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# Sea-Level Rise and U.S. Coasts: Science and Policy Considerations

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# Summary

Policymakers are interested in sea-level rise because of the risk to coastal populations and infrastructure and the consequences for coastal species and ecosystems. From 1901 to 2010, global sea levels rose an estimated 187 millimeters (mm; 7.4 inches), averaging a 1.7 mm (0.07 inch) rise annually. Estimates are that the annual rate rose to 3.2 mm (0.13 inches) from 1992 to 2010. Although the extent of future sea-level rise remains uncertain, sea-level rise is anticipated to have a range of effects on U.S. coasts. It is anticipated to contribute to flood and erosion hazards, permanent or temporary land inundation, saltwater intrusion into coastal freshwaters, and changes in coastal terrestrial and estuarine ecosystems.

Some states, such as Florida and Louisiana, and U.S. territories have a considerable share of their assets, people, economies, and water supplies vulnerable to sea-level rise. In 2010, roughly 100 million people lived in U.S. coastal shoreline counties. Increased flood risk associated with sea-level rise may increase demand for federal disaster assistance and challenge the National Flood Insurance Program. Federal programs support local and state infrastructure investments such as roads, bridges, and municipal water facilities that may be damaged or impaired. Sea-level rise also is anticipated to affect numerous federal facilities.

**Global and Relative Sea Levels.** Sea levels are expressed in terms of *global sea levels*, which is the average value of sea surface heights around the globe, and *relative sea levels*, which is the sea level relative to the land surface. Since 1900, expanding oceans due to warming ocean water and melting glaciers and ice sheets have been the main drivers of global sea-level rise. Oceans have warmed due to a combination of natural variability and the influence of greenhouse gas emissions on atmospheric temperatures. Similarly, glaciers and ice sheets since 1900 have been melting due to both natural variability and greenhouse gas emissions. In 2012, the U.S. National Climate Assessment expressed very high confidence in global sea levels rising at least 0.2 meters (8 inches) but no more than 2.0 meters (6.6 feet) by 2100.

There are regional and local variations in the rate of sea-level rise. Regional or local factors can be natural, such as the land rebounding upward after continental ice sheets melted at the end of the last ice age, or they may be due to human activities, such as groundwater pumping, oil and gas extraction, sediment compaction, and land management practices, among others. With few exceptions, sea levels are rising relative to the coastlines of the contiguous United States, as well as parts of the Alaskan and Hawaiian coastlines.

**Policy Considerations.** Policy choices related to sea-level rise have the potential to shape the future development and resiliency of U.S. coasts. Policy options include a continuation of current government programs and policies, actions that address the forces contributing to sea-level rise globally or locally, and actions that reduce the vulnerability to and consequences of sea-level rise on U.S. coasts. For all the policy options, there are underlying questions of costs and benefits and who bears the costs of pursuing or not pursuing the policies. A challenge for federal lawmakers is how to deal with the tension between federal efforts to manage national and federal government risks (e.g., federal disaster costs, coastal ecosystem shifts) related to sea-level rise and the local and state roles in shaping coastal development and ecosystem health. Related policy questions include the following: To what extent do federal programs, regulations, and funding influence how coasts develop and redevelop? Who is responsible for the costs associated with adjusting to sea-level rise? Who will bear the risks associated with vulnerable coastal development and infrastructure? Some stakeholders are concerned that governments at all levels are paying insufficient attention to the risks posed by sea-level rise; others are concerned that overestimating the risk of sea-level rise could result in foregoing current uses of coastal areas and promoting overinvestment and overdesign of sea-level rise mitigation and adaptation.

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# Introduction

Although the extent of future sea-level rise remains uncertain, sea-level rise generally is anticipated to have a range of economic, social, and environmental effects on U.S. coasts. *Global* sea level is rising due to warming and expanding oceans, melting glaciers, and melting ice sheets in Greenland and Antarctica, among other reasons. From 1901 to 2010, global sea levels rose an estimated 187 millimeters (mm; 7.4 inches), averaging a 1.7 mm rise annually; estimates are that from 1992 to 2010, the rate increased to 3.2 mm annually.[1] The rates of *relative* sea-level rise at specific locations are likely more important to coastal communities and coastal ecosystems than the global sea-level average trends.[2] Sea levels are rising between 9 mm and 12 mm per year (0.4 inches to 0.5 inches per year) along the Mississippi delta near New Orleans and between 1 mm and 2 mm (0.04 inches and 0.08 inches, or less) per year along some coastal shorelines in Oregon and Washington. Since the beginning of the 20th century, coastal and tidal areas have seen significant population growth and associated development and infrastructure investments. The consequences of sea-level rise are of interest to Congress not only because of the local impacts on coastal communities and ecosystems but also because of the direct and indirect impacts and risks for the federal government.

Following an introduction to sea-level rise issues for policymakers, the report is divided into three primary parts:

- Part I describes the phenomenon of sea-level rise. It introduces key terminology, measurements, trends, and causes. (See "Part I. What Is Sea-Level Rise?")
- Part II describes the types of effects that sea-level rise can have on U.S. coasts. It addresses effects on shorelines and coastal ecosystems and on coastal development and society. Part II describes federal actions to address sea-level rise and the tension between the federal role and actions taken by state, local, and private stakeholders. (See "Part II. Sea-Level Rise and U.S. Coasts.")
- Part III provides a primer on policy considerations. It raises considerations and questions associated with policies to address the causes and effects of sea-level rise. It also discusses federalism issues and general considerations associated with sea-level rise policies and investments. (See "Part III. Policy Considerations and Questions.")

