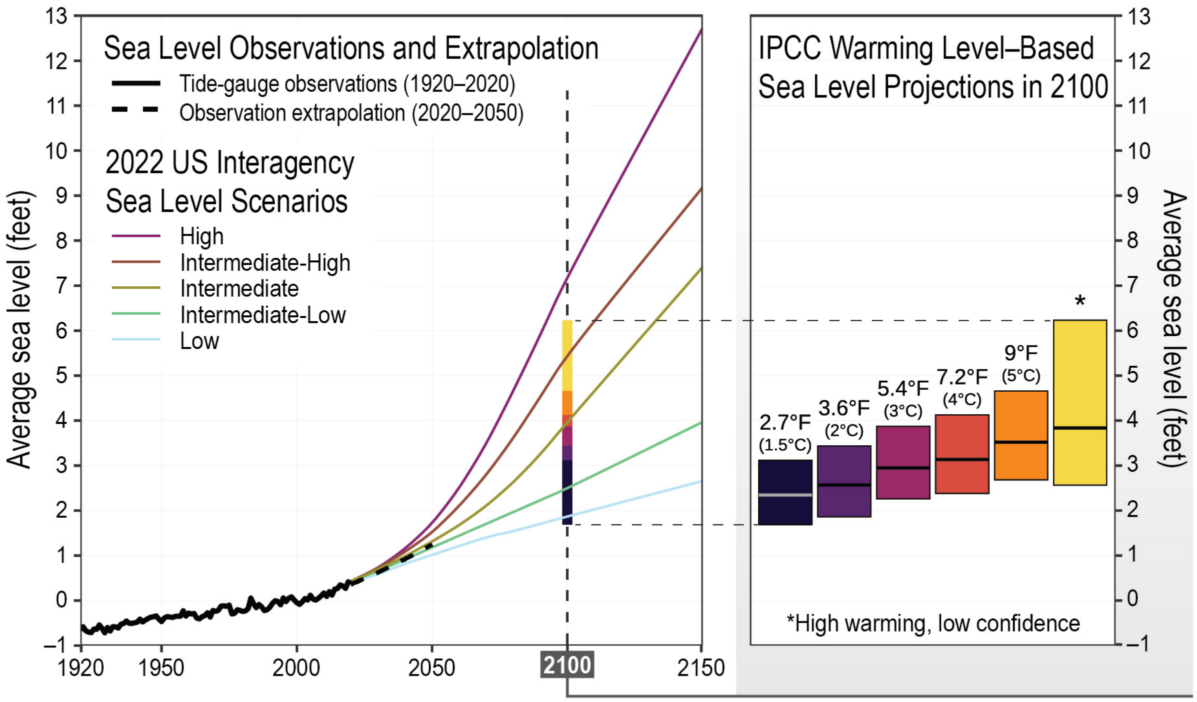
- Low, 1 foot (0.3 m) rise in global mean sea level relative to year 2000 baseline
- Intermediate-Low, 1.6 feet (0.5 m)
- Intermediate, 3.3 feet (1.0 m)
- Intermediate-High, 4.9 feet (1.5 m); and
- High, 6.6 feet (2.0 m) (Figure 9.1)

The SLR scenarios are downscaled to local and regional levels, considering future changes in land elevation, ocean heating and circulation, and Earth's gravitation and rotation from melting of land-based ice. They are constructed directly from the IPCC Sixth Assessment Report (AR6) emissions- and temperature-based projections (App. 3.3)[20] but use consistent framing (e.g., Sweet et al. 2017[21]) to support risk reduction planning.

Sea levels are rising along contiguous US coastlines faster than the global average, with about 11 inches (28 cm; *likely* range of 10–12 inches [25–30 cm]) occurring over the last 100 years (1920–2020) and with about half of this rise (5–6 inches [13–15 cm]) occurring in the last 30 years (1990–2020; Figure 9.1).[2] SLR rates vary across different regions. In the last 30 years, the greatest rise is observed along the US western Gulf Coast (about 9 inches [23 cm]), largely due to high rates of land subsidence[22] from subsurface groundwater and fossil fuel withdrawal.[23] About 6 inches (15 cm) of rise is observed along the northeast and southeast

Atlantic and eastern Gulf Coasts. Lower rates of rise are observed along the Hawaiian and US Caribbean island coastlines (4 inches [10 cm]) and the northwest (2 inches [5 cm]) and southwest (3 inches [8 cm]) Pacific coastlines.[2]

Accelerating Relative Sea Level Rise in the Contiguous US



Sea level is projected to continue to increase this century by amounts related to future global warming levels.

Figure 9.1. This figure shows accelerating sea level rise (SLR) trends and SLR scenarios along the contiguous US coastline. It also shows the relationship between projected SLR under different global surface temperature increases in 2100 (KM 2.2). The **left panel** shows observed increasing average sea levels during 1920–2020 (solid black line), an extrapolation out to 2050 based on observed sea levels over 1970–2020 (dashed black line), a range of scenarios describing plausible sea level rise out to 2150 (multicolored lines), and an overlapping stacked bar showing a range of projected changes in 2100 SLR under different levels of global surface temperature increase, based on the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. The **right panel** shows expanded versions of the projections shown in the stacked bar in the left panel. Black lines indicate the median value, the bars show the extent of the *likely* range (17th–83rd percentile) of SLR by 2100, and the associated warming levels are indicated above each bar. The “High warming, low confidence” case (yellow bar) refers to the potential range of rising seas under higher temperatures with rapid ice melt. The lack of overlap in 2100 between the High sea level scenario and the “High warming, low confidence” case in 2100 is not an indication of overestimation but rather a result of how the low-confidence processes are analyzed. Adapted from Sweet et al. 2022.[2]

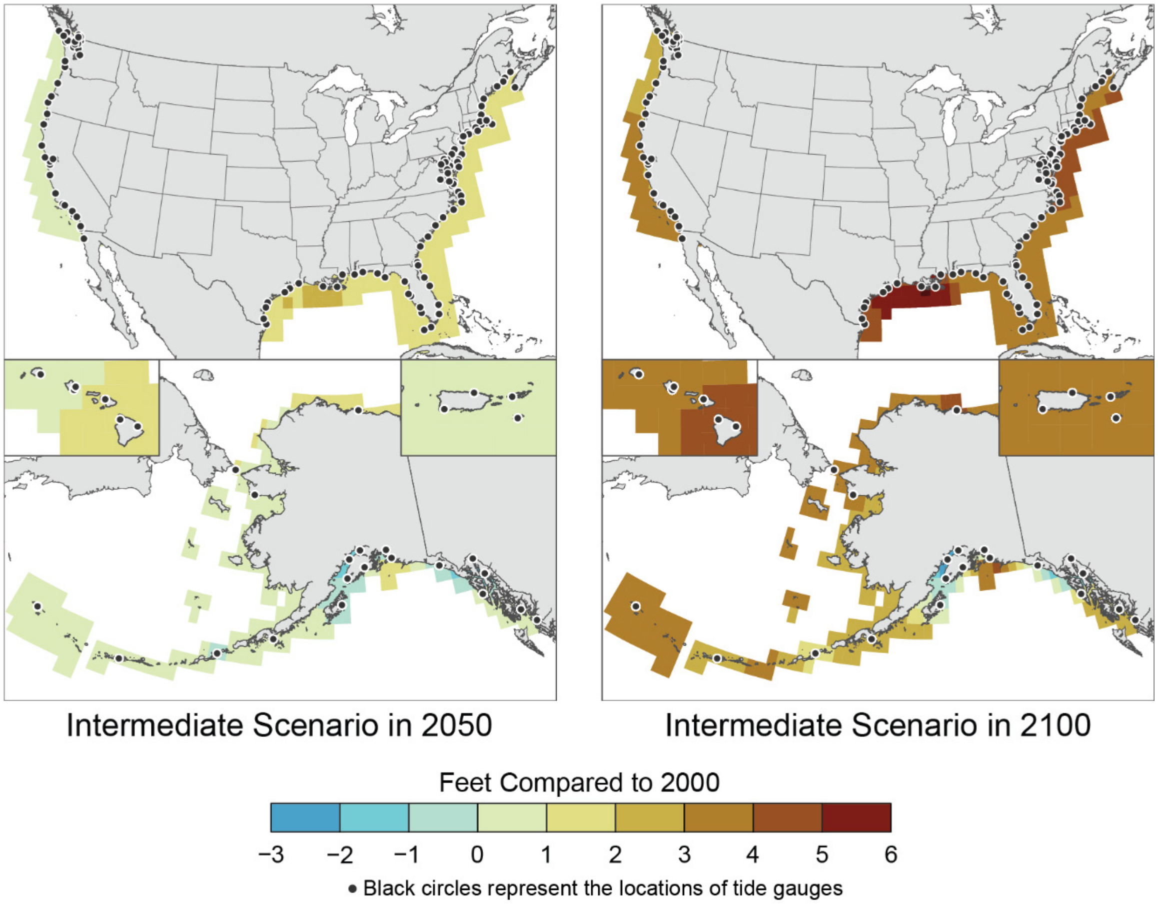
SLR rate suppression and acceleration along the northwest and southwest Pacific coastlines is in part due to oceanographic forcings associated with the El Niño–Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO).[24] Along the Pacific Coast, ENSO and PDO will continue to drive decadal variability in SLR, with rates that are above or below the global average.[24] The current rate remains higher than the global average.[24] Characterizing past (and future) rise for Alaska and the US-Affiliated Pacific Islands is complicated due to tectonic effects that cause both uplift and subsidence. Year-to-year changes associated with natural variability can also change the rates over different analysis periods, such as the 8–12-inch (20–30 cm) variability in sea levels that can occur along the Pacific Coast during different phases of the ENSO.[25,26,27]

Looking toward the future, an 11-inch (28 cm) average rise along the contiguous US coastline is expected by 2050 (relative to 2020, with a *likely* range of 9–13 inches [23–33 cm]; see Table A1.2 in Sweet et al. 2022[2] for 2000 to 2020 offsets) based on an observation-based trajectory of SLR (Figure 9.1). An 11-inch (28 cm) rise by 2050 matches the observed average SLR along the contiguous US coastline over the last 100 years (1920–2020), representing ongoing SLR acceleration that falls between the Intermediate-Low and Intermediate sea level scenarios.[2] By 2050, SLR amounts will continue to vary geographically, with regional differences like those observed in the recent historic record (e.g., 1990–2020). For example, under the Intermediate sea level scenario, which closely aligns with most regional SLR trajectories,[2] SLR is expected to be higher along the Atlantic versus the Pacific Coast and greatest along the western Gulf Coast (Figure 9.2).

Beyond 2050, future global emissions and resultant ocean and atmospheric warming and ice sheet responses will determine future SLR. As of 2021, global temperatures have increased by 2° –2.2°F (1.1°–1.2°C) beyond preindustrial levels (KM 2.1) and are headed for a warming level of about 5.4°F (3°C) by 2100 under the current trajectory,[28] which is consistent with the IPCC AR6 intermediate and high scenarios (SSP2-4.5 and SSP3-7.0). With such warming, it is *likely* that the Intermediate-Low sea level scenario with 2+ feet (0.6+ m) of SLR relative to 2020 levels will be exceeded by 2100, and 3.6+ feet (1.1+ m) will be exceeded by 2150 (App. 3.3; Figure 9.1).[2]

Failing to curb future emissions increases the probability of SLR equivalent to the Intermediate sea level scenario or perhaps even higher, such as the Intermediate-High and High sea level scenarios associated with the IPCC very high scenario (SSP5-8.5) that includes the addition of rapid ice sheet melt or disintegration during this century.[20] The probability of this low-likelihood outcome increases with higher global warming levels.[29] Under the Intermediate to High sea level scenarios, an average SLR of about 3.6–6.9 feet (1.1–2.1 m) along contiguous US coastlines by 2100 and 6.9–12.5 feet (2.1–3.8 m) by 2150 relative to 2020 would occur (Figure 9.1; App. 3.3).[2] Under the Intermediate-High and High sea level scenarios, contributions from the Antarctic ice sheet dominate and reduce overall SLR differences across US regions (KMs 2.1, 2.3).[2] Beyond 2150, global (and US) SLR will continue for millennia due to the long-term effects of warming this century. About 7–33 feet (2–10 meters) of global SLR over the next 2,000 years is *likely* if temperatures warm by 3.6° to 5.4°F (2° to 3°C) above preindustrial levels by 2100, similar to conditions about 125,000 years ago.[20,30]

Projected Sea Level Rise



By 2050 and 2100 under the Intermediate sea level scenario, sea level rise is projected to be higher along the Atlantic versus the Pacific Coast and greatest along the western Gulf Coast.

Figure 9.2. The figure shows relative sea level rise along the US coastlines under the Intermediate sea level scenario of the US Interagency Sea Level Rise Task Force[2] for 2050 (**left**) and 2100 (**right**). Relative sea level rise for the contiguous US is shown on the top, and for Alaska, Hawai'i (left insets), and Puerto Rico (right insets) on the bottom. The black dots along the coastline indicate tide-gauge locations used to characterize past SLR. Characterizing past (and future) SLR for Alaska and the US-Affiliated Pacific Islands is complicated due to tectonic effects that cause both uplift and subsidence. Figure credit: NOAA National Ocean Service.

Increases in Flooding Frequency Will Continue

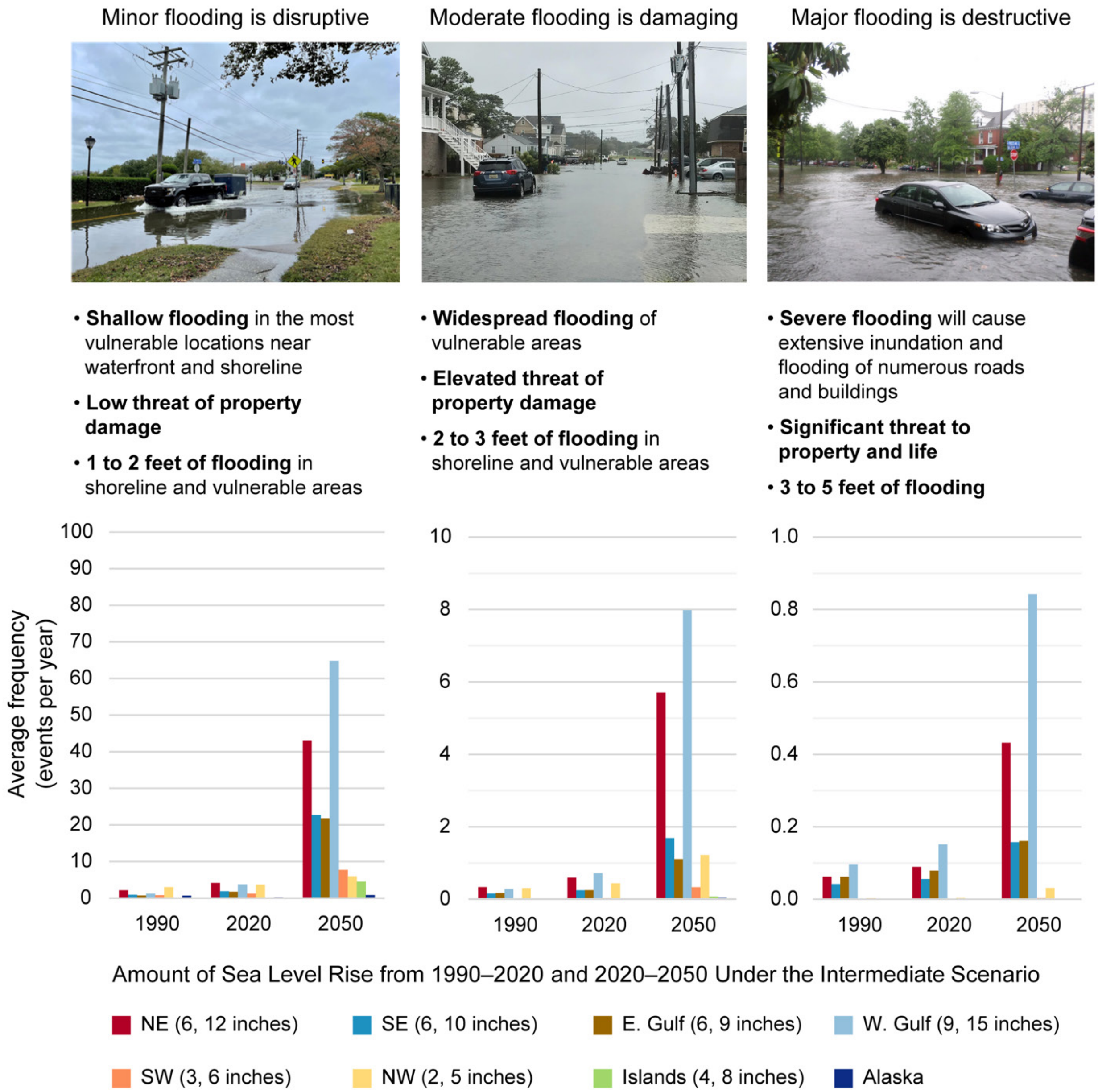
SLR will continue to cause permanent inundation for formerly dry lands and an escalation in the severity (depth, geographic extent, and frequency) of coastal flooding, ranging from powerful storm events to more frequent high tide flooding (HTF). As of 2020, the highest annual frequencies of coastal flooding—defined in a nationally consistent manner as minor (disruptive HTF, about 1.75–2 feet [0.5–0.6 m] above average high tide), moderate (damaging HTF, about 2.75–3 feet [0.8–0.9 m]), and major (destructive HTF, about 4 feet [1.2 m]) impacts[2,31]—are along the northeast Atlantic and western Gulf coastlines (Figure 9.3), due in part to greater exposure to strong storms and wide, shallow continental shelves allowing for higher storm surges.[32]

Annual frequencies of both minor and moderate coastal flooding increased by a factor of 2–3 along most Atlantic and Gulf coastlines between 1990 and 2020 (Figure 9.3). Minor HTF events, which are the most common impact of SLR, occur several times a year with accelerating frequencies (e.g., Sweet et al. 2019,[33] 2020,[34] 2021[35]). A typical HTF event lasts about two days and several high tides.[2] Along the coastlines of

Hawai'i, the US-Affiliated Pacific Islands, and US Caribbean islands, as well as some US Pacific coastlines, SLR is a growing problem. Flood impacts are occurring with much smaller flood heights than those shown in Figure 9.3, including in some cases where water levels are elevated only slightly above high tide.