## Sea-Level Rise Issues for Federal Policymakers

In 2010, roughly 100 million people lived in U.S. coastal shoreline counties (exclusive of the Great Lakes) and 2.9 million people resided in coastal shoreline counties of the U.S. territories.[3]

[1] For a discussion of these estimates and their sources, see "Global Sea Level" discussion below.

[2] For more on global and relative sea levels, see "Causes of Sea-Level Rise" below.

[3] According to National Oceanic and Atmospheric Administration (NOAA), 123.2 million people (39% of the U.S. population) lived in coastal shoreline counties (inclusive of Great Lakes shoreline counties) in 2010 (NOAA, *National Coastal Population Report, Population Trends from 1970 to 2020*, March 2013, http://oceanservice.noaa.gov/facts/coastal-population-report.pdf, hereinafter referred to as NOAA Coastal Population Report 2013). According to the report, the population of these counties grew by 39% from 1970 to 2010. If the territories (with a coastal shoreline population around 2.9 million) and the Great Lakes countries are removed, the coastal shoreline counties adjacent to ocean waters would be roughly 100 million in 2010. Also according to the report, in 2010, minority population groups represented 35% of the population residing in coastal shoreline counties, which was a higher percentage than the minority population nationally (28%).

Many of these people may not be directly exposed to sea-level rise but may experience indirect effects on their communities or shoreline amenities. Of the U.S. coastal shoreline population, nearly 8 million people live in the 1% coastal flood zone (i.e., area in which the annual probability of coastal flooding is 1 in 100 or higher).[4] Sea-level rise represents an increase in coastal flood and erosion hazards for exposed and protected shorelines, potentially expanding inland the 1% coastal flood zone. Higher sea levels may allow coastal storms to affect more people and cause more damage, which can result in broader social and economic effects.

Higher sea levels increase permanent or temporary coastal land inundation, change shoreline dynamics and coastal erosion, and increase saltwater intrusion and hydrodynamic changes to coastal freshwater aquifers.[5] These impacts are anticipated to result in more nuisance flooding and impeded drainage,[6] more loss of lands to inundation, more shifts in habitat types (e.g., freshwater wetlands converting to brackish wetlands), less freshwater supply, and potential water-quality impairment. These changes may affect coastal species as well as coastal developments and their amenities (e.g., sandy beaches).

Sea-level rise affects the federal government both directly and indirectly. Federal facilities (e.g., military installations) and federal projects often are located on U.S. coasts, such as navigation improvements and coastal storm damage reduction projects. Federally assisted infrastructure, such as roads and bridges, and docks, also may be affected by sea-level rise; they may experience more intermittent flooding or a decrease in their useful life. Private-sector enterprises and individuals own or control large portions of coastline real estate and infrastructure. If sea-level rise contributes to flooding and associated damages, the federal government can become involved through disaster assistance and the National Flood Insurance Program (NFIP) for homeowners and businesses.[7] Much public infrastructure is uninsured.

Several federal agencies are affected by sea-level rise and address sea-level rise in their work. The following are examples of how federal agencies are involved with sea-level rise:

- **Science**. Federal entities engaged in understanding sea-level rise include the National Oceanic and Atmospheric Administration (NOAA) in the Department of Commerce and the U.S. Geological Survey (USGS) in the Department of the

[4] M. Crowell et al., "An Estimate of the U.S. Population Living in 100-year Coastal Flood Hazards Areas," *Journal of Coastal Research*, vol. 26, no. 2, 2010, pp. 201-211. The 8 million people value refers to people living in the 100-year (1%) coastal floodplain. Current coastal populations in the conterminous United States that would be affected by a sea-level rise of 0.9 meters and a sea-level rise of 1.8 meters are estimated at 1.46 million and 3.85 million, respectively (M. E. Hauer, J. M. Evans, and D. R. Mishra, "Millions projected to be at risk from sea-level rise in the continental United States," *Nature Climate Change*, March 14, 2016). The states with the most people that would be affected are Florida, Louisiana, and New Jersey. A 2012 study had estimated almost 3.7 million people lived within one vertical meter of the local high-tide line in the contiguous United States (B. H. Strauss et al., "Tidally adjusted estimates of topographic vulnerability to sea level rise and flooding for the contiguous United States," *Environmental Research Letters*, vol. 7, no. 1 (March 14, 2012)).

[5] *Aquifers* are sources of underground water. *Estuaries* are partially enclosed water bodies where freshwater mixes with saltwater.

[6] *Nuisance flooding* is minor coastal flooding, for example, flooding of low-lying areas and structures during high tide. It is sometimes referred to as "sunny day" flooding because nuisance flooding often is not associated with a storm or precipitation. For more on nuisance flooding, see the section of the report titled "Coastal Nuisance Flooding."

[7] The Government Accountability Office (GAO) mentioned the National Flood Insurance Program (NFIP) in its inclusion of "Limiting the Federal Government's Fiscal Exposure by Better Managing Climate Change Risks" in its 2015 biennial High Risk List. For more on the challenges facing the NFIP, see GAO, *Climate Change: Better Management of Exposure to Potential Future Losses Is Needed for Federal Flood and Crop Insurance*, October 29, 2014, pp. 15-28, at http://www.gao.gov/products/GAO-15-28. For more on the NFIP, see CRS Report R44593, *Introduction to FEMA's National Flood Insurance Program (NFIP)*, by Jared T. Brown.