By 2050 under the Intermediate sea level scenario (Figure 9.1), minor, moderate, and major coastal flood frequencies will all increase by a factor of about 5–10 in many regions relative to 2020 in the absence of adaptation (Figure 9.3). In effect, a flood regime shift would occur; for example, the frequencies of moderate flooding are projected to occur as often as minor, disruptive HTF occurs now (circa 2020). By 2100 under the Intermediate sea level scenario, major flooding would occur almost daily along US coastlines.[2] These increases in flood frequency could be further amplified with higher amounts of SLR, worsening storm conditions, natural climatic variability (e.g., ENSO), or other reasons such as long-term tidal cycles and land subsidence or uplift.[31,36]

US Regional Average Flood Frequencies



Minor, moderate, and major coastal flood frequencies will increase by a factor of about 5–10 in many regions of the US relative to 2020 in the absence of adaptation.

Figure 9.3. (**top**) Descriptions of three coastal flood types—minor (disruptive), moderate (damaging), and major (destructive)—provided by NOAA National Weather Service, reflect today's vulnerabilities within coastal communities. (**bottom**) These graphs show annual average frequencies of minor, moderate, and major flooding by region (multicolored bars). The flood frequencies are based on a set of 187 NOAA tide gauges, with 14 in Hawai'i and the US-Affiliated Pacific Islands, 4 in Puerto Rico, and 4 in the US Virgin Islands (collectively shown as Islands). Note that this figure uses the US regions defined in Sweet et al. (2022),[2] which differ from the NCA5 regions: NE = northeast Atlantic, SE = southeast Atlantic, NW = northwest Pacific, SW = southwest Pacific, E. Gulf = eastern Gulf, W. Gulf = western Gulf. Observations are shown for 1990 and 2020, and projections are shown for 2050 under the Intermediate sea level scenario for all US coastal regions. The amount of SLR for each region during 1990–2020 and 2020–2050 under the Intermediate scenario is provided below the graph. The amount of SLR for Alaska is not shown because Alaska's SLR varies along the shoreline due to both tectonic uplift and subsidence; the SLR values for Alaska are shown on Figure 9.2. The annual average frequencies of minor, moderate, and major flooding are projected to increase more in the next 30 years (2020–2050) than they did in the

past 30 years (1990–2020) regardless of any future worsening of storm events. In some Atlantic and Gulf Coast regions exposed to hurricanes, more severe and catastrophic coastal flood levels are possible and will become more likely as sea levels rise. Figure credit: NOAA National Ocean Service. Photo credits: (left) City of Norfolk Staff Photographer Andrew Cooper; (center and right) Jeff Orrock, NOAA.

Waves, Storminess, and *Landscape Variability Amplify Flood Risk*

Climate-driven changes to coastal water levels, including waves, storm surge, river flows, and landscape changes, are important considerations when planning for future flood risk.[37,38,39] Wave-driven water levels, for example, comprise 25%–90% of extreme coastal water levels along exposed US coastlines.[2,40,41] Across most US coasts, many extreme events are increasing in intensity, frequency, and geographic extent (KM 2.2) because of human-caused climate change (KM 3.1). For example, hurricanes are intensifying more rapidly and decaying more slowly, leading to stronger storms extending farther inland with heavier rainfall and higher storm surges, resulting in less time for communities to prepare (KM 2.2). Climate change is also increasing coastal hazards through changes in the frequency, magnitude, and impacts of compound events (Figure 9.3; Focus on Compound Events).[42,43] In the coastal zone, compound flood events are commonly due to the joint occurrence of heavy precipitation, high river flows, elevated groundwater levels, soil saturation, and elevated ocean water levels.[38,44,45]

Key Message 9.2

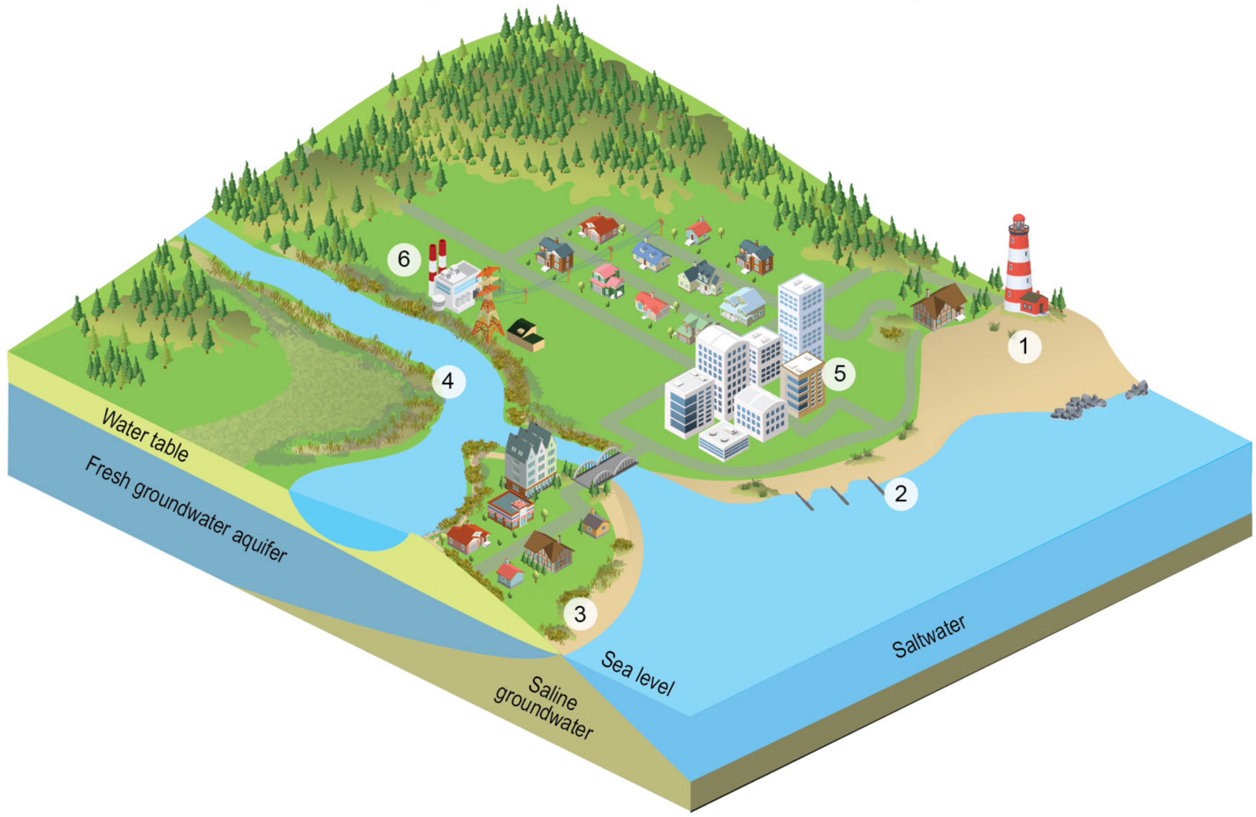
Coastal Impacts on People and Ecosystems Are Increasing Due to Climate Change

Climate change–driven sea level rise, among other factors, is affecting the resilience of coastal ecosystems and communities (*very likely*, *high confidence*). The impacts of climate change and human modifications to coastal landscapes, such as seawalls, levees, and urban development, are both limiting the capacity of coastal ecosystems to adapt naturally and are compounding the loss of coastal ecosystem services (*very likely*, *high confidence*). Proactive strategies are necessary to avoid degraded quality of life in the coastal zone, as the combination of reduced ecosystem services and damage to the built environment from exacerbated coastal hazards increasingly burdens communities, industries, and cultures (*very likely*, *high confidence*).

On the coast, natural landscapes are intertwined with the cultures, economies, and built infrastructure of humans (Figure 9.4). Coastal landscapes (e.g., beaches, dunes, barrier systems, coastal wetlands, and cliffs) evolve across a range of timescales (from minutes to millennia) in response to physical forcing (e.g., tides, waves, storms, climate variability), as well as biological (e.g., vegetation type and density, ecosystem characteristics) and geological (e.g., sediment flows, tectonics, substrate composition) controls.[46] Climate change is exacerbating coastal hazards, with rising seas and more intense storms leading to increases in both flood risks and shoreline change and erosion (KM 9.1).[47,48,49,50]

Coastal communities face heatwaves, heavy rainfall, landslides, compound flooding, and other climate hazards that are not unique to coastal environments.[14] The health, function, and productivity of coastal ecosystems are also being degraded by stressors from human actions (e.g., development, dredging, wetland infill, sediment diversions). Combined, these threats jeopardize attachment to place,[51] economies, and safety (Figure 9.5).[52,53] Understanding the interactions and interconnections between hazards (KM 9.1), communities, and coastal ecosystems is necessary for taking informed action to mitigate and adapt to climate change (KM 9.3).

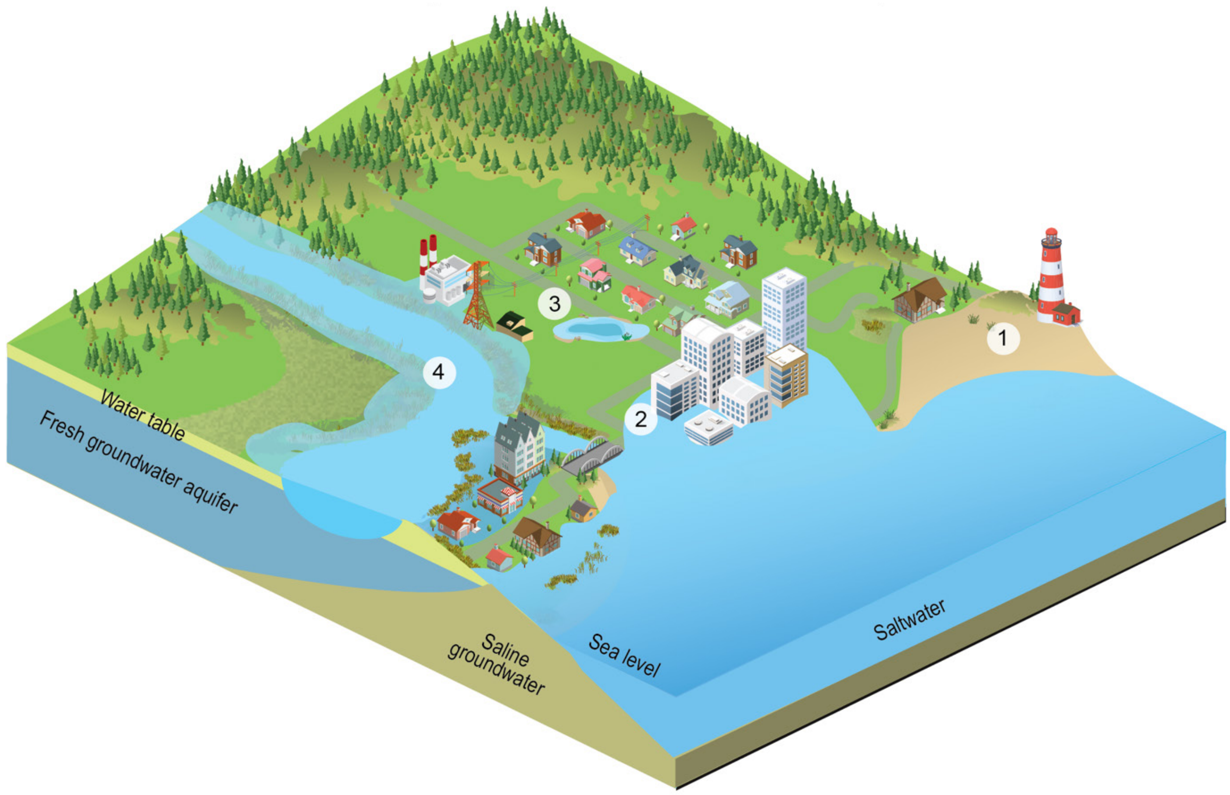
Existing Conditions in a Coastal Community



Coastal landscapes and man-made interventions provide economic, cultural, and community protection from existing climate hazards under existing conditions.

Figure 9.4. This hypothetical coastal community shows some of the natural and built environments found in our Nation's actual coastal communities. This community has several types of open coast shorelines, including 1) cliffs, 2) low-lying beaches, and 3) a barrier island. Behind the barrier island is 4) a tidal estuary fringed with marshes. There are two residential neighborhoods, 5) a commercial hub, and 6) an industrial zone that is water dependent. The riprap at the cliff base and beach groins (narrow perpendicular structures extending from the beach into the ocean) provide protection from coastal erosion due to waves. Subsequent figures in this chapter will illustrate the possible impacts of climate change on this community (Figure 9.5) and adaptation strategies to increase its resilience (Figure 9.6). Adapted from Dupigny-Giroux et al. 2018.[54]

Increasing Hazards in a Coastal Community



Coastal communities are expected to flood due to rising sea levels and rising groundwater levels.

Figure 9.5. Future climate impacts to our coastal landscapes and communities will be variable. 1) Increased sea level and wave energy will result in shoreline erosion and the collapse of coastal cliffs, which can alter iconic landscapes and damage places of value, including historical or cultural sites. 2) Flooding and wave hazards, including 3) flooding from higher groundwater tables, are anticipated, threatening homes and businesses as well as infrastructure and utilities. 4) Some ecosystems may be able to adapt or migrate to keep pace with future sea levels, and others may become inundated and converted to open water. Adapted from Dupigny-Giroux et al. 2018.[54]

Impacts on Communities and People

Our Nation's coasts underpin substantial sectors of our economy, serving as the entry and exit for goods and services (Focus on Risks to Supply Chains), generating revenue through recreation and tourism, and supporting thriving and diverse fisheries and other water-based industries. Coastal counties contribute $11 trillion annually (in 2022 dollars) in goods and services and employ 58.3 million people.[8] Increasing impacts to coastal systems due to exacerbating hazards will ripple across the US.

As extreme storms intensify and/or the impacts are exacerbated by SLR (KMs 2.2, 3.5), damages are increasing by the billions, with significant damage centered where tropical cyclones (e.g., hurricanes) make landfall[55] and where extratropical cyclones are the more common driver of coastal hazards.[48,56] Extreme storms and more frequent high tide flooding (HTF) bring cascading impacts, including loss of energy accessibility and continuity (KM 5.2); loss of ecosystem services (KMs 8.1, 8.3); impacts to agriculture from flooding and saltwater intrusion into groundwater (KM 30.1); flooding, erosion, and landslide disruptions to transportation (KM 13.1), utilities, infrastructure, emergency services, and teleconnections (KM 12.2); and population migration and displacement (KM 20.3).

Coastal hazard assessments that consider SLR, storm surge, waves, rainfall, and coastal change (e.g., beach and dune change, cliff change) can better depict potential future coastal response and societal impacts.[37,57,58] Compared to assessing only SLR-driven flooding, including these processes greatly expands the floodplain region in the northern Gulf of Mexico[58] and triples the estimated number of people on the Pacific Coast exposed to flooding.[37]

During an extreme event, more ocean water can wash over barrier islands and flow into bays via inlets, enhancing flood risk and amplifying storm surge within inland coastal bays by more than 20%.[59,60,61] Continued population growth and urbanization will expose an ever-increasing number of people to coastal flood risks.[3,62,63,64]

Although extreme storm events make newspaper headlines, SLR brings chronic challenges that could be equally or more damaging over the long term.[2] Coastal groundwater investigations in Pacific Island settings,[65] low-lying atolls,[66] karst aquifers,[67] barrier island systems,[68] and active tectonic margins[69,70] have demonstrated that climate-driven groundwater rise will impact coastal communities and ecosystems due to saltwater intrusion into groundwater sources, more saturated soils, and ponding at the surface comparable in magnitude to SLR-driven overland flooding. Seawater intrusion into coastal aquifers can increase salinity beyond potable levels, endangering access to fresh water for millions of people.[71]

The combination of rising groundwater and HTF in coastal communities will continue to impact stormwater and wastewater infrastructure, including septic systems, and increase the occurrence of urban flooding.[72,73,74,75,76] This could cause public health concerns, such as pollutant discharges into the environment[77] and the spread of environmental infectious diseases (KM 15.1). Additionally, contaminated sites, such as Superfund sites, face increasing exposure to rising groundwater and flood damages, which could lead to future public health and environmental concerns if buried contaminants are mobilized and enter groundwater or river systems (KM 28.2). HTF and rising groundwater will also increase occurrences of roadway flooding, potentially impeding traffic, delaying emergency response efforts, flooding properties, and negatively impacting real estate values and commerce.[78,79,80,81,82] In agricultural areas, rising groundwater and saltwater intrusion in irrigation systems are reducing crop productivity, resulting in barren farmlands in the absence of salt-tolerant crops.[83,84]

The impacts of worsening coastal hazards are not equally distributed across US communities (KM 20.1; Box 20.1).[85,86,87] Disparities in wealth, economic and educational opportunities, infrastructure quality and quantity, and investment in flood risk-reduction measures all contribute to variable physical and socioeconomic impacts on coastal residents.[88,89,90] Many Tribal and Indigenous communities face severe impacts from extreme storms, erosion, permafrost thaw, and SLR, with limited resources to support adaptation (KMs 16.1, 29.4, 29.7; Ch. 30). Historic redlining policies forced communities of color into the least valuable, often low-lying lands that have increased flood risks, higher exposure to toxic substances, and more climate change–exacerbated hazards than non-redlined neighborhoods.[91,92,93] Communities that are economically disadvantaged have a higher statistical risk of flood exposure than wealthier communities.[86,87,88] This inequity is further increased because the impact of coastal flooding on individuals and communities is not only based on flood damages but also the ability to pay for the costs of recovery.[85] Decades of limited community inclusion in decision-making and disinvestment in critical infrastructure and community services have generated greater risk to physical and socioeconomic impacts of coastal hazards.[94]

In addition to direct impacts from acute events, chronic impacts are also experienced unequally among coastal residents. Changes in ecosystem services such as fisheries habitats will impact Indigenous practices in which culture and biodiversity are inextricably linked. In the Hawaiian Islands, *loko iʻa* (Hawaiian fishponds) are low-intensity forms of aquaculture that traditionally provided food security, contributing to coastal community resilience (KMs 30.1, 30.5).[95,96] These systems are threatened by SLR, with consequences on local livelihoods and cultural practices. Other communities, such as subsistence fishers and fisheries-based rural villages, will similarly suffer as negative impacts on coastal fisheries habitat threaten their way of life (KMs 10.1, 10.2).