Interior. NOAA, USGS, and other federal agencies survey coastlines and conduct research to understand coastal processes, hazards, and resources.

- **Flood Mitigation and Recovery**. The Federal Emergency Management Agency (FEMA) in the Department of Homeland Security works to reduce flood losses through risk-mitigation activities and disaster response and recovery, including the NFIP.[8]
- **Federal Facilities, Projects, and Programs**. The Department of Defense, the U.S. Coast Guard, and the National Aeronautics and Space Administration (NASA) have extensive coastal facilities that are central to their missions. The U.S. Army Corps of Engineers (Army Corps) in the Department of Defense also has significant civil works in coastal areas, including its navigation improvements and its coastal flood risk reduction projects. A significant number of federal agencies have a portion of their projects and programs that are relevant to or used in coastal areas that may be affected by sea-level rise, such as Department of Transportation and Department of Housing and Urban Development.
- **Environmental Protection and Restoration**. Department of the Interior agencies (e.g., U.S. Fish and Wildlife Service, National Park Service), NOAA, Army Corps, and U.S. Environmental Protection Agency (EPA) also are involved in coastal ecosystem restoration and protection activities.
- **Regulatory and Planning**. Much private and nonfederal coastal construction may also require Army Corps and EPA permits. Coastal states and territories develop and maintain their coastal zone management programs under the federal Coastal Zone Management Act (CZMA; P.L. 92-532, 16 U.S.C. §1451-1464) as implemented by NOAA.[9]

Future development and economic growth along U.S. coasts may depend, to a certain extent, on the perceived risk of coastal hazards and the efficacy and efficiency of policies and investments at the local, state, and federal levels to mitigate that risk. Arguably, rising sea levels and extreme coastal storms during the 20th and now 21st centuries generally have not curtailed growth and investments along U.S. coasts. A long-standing concern has been the extent to which the federal government may contribute to vulnerable coastal development directly or inadvertently (e.g., federal disaster assistance, federal infrastructure programs, and federal tax policies). For example, some contend that local stakeholders may make decisions that benefit them under the anticipation that they will receive federal disaster assistance when a coastal flooding occurs.

# Part I. What Is Sea-Level Rise?

Two descriptions of sea level are commonly used by scientists: global sea level (GSL) and relative sea level (RSL).

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8 For more on the pre-disaster mitigation program at the Federal Emergency Management Agency (FEMA), see CRS Report RL34537, *FEMA's Pre-Disaster Mitigation Program: Overview and Issues*, by Francis X. McCarthy.

9 For more on the Coastal Zone Management Act (CZMA; P.L. 92-532, 16 U.S.C. §1451-1464), see this report's section titled "Existing Federal Coastal Management Statutes ," or CRS Report RL34339, *Coastal Zone Management: Background and Reauthorization Issues*, by Harold F. Upton.

## Global Sea Level

Global sea level (GSL, sometimes *global mean sea level*) is the average height of the Earth's oceans, as measured by satellite altimetry relative to a calculated reference ellipsoid.[10] These global measurements, available since the first satellite ocean altimeters were placed in orbit in 1992, are combined so that height of the world's oceans can be averaged into one number. The GSL value is significant because it allows scientists to measure trends, namely GSL rise, without having to consider whether the land surface is moving up or down along the coastline.

Since 1992, satellites have measured an average GSL rise of about 3.2 mm per year (with a measurement error of +/- 0.4 mm per year, so that the range of GSL rise is 2.8 mm-3.6 mm per year).[11] (See **Table 1** and **Figure 1**.) Thermal expansion of the oceans and melting from glaciers have been the dominant contributors to 20th-century GSL rise.[12] Meltwaters from the Greenland and Antarctic ice sheets have also contributed to GSL rise, and these contributions may have increased in the 21st century.[13] Another contributing factor comes from water storage on land—water impounded behind dams would reduce the amount of GSL rise because less water reaches the oceans, whereas groundwater pumped from wells would contribute to GSL rise because more water reaches the oceans as runoff or in other parts of the hydrologic cycle.[14]

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[10] The *reference ellipsoid* is a theoretical construct that is related to gravity, or the center of mass of the Earth. The satellite system makes measurements of the sea surface as the satellite orbits the globe. The satellite then compares those measurements to the reference ellipsoid to calculate the height of the sea surface. The global sea level (GSL) is essentially the average of all the global satellite measurements.

[11] Intergovernmental Panel on Climate Change (IPCC), Chapter 13 in *Climate Change 2013: The Physical Science Basis*; *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. T. F. Stocker et al. (Cambridge, U.K., and New York, NY: Cambridge University Press, 2013), p.1150. Hereinafter referred to as IPCC, The Physical Science Basis, Working Group I, 2013. Some references indicate a GSL rise of about 3.3 mm per year. Both values are within the range of uncertainty indicated above.

[12] See NOAA, National Ocean Service, *Is Sea Level Rising?*, at http://oceanservice.noaa.gov/facts/sealevel.html. For a more detailed summary, see IPCC 2013, p. 1139. *Thermal expansion* refers to the phenomenon in which as the oceans warm, the volume of seawater expands. *Glaciers* refer to all land ice masses, including those peripheral to (but not including) the Greenland and Antarctic ice sheets (IPCC 2013, p. 1151).

[13] IPCC, The Physical Science Basis, Working Group I, 2013, p. 1153. The IPCC states that the Greenland ice sheet contribution to GSL rise has *very likely* increased from 2002 to 2011 compared with 1992 to 2001 and that the Antarctic ice sheet contribution has *likely* increased over the same comparative time periods. In the IPCC report, the term *very likely* means a 90%-100% probability and the term *likely* means a 66%-100% probability. Some scientists have indicated that melting of the Antarctic ice sheet was a primary contributor to higher sea levels about 130,000 years to 150,000 years ago and could be a major factor in a future with continued atmospheric warming (Robert M. DeConto and David Pollard, "Contribution of Antarctica to Past and Future Sea-Level Rise," *Nature*, vol. 531 (March 30, 2016)).

[14] Researchers disagree on the magnitude of the contribution from water storage on land to sea-level changes. However, it appears that water impoundment may be a larger contributing factor than groundwater depletion. See, for example, Yoshilda Wada et al., "Fate of Water Pumped from Underground and Contributions to Sea-Level Rise," *Nature Climate Change*, vol. 6 (May 2, 2016), pp. 777-780. See also IPCC 2013, pp. 1155-1156.

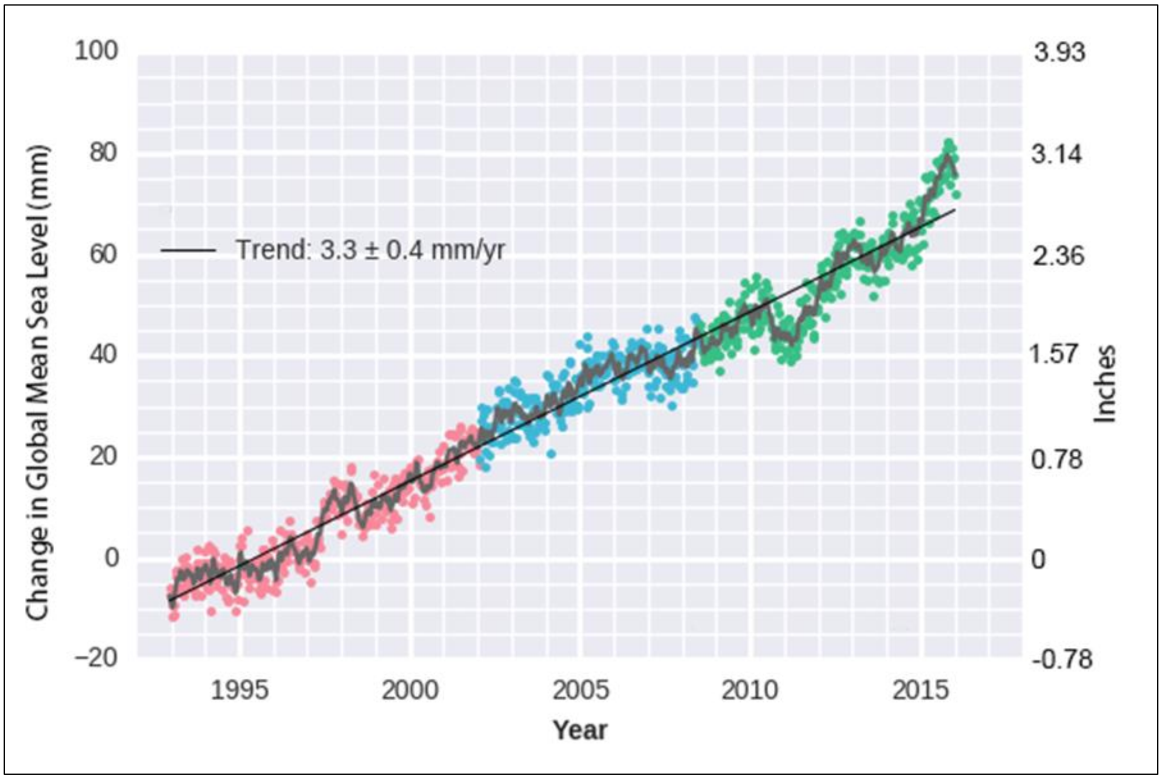
**Table 1. Global Sea Level (GSL) Trends**

| Range of Years | Average Increase (mm per year) | Range of Average Increase (mm per year) |
|---|---|---|
| 1901-2010 | 1.7 (0.067 inches) | 1.5-1.9 (0.059-0.074 inches) |
| 1992-2010 | 3.2 (0.13 inches) | 2.8-3.6 (0.11-0.14 inches) |

**Source:** Intergovernmental Panel on Climate Change (IPCC), Chapter 13 in *Climate Change 2013: The Physical Science Basis*; *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. T. F. Stocker et al. (Cambridge, U.K., and New York, NY: Cambridge University Press, 2013). Hereinafter referred to as IPCC, The Physical Science Basis, Working Group I, 2013.

**Notes:** The GSL trend from 1901 to 2010 was determined using a variety of measurements and estimation techniques; the trend from 1992 to 2010 was determined using satellite altimetry measurements.