The steady rise in flood insurance prices reduces home affordability in coastal regions, with many heirs and low-income and moderate-income property owners unable to afford flood insurance (KMs 16.1, 21.5).[97,98] Aside from home affordability, cascading effects such as climate gentrification—when affluent residents move into low-income areas less exposed to climate hazards, displacing the previous residents[99,100,101]—and lack of workforce will continue impacting culture, diversity, and economic productivity in coastal areas.[99,102,103,104]

Natural Resilience of the Coast Is Changing

For centuries, humans have been reshaping the coast to meet societal needs through urban development, sediment retention and diversion, and coastal defense structures.[105,106,107] These interventions have driven many coastal systems dangerously close to irreversible and profound change (KM 8.1).[108,109] Ecosystem losses due to erosion, more frequent flooding, and coastal squeeze (where human development or natural elevation change limits or prevents inland migration of coastal habitats) will increasingly limit the capacity of coastal landscapes to adapt naturally and diminish their ability to provide valuable ecosystem services (Figure 9.5; KM 8.1).[47,110,111,112,113]

Mangroves and salt marshes, collectively referred to as tidal wetlands, provide culturally and economically essential fisheries habitat and absorb and store floodwaters (Focus on Blue Carbon).[114,115] SLR and increasing coastal hazards (KM 9.1), as well as eutrophication, sediment availability, poor drainage, and coastal squeeze can all drive tidal wetland loss.[116,117] Some tidal wetlands may survive in place due to accretion, while others may migrate upland and convert other ecosystems (e.g., upland habitat, agriculture, and forests) into tidal wetlands.[118,119]

Throughout the US, a net loss of tidal wetlands is expected, but the rate and extent to which the loss occurs will vary significantly by geography and climate change scenario.[120] For example, in Chesapeake Bay,[121] Florida,[122] and New Jersey,[117] a net loss of tidal wetlands is expected. Along the Gulf Coast, mangroves are overtaking salt marshes, reflecting a shift in vegetation dynamics and habitat.[123] Coastal development and steep topography limit inland migration along the Pacific Coast, and tidal wetland conversion to open water and net tidal wetland loss due to SLR appear inevitable.[124]

Barrier islands and reef systems act as a first line of flood defense, absorbing wave impacts as large storms make landfall, thereby reducing flood risk for coastal and inland communities.[125,126,127,128,129] Barrier island and mainland beach systems may migrate landward naturally to keep pace with SLR, or they may be outpaced and narrow and/or flatten depending on their elevation, how frequently storm waves wash over them, sediment supply, and the persistence of vegetation, all of which can be affected by human modifications.[61,130,131,132,133,134,135]

Long-term observations, projections of coastal change and erosion, and improved understanding of complex coastal feedback processes help define the conditions and tipping points that may limit natural adaptation (KM 8.1).[136,137] Climate adaptation that restores natural processes and works with coastal ecosystems and landscapes may reduce flood risks while providing multiple co-benefits, including carbon sequestration (KM 8.1; Focus on Blue Carbon). For example, acquired or restored open-space areas (e.g., undeveloped, agricultural, or park lands) along the coast can provide accommodation space for inland wetland and coastal habitat migration as seas rise.[138,139]

Allowing coastal ecosystems to evolve naturally may negatively impact some communities and wildlife species, such as the reshaping of barrier islands in response to extreme events that can increase inland storm surge (KM 9.1); however, these natural changes may have beneficial impacts for other species and communities through habitat creation and water quality improvements.[50,134] All changes across the landscape have implications for changes to biodiversity via species declines, species range and phenological shifts, disease, and impacts from invasive species (KM 8.2), affecting seagrasses, corals, mangroves, fisheries, shorebirds, and marine mammals (KMs 21.2, 22.1, 23.2, 26.3, 27.3, 28.2, 30.4).

Key Message 9.3

Adaptation Reduces Risk and Provides Additional Benefits for Coastal Communities

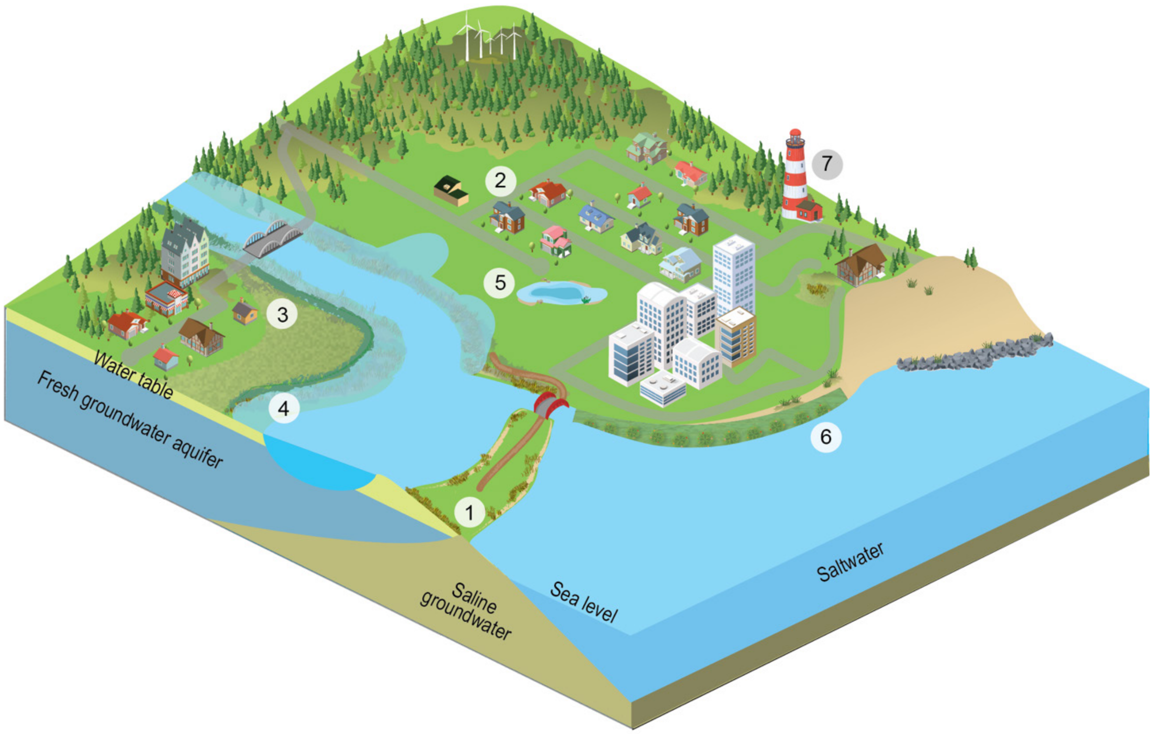
Accelerating sea level rise and climate change will transform the coastal landscape, requiring a new paradigm for how we live with, or adapt to, these changes (*high confidence*). Although incremental in nature, nature-based solutions and planned relocation strategies may help communities adapt to increasing coastal hazards if they are community-led and equity-centered (*medium confidence*). Maintaining cultural and economic connections within coastal communities will require equitable transformative adaptation that addresses systemic interconnections between ecosystems, communities, and governance (*medium confidence*).

Despite projected climate change impacts, coastal communities remain valued places for living and working. Relentless growth in, and enthusiasm for, the coast creates a tension between the need to adapt to climate change and our existing relationships with the coast.[14,140] Although adaptation is occurring in some locations, small-scale and incremental adaptations are not sufficient for the pace and scale of changes that are already occurring (KMs 9.2, 31.1).[13,14,15] Accelerating SLR and increasing coastal hazards (KM 9.1) are affecting larger geographic areas along the coast, expanding the scale and complexity of the adaptation responses and the number and diversity of stakeholders at risk.[13]

Adaptation that includes a broad suite of strategies that address the root causes of coastal vulnerability, consider the needs of diverse stakeholders, center equity (KM 31.2), and reframe societal values and assumptions can lead to transformative and systemic change that can allow coastal communities to thrive and maintain a relationship with the coast (KMs 22.1, 31.3).[141] Example strategies can include updated land-use policies,[142,143] community infrastructure investments, nature-based solutions (NBSs), and planned relocation.[14,144] Individually, these strategies are incremental steps, but when combined in a manner that considers long-term community goals and inclusive and sustained engagement with frontline communities, they can lead to equitable transformative adaptation (Figures 9.6, 22.6, 31.3; Box 9.1; KMs 31.2, 31.3).[14,145]

Transformative adaptation requires fundamental shifts in systems, values, and practices to equitably address the risks of climate change (KM 31.3), including integration of local perspectives, which leads to more equitable distribution of resources.[9] Community-led adaptation actions and NBSs can also enhance a sense of place by recreating lost relationships with the coast or fostering new ones between people and the environment.[14]

Adaptation Strategies for a Coastal Community



Timely implementation of adaptation strategies, including planned relocation, can reduce the impacts of climate change on coastal communities.