**Figure 1. Global Sea-Level Rise from Satellite Measurements**

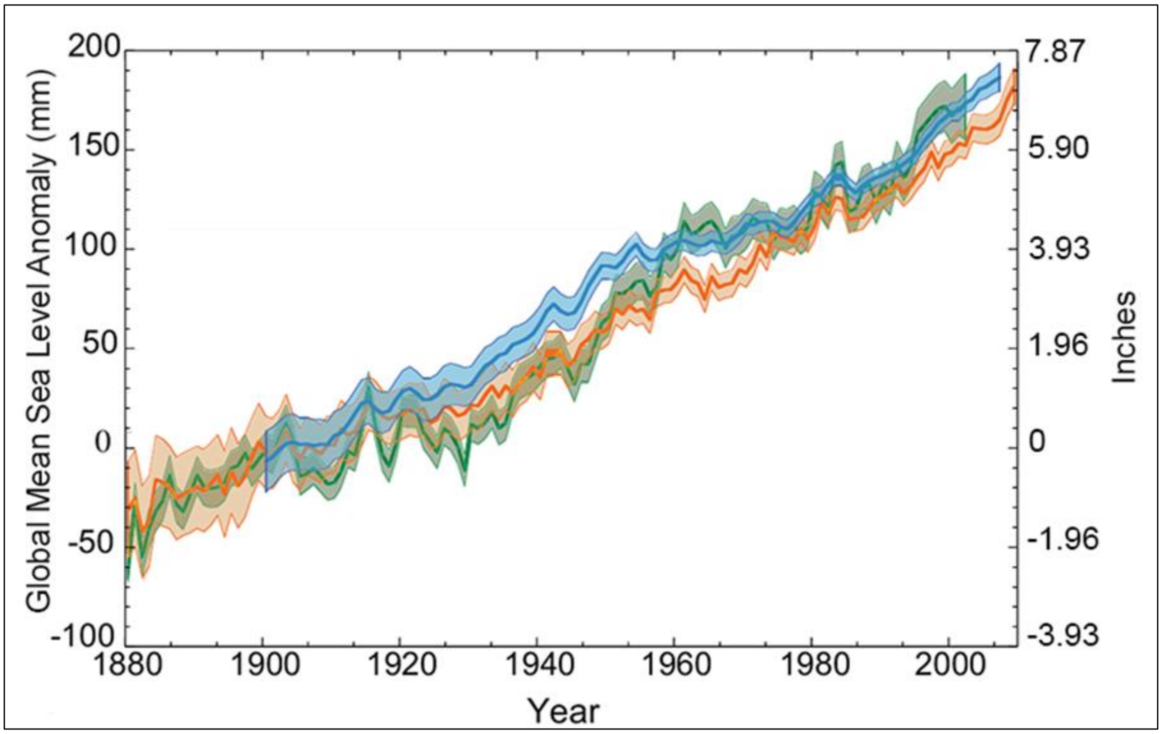



**Source:** University of Colorado (CU), CU Sea Level Research Group, *Global Mean Sea Level Time Series,* at http://sealevel.colorado.edu/.

**Notes:** The graph includes measurements from three different satellites, as shown by the three colors. Seasonal variations have been subtracted from the measurements. The trend reported in this graph is a rise of 3.3 millimeters (mm) per year (+/- 0.4 mm per year), slightly higher (by 0.1 mm per year) than the value reported by IPCC, The Physical Science Basis, Working Group I, 2013. See also NASA, Global Climate Change, *Sea Level*, at http://climate.nasa.gov/vital-signs/sea-level/, which reports a trend of 3.5 mm per year (+/- 0.4 mm per year). The uncertainty range of 0.4 mm per year means that all of these estimates are virtually the same number.

Since the early 1990s, the satellite record has provided a relatively direct measurement of GSL. However, this record is short—about 25 years—compared with other sea-level measurements using tide gages. Tide gage records stretch back to the 18th century in Europe,[15] and systematic tide gage measurements began in the United States in the 19th century.[16] Several investigations have applied a variety of techniques to estimate the trend in GSL since the beginning of the 20th century using tide gage data. (See **Figure 2**.) The IPCC reported that even though different strategies were employed to account for changes in land motion, it is *very likely* that GSL rose an average of 1.7 mm per year (+/- 0.2 mm per year) from 1901 to 2010 (about 187 mm total, or approximately 7.4 inches).[17] The IPCC also reported that it is *likely* that the rate of GSL rise increased from the 19th century to the 20th century. The average rate of 1.7 mm per year since 1901 is less than the rate measured by satellite altimeters since 1992; however, the rise in GSL has not been constant, according to the IPCC. For example, the IPCC reported that the trend of GSL rise in the satellite era is *very likely* higher than the average rate since 1901 but noted that it is also *likely* that GSL rose between 1920 and 1950 at a rate similar to that observed since 1992.[18]

**Figure 2. GSL Rise Since 1880 from Tide Gage Measurements**




**Source:** IPCC, The Physical Science Basis, Working Group I, 2013, Figure 3.13(a) in Chapter 3, p. 287. Figure modified by CRS.

[15] IPCC, The Physical Science Basis, Working Group I, 2013, p. 1146.

[16] Chris Zervas, *Sea Level Variations of the United States 1854-2006*, NOAA Technical Report NOS CO-OPs 053, December 2009, p. iii, at http://tidesandcurrents.noaa.gov/publications/Tech_rpt_53.pdf. Hereinafter referred to as Zervas, 2009.

[17] IPCC, The Physical Science Basis, Working Group I, 2013, p. 1150. In the IPCC report, the term *very likely* means a 90%-100% probability and the term *likely* means a 66%-100% probability.

[18] Ibid.

**Notes:** Three plots of GSL trends are shown in the figure from three studies that used different approaches to estimate sea-level values (see IPCC 2013, for the study references). The dark blue, red, and green lines show the average values for GSL computed in each study, and the shading represents the uncertainty with each GSL value. Global mean sea level anomaly (Y-axis) refers to global mean sea level (referred to as global sea level, or GSL, in this report) plotted relative to five-year mean values that start at the year 1900 using tide gage data.

Other factors complicate interpretation of satellite measurements, such as the role of volcanic eruptions.[19] One recent study noted that the eruption of Mt. Pinatubo in 1991 had a cooling effect on the atmosphere, which affected sea-level rise, suggesting that the era of satellite measurements began in a highly anomalous environment.[20] The study used a combination of modeling and analysis of satellite altimeter data to surmise that the Mt. Pinatubo eruption may have masked an acceleration of GSL that might otherwise have occurred. They study further concluded that barring another volcanic eruption, satellites may detect an acceleration of GSL rise in the coming decade.

## Regional Variation in GSL

GSL represents the average value for the elevation of the surface of the world's oceans, but any particular location in Earth's oceans will likely differ from the average value. Several factors influence sea-surface height at any particular location on Earth. For example, average sea-surface heights off Bermuda are typically 1 meter higher than average sea-surface heights off Charleston, SC, because the Gulf Stream changes direction toward Bermuda.[21] For the United States, average sea-surface heights are about 20 centimeters higher on the Pacific Ocean side than the Atlantic Ocean side because the water is less dense, on average, in the Pacific due to prevailing weather and ocean conditions.[22]

Overall GSL is rising, as **Figure 1**, **Figure 2**, and **Table 1** show; however, significant regional variation in trends of sea-surface height around the globe—in addition to the factors discussed above—adds further complexity. For example, coastal communities on the U.S. West Coast did not experience significant sea-level rise from 1993 to 2012, even though the global average rose 3.2 mm per year, because the eastern Pacific Ocean exhibited a decrease in sea-surface height (shown in blue on **Figure 3**). That decrease in sea-surface height has been attributed to natural climate variability, such as El Niño, and the resulting changes to winds, ocean currents, temperature, and salinity, all of which affect sea level.[23] However, some research indicates that the trend may have stopped and even reversed since 2012. This research indicates that another natural source of climate variability, the Pacific Decadal Oscillation (PDO),[24] is undergoing a

[19] J.T. Fasullo, R.S. Nerem, and B. Hamlington, "Is the Detection of Accelerated Sea Level Rise Imminent," *Scientific Reports*, vol. 6 (August 10, 2016); Hereinafter referred to as Fasullo et al., 2016. Other studies have also identified the effect of instrument drift (i.e., bias in the measurements) and natural short-term climate variability, such as El Nino. See, for example, Christopher S. Watson et al., "Unabated Global Mean Sea-level Rise over the Satellite Altimeter Era," *Nature Climate Change*, vol. 5 (May 11, 2015); and Anny Cazenave et al., "The Rate of Sea-Level Rise," *Nature Climate Change*, vol. 4 (March 23, 2014).

[20] Fasullo et al., 2016.

[21] UK Natural Environment Research Council, National Oceanography Centre, Permanent Service for Mean Sea Level, "Sea Level: Frequently Asked Questions," at http://www.psmsl.org/train_and_info/faqs/.

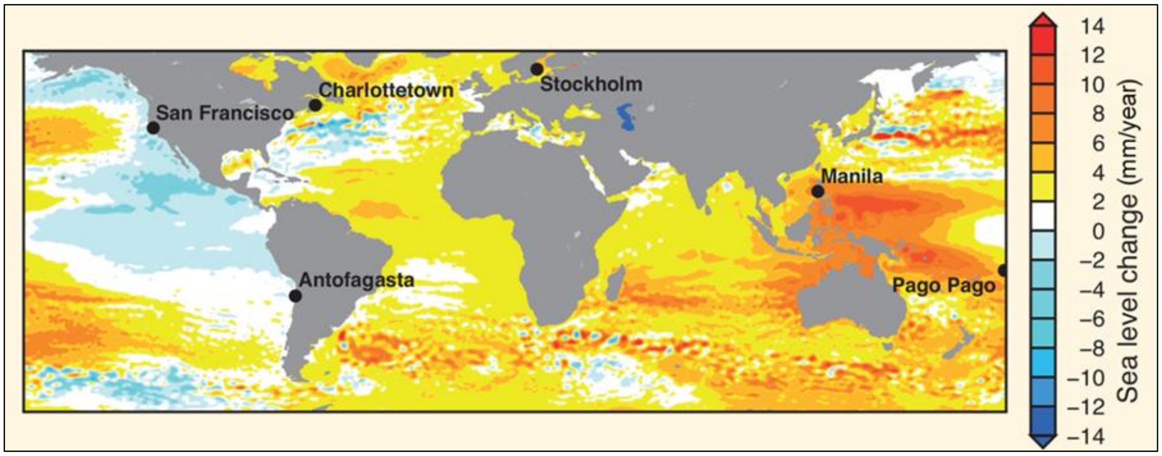
[22] Ibid.