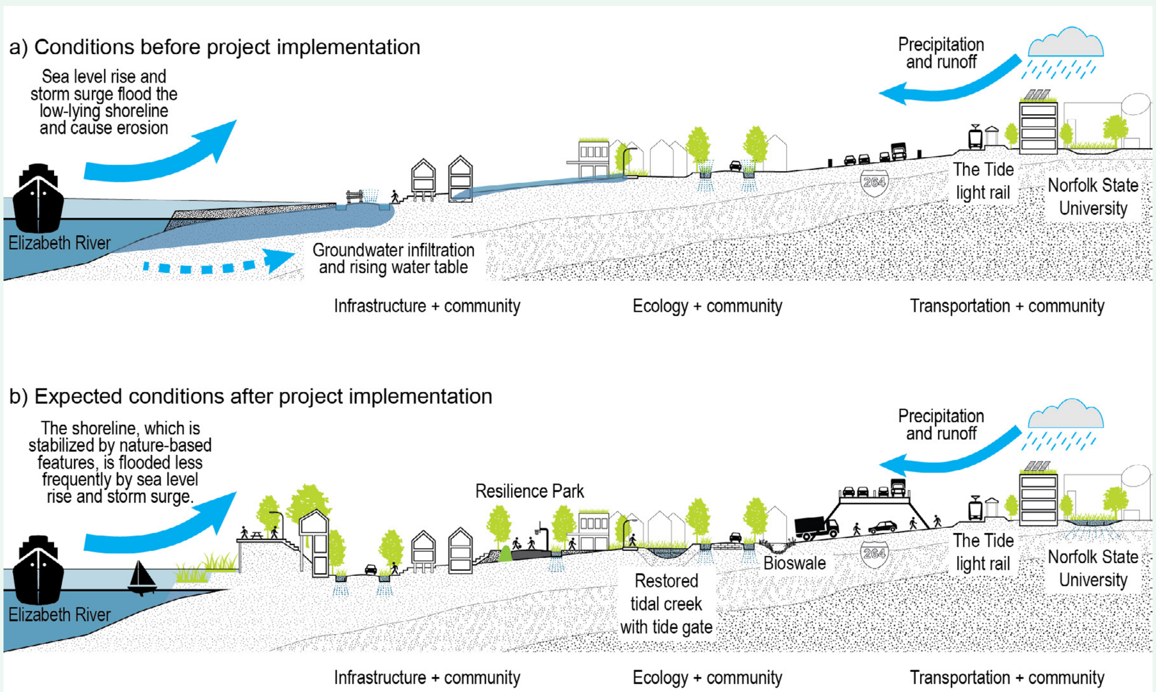
Figure 9.6. Many strategies can reduce climate-driven coastal hazards. 1) Critical infrastructure, housing, and businesses can relocate out of harm's way. Retreated lands create space for parks and recreational areas, nature-based solutions (NBSs) for flood risk-reduction, or migration space for coastal ecosystems, while also accommodating rising waters. 2) Relocated communities may move into established communities, or 3) they may create new residential centers. Intentional and equitable stakeholder engagement helps ensure that historic inequities are not perpetuated during relocations. 4) NBSs, such as restoring wetlands, can slow and store rising waters. 5) Housing and structures can be relocated away from rising groundwater tables. 6) Combinations of green and gray infrastructure (hybrid strategies) may be required; for example, a living seawall provides shoreline protection and beneficial habitat for marine organisms. 7) Cultural assets that define a community's character, such as this lighthouse, can be elevated or moved. Adapted from Dupigny-Giroux et al. 2018.[54]

Box 9.1. On the Road to Adaptation: Norfolk, Virginia

Norfolk, Virginia, home to 245,000 residents and the world's largest naval complex, lies at the mouths of the James and Elizabeth Rivers and Chesapeake Bay. The rate of sea level rise is currently about 0.2 inches (4.7 mm) per year and accelerating. Today, high tide flooding (HTF) occurs 10–15 times annually and by 2050 could occur 85–125 times per year on average.[2,146] Large-scale resilience projects that feature nature-based solutions (NBSs) are under construction as a result of citizen-led strategies that informed the city's land use, regulations, and investments.[147]

The Ohio Creek Watershed Project, funded by a $112 million National Disaster Resilience Competition grant, addresses HTF, storm flooding, and shoreline erosion that caused community isolation and fragmentation (Figure 9.7). The neighborhoods are predominantly Black and include a public housing development and hundreds of homes on the National Historic Register. An extensive community involvement process made sure that residents from the impacted neighborhoods were heard and that societal challenges would be addressed. The project's centerpiece is Resilience Park, including a restored tidal creek and flood berm, wetlands, and NBSs. Surrounding neighborhoods will have accessible roads during HTF events and gain community gathering spaces and places for work and play.

Present and Future State of the Ohio Creek Watershed



Strategies that consider long-term community goals and inclusive and sustained engagement with frontline communities can lead to equitable transformative adaptation.

Figure 9.7. By centering the concept of community, neighborhoods will receive shoreline protection to address sea level rise and higher storm surge, updated infrastructure to address rising groundwater and increasing precipitation and runoff, a large gathering space known as Resilience Park, and accessible transportation for people and vehicles. This example of transformative adaptation involves traditional engineering projects and nature-based solutions. Adapted with permission from Waggonner & Ball ©2022.[148]

Nature-Based Solutions in Coastal Communities

NBSs integrate natural processes with traditional engineering approaches to reduce flood risk while also preserving or enhancing the ecological value of natural landscapes (e.g., maintaining essential habitat for protected species) and providing potential societal, economic, and other co-benefits (Focus on Blue Carbon).[149,150] NBSs can include ecosystem conservation and restoration or recreation of natural processes that reduce flood risks, hybrid solutions (e.g., living shorelines), and the greening of traditional infrastructure (e.g., ecological riprap).[151,152] Although NBSs are effective in reducing temporary flooding resulting from storms, they may provide only modest benefits in preventing permanent inundation from SLR.[149,153] However, when NBSs are paired with planned relocation, protection from flooding and SLR is provided by moving a community out of harm's way while also reestablishing the natural flood risk-reduction benefits of coastal ecosystems.[52]

Mangroves and other coastal wetlands reduce wave energy,[154,155] decrease coastal erosion,[156,157] and provide flood attenuation.[114,158,159] Wetlands helped communities avoid $795.2 million (in 2022 dollars) in direct flood damages during Hurricane Sandy.[127] Beaches and dunes reduce storm surges and absorb wave energy.[160] Coral reefs damp wave energy and provide flood protection for adjacent communities, with an estimated flood risk-reduction benefit of over $2.2 billion annually (in 2022 dollars) in the contiguous US[161,162] and more than $1.1 billion (in 2022 dollars) annually in Hawai‘i, Guam, American Sāmoa, the Commonwealth of the Northern Mariana Islands, Florida, Puerto Rico, and the US Virgin Islands.[163]

Hybrid solutions can reduce shoreline erosion[164,165] and enhance the engineering design life and flood risk-reduction performance of traditional infrastructure.[166] Flood risk-reduction benefits of hybrid solutions have been demonstrated across varying hydrodynamic conditions.[165] NBS guidance documents[149,167,168,169] are continually published, and implementation of NBS strategies is increasing. The ability to include adaptive elements in NBSs for future changing conditions[144,170,171] makes them an important component of the adaptation landscape over the coming decades.

Planned Relocation Strategies in Coastal Communities

Planned relocation is the process of moving individual properties, infrastructure, or whole communities preemptively away from, or in response to, the impacts of natural hazards.[172] Historically, most communities have remained in place post-disaster by adapting or rebuilding using engineered solutions (KM 20.3).[173] However, as climate change impacts increase, adapting and rebuilding in place will become more challenging (KM 31.1). With accelerating SLR, particularly under low-likelihood, high-impact SLR scenarios (Figure 9.1), planned relocation may become more cost effective than adapting in place, with a lower long-term risk of loss of life and property if engineered solutions fail.[174]

In the US, planned relocation generally occurs reactively (i.e., post-disaster) rather than proactively (i.e., relocating at-risk communities before a disaster). For example, targeted buyouts of assets most at risk of future repetitive damage occurred after Hurricane Sandy in Staten Island, New York.[175] Residents and communities have also relocated after natural disasters, such as Isle de Jean Charles, Louisiana;[176] Kivalina, Alaska;[177] and the Quinault Indian Nation (Box 20.1). As planned relocation expands, there is an urgent need to assess lessons learned from past relocations and lean into transformative adaptation that improves community well-being and addresses social, ecological, and intergenerational justice.[178,179]

Proactive planned relocation may become the most viable response for many future coastal communities as SLR continues and coastal lands become submerged.[38,180] However, discussions of planned relocation remain challenging and controversial.[12,174] Impediments include resistance to change;[181] disagreements about when communities and infrastructure may be irrevocably lost and, thus, the appropriate timing for relocation; lack of community-led decision-making; cost effectiveness compared to defending in place;[174,182] disruptions to community cohesion and social capital;[183,184] and identification of suitable replacement locations.[185]

Transformative Adaptation Opportunities in Coastal Communities

Transformative adaptation that is proactive and intentional and involves fundamental shifts in systems, values, and practices (KM 31.3) provides opportunities to meet the challenges of shifting and receding shorelines. Transformative adaptation along the coast considers aspects such as funding and economic security, alignment of governmental entities, attachment to place and livelihoods, and technical expertise.[52,53]

Intentional and equitable transformative adaptation is an opportunity to redress root causes of inequities and disparate impacts of climate change in coastal communities.[14,15] Achieving this would require sustained funding dedicated to proactive planning, design, and execution.[186] This would prevent reactive strategies that have historically exacerbated inequities and focused resources on wealthy, typically White communities (KM 20.3)[187]—a particular challenge in areas where there are large disparities in wealth and where lower-income homeowners and renters lack affordable flood insurance.[103]

Current adaptation strategies that are increasingly being implemented on the coast could shift toward transformative adaptation if local communities are centered and inequities are transparently addressed (KMs 31.2, 31.3; Figure 31.2). This will require an incremental shift in practice, resulting in additional shifts in systems (e.g., permitting), values (e.g., recognizing and addressing past injustices), and risk tolerance (e.g., increasing comfort in natural shoreline protection over more traditional hardened structures).

Traceable Accounts

Process Description

This assessment builds upon and amplifies the Key Messages within the "Coastal Effects" chapter of the Fourth National Climate Assessment, as those Key Messages are still relevant, yet they have become even more urgent.[188] The US Interagency Sea Level Rise Task Force's (hereafter "Task Force") report[2] provides clear evidence that sea level rise (SLR) is already accelerating and that current SLR tends are tracking on the Intermediate-Low curve or higher along the Nation's coasts.