[23] IPCC, The Physical Science Basis, Working Group I, 2013, pp. 1148-1149. In contrast, sea-surface heights in the western Pacific Ocean rose almost three times the global average of 3.2 mm per year (shown in red and orange in **Figure 3**), due largely to the same natural climate variability.

[24] The Pacific Decadal Oscillation (PDO) has been described as a long-lived El Niño-like pattern of Pacific climate variability, resulting in sometimes widespread variations in the Pacific Basin and North American climate. The PDO appears to wax and wane every 20 years to 30 years. See NASA, Jet Propulsion Laboratory, *Ocean Surface*
(continued...)

shift that is leading to higher sea levels in the eastern Pacific and lower sea levels in the western Pacific since 2012, the opposite of what is shown in **Figure 3**.[25]

**Figure 3. Rate of Change of Sea Surface Heights from 1993 to 2012**




**Source:** IPCC, The Physical Science Basis, Working Group I, 2013, Figure 13.1, p. 1148. Figure modified by CRS.

**Notes:** The changes were derived from satellite measurements. For comparison, the global average for sea level rose about 3.2 mm per year over the time period 1993-2012; this map shows the wide regional variation from falling sea levels (cooler colors, such as off the west coast of North America) to rapidly rising sea levels (warm colors, such as in the western Pacific, near Manila).

## Relative Sea Level

Relative sea level (RSL) refers to the elevation of sea level relative to the land surface from which it is measured. In many parts of the U.S. coastline, the elevation of the land surface is changing, due to a number of different causes. A change in RSL represents the combination of the change in land surface elevation and the change in GSL. At any two spots along the U.S. coastline, the trend in RSL value may be significantly different. This variation occurs because of the regional variation in GSL (discussed above) combined with regional variation in how the land surface elevation is changing. **Figure 4** illustrates how different the change in the trend of RSL can be within the United States.

As the colored dots on **Figure 4** indicate, the trend and direction of RSL varies dramatically in the United States. RSL is rising at a rate of 9 mm-12 mm per year along Louisiana's Mississippi Delta region near New Orleans, and RSL is dropping along parts of the Pacific Northwest coastline and southern Alaska. The land surface is sinking in places such as coastal southern Louisiana, increasing the rate of RSL rise, and the land surface is rising in parts of Alaska, outpacing the rise of GSL.

RSL rise has been recorded primarily using tide gages. In the United States, the National Water Level Observation Network, currently operated by NOAA, provides tide gage sea-level data from 210 stations,[26] two of which date to the 1850s.[27] The tide gage network was established to ensure

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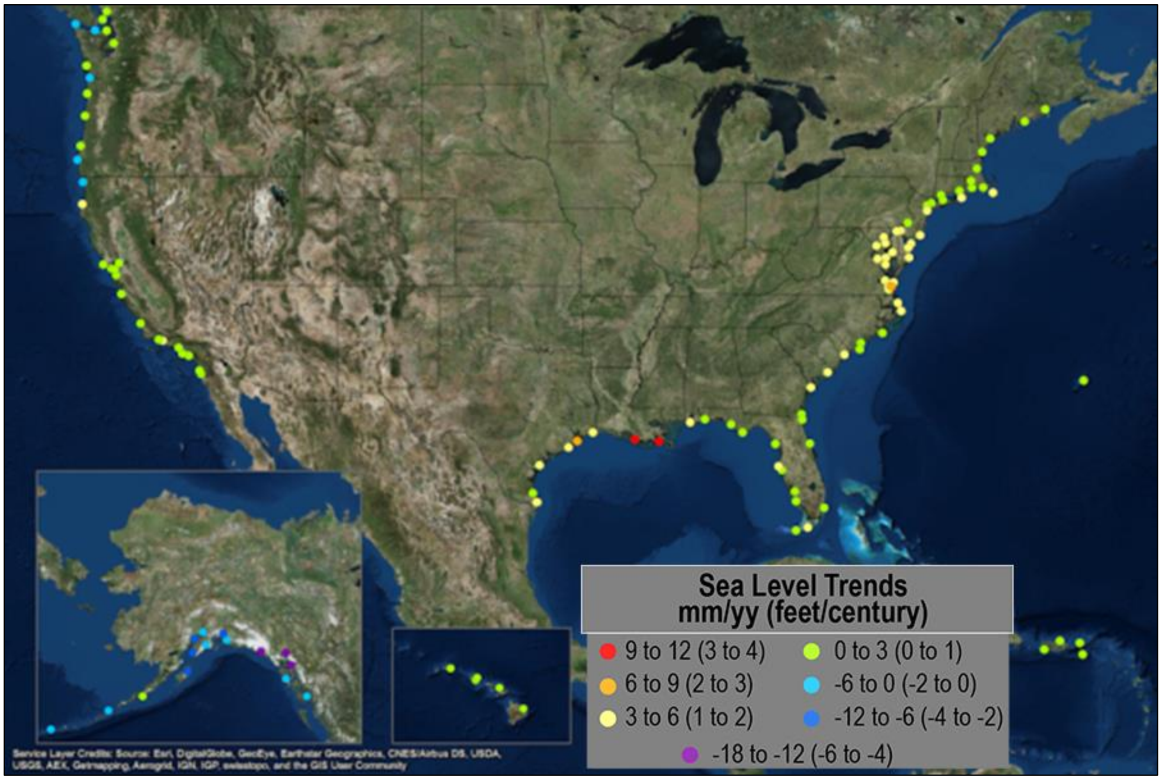
*Topography from Space,* Pacific Decadal Oscillation (PDO), at http://sealevel.jpl.nasa.gov/science/elninopdo/pdo/.