Impacts associated SLR and extreme coastal storms are increasing per observations, coastal ecosystems and communities are facing increasing risks, and transformative adaptation grounded with nature-based solutions may provide our best hope to retain a sense of balance between the coasts and our coastal communities. The author team required a depth and breadth of expertise across the Atlantic, Gulf, and Pacific Coasts, as well as the coastlines of Hawai'i and the US-Affiliated Pacific Islands, the US Caribbean, and Alaska; the leading edge of SLR science; the physical processes that shape our coastlines; the systemic inequities that continue to put frontline communities at greatest risk; and the human actions that have altered the coasts and transformed the shoreline to suit societal desires.

Prospective authors were nominated by their respective agencies, universities, organizations, or peers. The chapter lead and federal coordinating lead authors discussed and vetted prospective authors with a goal of creating a cohesive author team committed to bringing their formidable experience and skillsets together to develop this chapter.

This chapter was developed through weekly teleconferences, email exchanges, technical discussions of the relevant evidence base, and expert deliberation by the authors. The author team, along with the US Global Change Research Program, held a public engagement workshop with participants from federal, state, and local agencies; consultants; and interested members of the public. The workshop used innovative approaches and breakout groups that explored what the participants loved most about the coast before diving into the key topics that framed this chapter and the development of the Key Messages.

The urgent need for adaptation, with an emphasis on nature-based solutions and planned relocation, was a clear driver for Key Messages 9.2 and 9.3. Additional literature is required that presents lessons learned and successful implementations, even if at a small scale, to achieve the scale of planned relocation that is expected to be required in the US over the next century.[179] The authors extensively reviewed the literature on transformative adaptation and adaptation that centered equity, community values, and included strong community participation. The concept of transformative adaptation and planned relocation required dialogue across many chapters, with an emphasis on Chapter 20 (Social Systems and Justice) and Chapter 31 (Adaptation) to achieve consistency and portray a sense of urgency for the Nation along these paths.

Consensus on the Key Messages and supporting literature required multiple iterations, discussions with other chapters, and careful review and revisions in response to comments from the public and the National Academies of Sciences, Engineering, and Medicine.

Key Message 9.1

Coastal Hazards Are Increasing Due to Accelerating Sea Level Rise and Changing Storm Patterns

Description of Evidence Base

Multiple lines of evidence, including satellite and tide-gauge observations and model simulations, show that substantial SLR has occurred to date, globally and for the US, as documented and synthesized in the Working Group I contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (AR6) and the Task Force report on SLR.[2,189] Observations show that SLR is accelerating at global, national, regional, and local levels, and AR6 projections and the sea level scenarios from the Task Force report suggest that these trends are expected to continue over the next several decades and through the end of this century and beyond (see https://sealevel.nasa.gov/data_tools/18).[2,189] Beyond 2150, SLR is expected to continue for the next several thousand years due to the long-term effects of emissions and warming over this past century, irrespective of future emissions occurring after 2100. These lines of evidence are synthesized, and a large body of relevant literature is documented (e.g., Dangendorf et al. 2019;[190] Frederikse et al. 2020;[191] Fox-Kemper et al. 2021;[20] Hamlington et al. 2021;[192] Edwards et al. 2021[193]), in the Task Force report on SLR[2] and IPCC AR6.[189]

An additional body of literature and references therein links this increase in average sea level to a broad range of risks and adverse impacts in the coastal zone. Extreme water levels will continue to rise with SLR, causing deeper, more frequent, more severe, and more widespread flooding (e.g., Sweet et al. 2021,[35] 2022;[2] Taherkhani et al. 2020;[194] Thompson et al. 2021;[36] Vitousek et al. 2017[41]). Observational and model simulation evidence also indicates that many types of extreme events are increasing in intensity, frequency, and geographic extent as a result of human-caused climate change and that hurricanes, in particular, are intensifying and causing heavier rainfall and higher storm surges, all of which compounds these flood risks (see evidence base underlying Key Messages 2.2 and 3.6 and USGCRP 2017[195]). Extreme water levels and flooding lead, in turn, to additional coastal zone impacts (e.g., erosion, damage to property and infrastructure, ecosystem impacts). Compound flooding associated with other coastal storm types (e.g., atmospheric rivers, extratropical cyclones) is also projected to increase with a warming climate.[196,197,198]

A further body of literature documents how population growth, migration, and development trends in the coastal zone have exacerbated societal risks and exposure of populations and the built environment to increasing SLR- and flooding-related hazards.[199,200,201]

Major Uncertainties and Research Gaps

For near-term impacts (to 2050), uncertainties and research gaps include the impact of natural climate variability on the observation-based trajectories, coastal adaptation, and policy actions to reduce future hazards and improved incorporation of interacting and compounding drivers into projections of coastal water levels and overall coastal flood hazards, such as winds, surge, waves, rising water tables, and extreme rainfall. In addition, more detailed understanding of, and data on, compound flood hazards is a key area of research needed to better understand and communicate flood risks and inform adaptation efforts.

For longer-term impacts (after 2050), major uncertainties and research gaps include improved modeling and observational capabilities to assess long-term global average SLR trajectories as a function of uncertainties in both emissions pathways and the sensitivity of ice sheet dynamical processes to a given level of warming, particularly the "low-confidence" ice sheet processes, as per IPCC AR6.[20] Projections that include these ice sheet processes, particularly under higher-emissions futures, result in substantially higher global average SLR values by the end of this century and beyond. Pathways to such futures include outcomes such as earlier-than-projected ice shelf disintegration in Antarctica; abrupt, widespread onset of marine ice sheet instability and/or marine ice cliff instability in Antarctica; and faster-than-projected changes in surface-mass balance on Greenland, potentially associated with changes in atmospheric circulation, cloud processes, or albedo changes.[2] Monitoring the sources of ongoing SLR and the processes driving changes in sea level is critical for assessing scenario divergence and tracking the trajectory of observed SLR, particularly during the period when future emissions pathways might increase the risk of triggering these low-confidence processes.

Description of Confidence and Likelihood

Based on a spatially weighted average of about 100 NOAA tide gauges and following methodologies in Sweet et al. (2022),[2] there is *high confidence* that sea levels along the contiguous US have risen about 11 inches (*likely* range between 10 and 12 inches) on average over the 1920–2020 period, with about 5–6 of those inches occurring since 1990, indicating that sea level rise is accelerating. There is also *high confidence* that the probability of minor, moderate, and major coastal flooding increased by about 2–3 times between 1990 and 2020 (as defined by contemporary NOAA weather-related impact thresholds calibrated to historic NOAA tide-gauge water level heights). Thus, it is *very likely* that the severity and risks of hazards are increasing.

There is *high confidence* and it is *likely* that sea levels will rise about 11 inches (*likely* range of about 9–13 inches) between 2020 and 2050 based on both extrapolating rates and accelerations estimated from historical tide-gauge observations and model projections, with both approaches producing projections within similar ranges. In response to 11 inches of SLR by 2050, there is *high confidence* and it is *very likely* that the probability of minor, moderate, and major coastal flooding will occur 5–10 times more often by 2050 in many regions without additional flood risk-reduction measures, as compared to contemporary standards.

Key Message 9.2

Coastal Impacts on People and Ecosystems Are Increasing Due to Climate Change

Description of Evidence Base

A growing body of literature captures the limited ability of coastal ecosystems to adapt to climate-driven changes, particularly due to human modification. Multiple lines of evidence show that physical changes in the coastal zone in response to climate change are occurring, including upland conversion and marsh expansion,[121,122,202] expansion of mangrove systems,[123] and marsh and beach loss due to erosion and barriers that limit inland migration of these ecosystems.[47,50,110,119,138,203] The consequent loss of ecosystem services, such as storm protection, wetland carbon sequestration, sensitive habitat, and industry, including agriculture, tourism, recreation, and fishing, has been well documented (e.g., Siverd et al. 2020;[204] Weiskopf et al. 2020[205]), and the amplification of these losses via human modifications of the coast are well supported in the peer-reviewed literature.[105,113,206]

With ecosystem loss, exacerbated coastal hazards, and growing coastal populations, increasing damages and costs have been observed (e.g., Bouwer 2019;[207] Hino et al. 2019;[79] Smiley et al. 2022;[208] Al-Attabi et al. 2023[209]), and ongoing health and safety concerns due to increasing flood frequencies, contaminated water supplies, degraded water quality, exposure to toxic substances, and strains on mental health due to the ongoing threat of disasters have been documented (e.g., Coutu 2018;[210] Makwana 2019;[211] Erickson et al. 2019;[212] Gobler 2020;[213] Raker 2022[214]). Additionally, many studies have shown that 1) overburdened, under-resourced, economically disadvantaged, or otherwise vulnerable populations (e.g., children, people with disabilities) face a greater burden from disasters (e.g., Conzelmann et al. 2022;[215] Raker 2022;[214] Smiley et al. 2022[208]) and are limited in their ability to recover from these impacts, and 2) existing inequities continue to be magnified (e.g., Erman et al. 2020;[216] Griego et al. 2020;[217] Sou et al. 2021;[218] Dundon and Camp 2021;[219] Bento and Elliott 2022[220]). Municipal coastal officials, elected officials, and staff continually document increasing challenges within their communities through participation in professional organizations (e.g., National League of Cities, Association of State Floodplain Managers, regional communities of practice). Specific challenges include the combination of increasing development and land-use pressures and exacerbating coastal hazards that put more homes, businesses, and individuals at risk. Numerous municipalities are installing backflow preventers, documenting high tide flooding, and attempting to manage magnified impacts from rainfall occurring concurrently with high tide flooding and other coastal hazards (e.g., EcoSystems 2014;[221] WSAV 2018;[222] Coutu 2021[223]).

Major Uncertainties and Research Gaps

Future coastal landscape change is difficult to model and predict broadly in the spatially detailed form required by decision-makers, due to the multitude and complexity of the processes and feedbacks acting within and across different coastal ecosystems.[137,224,225]

National-scale efforts are emerging to assess the risk of losing vital coastal wetland habitats[112,226] and to monitor the daily to annual status of sandy beaches using satellite imagery.[227,228,229] However, monitoring alone cannot save these at-risk ecosystems; improved understanding and ability to model the thresholds and/or tipping points associated with ecosystem loss versus survival are needed broadly to support proactive planning for management of coastal resources and communities.[58,137] Information is needed about when and where saltwater intrusion may occur and its impacts.[69,230,231]

Anticipating and accounting for future human modifications that may reshape the coast and/or affect ecosystem behaviors are areas of considerable uncertainty.[232] Multidisciplinary scenario development can help to explore the physical changes that may occur, how humans may choose to respond to these changes, and the resources that may be available to support these modifications, such as emplacement or removal of gray and green infrastructure, planned relocation, or trade-offs.[233,234] A better understanding of when and in what form humans may take future action can in turn help inform understanding of the landscape response, which can better frame the immediate and longer-term risks to coastal populations in the future.[232,235]

Description of Confidence and Likelihood

Based on observations and predictive modeling the authors have *high confidence* that the long-term sustainability of our coastal ecosystems and human systems is *very likely* being affected by climate changes, particularly due to land loss. Observations and modeling have also given us *high confidence* that human measures that have historically been used to limit coastal change and have predominantly relied on hard, fixed infrastructure solutions to protect development are *very likely* to make coastal areas less resilient to future change amplified by climate drivers. With this reduction in resilience, numerous studies have shown there is *high confidence* that coastal ecosystems are *very likely* to be limited in their ability to provide the services on which humans depend. There is *high confidence* based on the array of literature and studies available that the loss of these services are *very likely* to require proactive strategies to address significant and cascading impacts on cities, communities, and ways of life in the coastal zone.

Key Message 9.3

Adaptation Reduces Risk and Provides Additional Benefits for Coastal Communities

Description of Evidence Base

Because coastal hazards will continue to worsen and the impacts to the natural and built environment will increase, coastal communities will have to adapt (or continue to adapt) to climate change. Business-as-usual strategies are not expected to be sufficient in the future because they do not address the root causes of vulnerability in coastal communities[9,14,15] nor acknowledge that sea levels will continue to rise beyond typical infrastructure planning time horizons.[141,236]

Consensus is growing to support nature-based solutions (NBSs) and strategies such as planned relocation as essential components of climate adaptation.[149,153,169,237] There is a growing body of literature that demonstrates that NBSs can successfully provide flood risk protection.[115,160,164,165,237] Multiple studies based on laboratory experiments have demonstrated the capacity of NBSs to attenuate wave energy, currents, and storm surges under a range of controlled conditions.[238,239] Additional studies based on field measurements during extreme coastal events have validated these findings within a range of geographical settings and environmental and extreme weather conditions.[154,156,240] Numerical modeling studies have expanded these findings to low-frequency events and a broader range of extreme conditions.[114,161,162] There is growing evidence on the functionality and performance of NBSs for flood risk reduction. This body of literature supports an increasing number of guidelines and practical guidance for NBS planning, design, and implementation.[149,169] State agencies are beginning to require prioritizing NBSs for coastal adaptation, where possible, in lieu of hardened infrastructure.

Planned relocation continues to be a topic of contentious debate in coastal communities, but there is growing evidence that demonstrates openness by communities to include these strategies in long-term planning discussions.[241] This is particularly true if the definition of planned relocation is broadened to include different land-use policy levers that are common planning tools, such as setbacks or easements,[242] as well as discussions and planning that are led by the community.[243]

Transformative adaptation to SLR is possible, in part, due to the array of efforts used to provide meaningful and understandable information to coastal stakeholders. In the coastal zone, stakeholders span a wide array of sectors, grappling with different priorities, timelines, and urgencies that often lead to differing needs. For example, ecologists designing a wetland restoration require probabilistic estimates of near-term SLR, while planners of critical infrastructure need to understand the full suite of possible risks across both the near term and long term to make wise decisions and investments for the communities they serve. The current state of the science and the corresponding guidance on how to make decisions in the face of the knowns and unknowns around rising seas (e.g., The Application Guide for the 2022 SLR Technical Report) are essential indicators that transformative adaptation, inclusive of NBSs and migration, is achievable.[1]

Major Uncertainties and Research Gaps

Although it is generally understood that riverine flood risk-reduction projects, such as increasing levee heights, could exacerbate flood risks in downstream communities, the potential for a similar deflection of flood risks from one community in coastal environments is less understood. In San Francisco Bay, a modeling study showed that the addition of a levee or seawall to protect one community could increase flood risks elsewhere on the estuarine shoreline.[6] This concept may be important to consider more broadly along the coast, as it intersects with equity considerations if communities with fewer resources to adapt are confronted with increased risks diverted from communities with greater resources.

Despite the growing number of studies investigating and validating the performance of NBSs for flood risk reduction, research gaps remain with respect to uncertainty in flood risk-reduction benefits under a range of future environmental conditions and hazards, given the intrinsic dynamic nature of NBS systems. Specifically, what strategies work in active coastal zones with high wave energy? Furthermore, research is lacking with respect to NBS strategies in extreme environments, especially the Arctic, where traditional vegetation-centric approaches are not practical. This is especially relevant in western Alaska, where communities are experiencing increasing flood hazards and traditional flood protection is extremely costly. While there has been progress on developing standards and guidelines for using NBSs to reduce flood risk,[149,167,168,169] there remains a need for professional engineering organizations and nongovernmental organizations to expand the existing documentation.

Uncertainties and research gaps on planned relocation tend to focus on the process and willingness of communities to relocate: What are the tipping points that encourage a community to adopt community-wide planned relocation? Where should people move to, and are receiving communities prepared to take in increased populations? How does relocation get paid for? How can the psychological barriers to planned relocation be overcome?

There is a lack of literature exploring the governance structures, laws, and policies necessary to support transformative adaptation, including planned relocation. Spanning the gap between adaptation planning and successfully implementing adaptation solutions on the ground requires overcoming governance challenges.[244] Although the number of legal analyses relevant to adaptation is growing, these analyses are still limited in their practical application and scope.[245,246] Research has demonstrated the value of multidirectional policies, laws, and efforts at stimulating climate planning and adaptation, particularly the benefit of top-down laws directing the need to plan and implement adaptation without being overly prescriptive;[53] however, this work is in its early stages. Comprehensive analyses that explore how current policies impede or foster transformative climate adaptation would help to synthesize and identify where improvements could be made within governance structures to support successful adaptation.

There is limited research on the economic and social drivers of, and impediments to, transformative adaptation in coastal communities. Research is also lacking on the social psychology prerequisites needed for successful transformative adaptation. How will a coastal community know when residents are ready to start down the path of transformative adaptation? How can psychological readiness be fostered, including effective communication of future conditions that may compel this sort of action?

Beyond NBSs and planned relocation, many incremental adaptations are well understood in terms of implementation and impact alone. For example, many communities have experience with raising roads, resizing drainage culverts, and building shoreline stabilization structures. However, research that results in effective guidance is lacking for larger measures, such as infrastructure abandonment or relocation and the aggregation of smaller measures. While there is an emerging body of research on this topic for individual actions,[174,247,248] analysis at the community level across a range of adaptation actions and timelines is lacking.

The body of research supporting transformative adaptation is growing; however, much of this research is not tailored for coastal communities. There is a gap in research on the preconditions for, and drivers of, success in coastal communities. Furthermore, there is also a gap in research that assesses the effectiveness of mitigation and adaptation approaches under low-likelihood, high-impact scenarios, given that these approaches necessarily change under extreme SLR scenarios.

Description of Confidence and Likelihood

Increasing coastal hazards, changing weather patterns, and extreme storms are causing widespread and rapid changes along our Nation's coasts (high confidence). At present, adaptation efforts are most often incremental in nature and sector-specific (e.g., focused on adapting a wastewater treatment plant or stretch of roadway) as opposed to community-wide in scale (high confidence). As SLR accelerates, exposing greater populations and geographies to coastal hazards, this adaptation approach will become ineffective.

Adaptation responses that move beyond traditional solutions may include nature-based solutions and planned relocation. There is medium confidence that nature-based solutions and planned relocation strategies, when they are community-led and equity-centered, can provide an equitable response to coastal hazards and climate change impacts. There is medium confidence that transformative adaptation that centers the community within the planning, design, and implementation of multi-benefit solutions can better maintain the social, cultural, and economic connections communities require to thrive.

The statements in this Key Message are supported both in the literature cited and in the author team's understanding of the state of the adaptation practice across a wide variety of coastal communities, both in geography and in social systems. This community-focused lens supplements the published literature and allows the authors to reflect the most current consensus on this topic.

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