[25] B.D. Hamlington et al., "An Ongoing Shift in Pacific Ocean Sea Level," *Journal of Geophysical Research: Oceans,* vol. 121 (May 9, 2016), doi:10.1002/2016JC011815.

[26] NOAA, Tides & Currents, *The National Water Level Observation Network (NWLON)*, at
(continued...)

that nautical maps; shoreline maps; and elevations of homes, levees, and other coastal infrastructure were accurately referenced to sea level.[28] Trends detected in the tide gage network data, along with other sources of information, provide the long-term record of RSL for the U.S. coastlines.

**Figure 4. Relative Sea Level (RSL) Trends for the United States**




**Source:** National Oceanic and Atmospheric Administration, Tides & Currents, "U.S. Sea Level Trend Map," at http://tidesandcurrents.noaa.gov/sltrends/slrmap.htm. Modified by CRS.

**Note:** Map represents sea-level trends for 2014.

# Causes of Sea-Level Rise

GSL and RSL pose different policy challenges. **Figure 5** illustrates the factors contributing to GSL and RSL rise. The drivers for rising GSL since 1900 are predominantly thermal expansion of the oceans due to warming ocean water and melting glaciers and ice sheets (**Table 2**). The oceans have warmed due to a combination of natural variability and the influence of greenhouse gas (GHG) emissions on atmospheric temperatures. Similarly, glaciers and polar ice sheets have melted since 1900 due to a combination of natural variability and GHG-induced climate change and deposition of pollutants.

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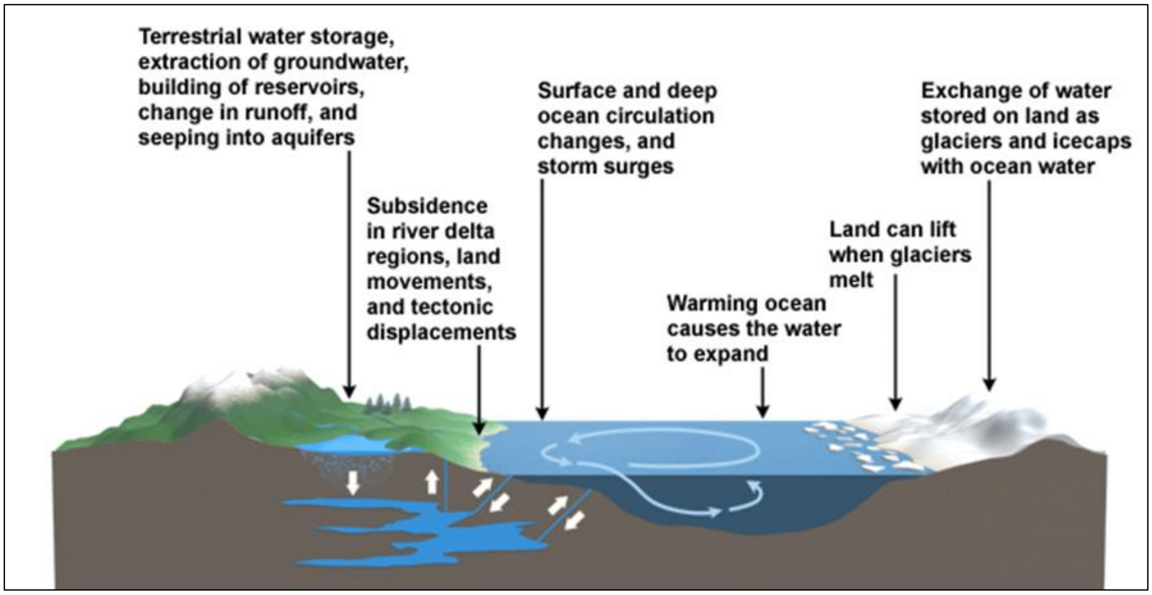
http://tidesandcurrents.noaa.gov/nwlon.html.

[27] Two stations, located in the Battery, New York City, and in San Francisco, have tide gage records from the 1850s.

[28] Zervas, 2009, p. iii.

The global factors driving RSL change include those that influence GSL, but in some cases regional or local factors are responsible for the largest changes in RSL along the coastlines. These regional or local factors can be natural, such as the land rebounding upward after continental ice sheets melted at the end of the last ice age,[29] or they can be due to human activities, such as groundwater pumping, oil and gas extraction, sediment compaction, land management practices, or other factors. (See **Table 2**.) Understanding the relative contributions from these different drivers of RSL rise is important for crafting responses to help coastal communities predict, mitigate, and adapt to the changing risks that sea-level rise brings.

**Figure 5. Factors Contributing to Sea-Level Rise**




**Source:** The COMET Program, University Corporation for Atmospheric Research, *Climate Change and Sea Level Rise*, at http://apollo.lsc.vsc.edu/classes/comet/climate/impacts/slr/powerpoint.htm.

**Table 2. Factors Influencing GSL Rise and RSL Rise**

| GSL | RSL |
|---|---|
| • Thermal expansion<br>• Melting of glaciers and ice sheets | • Thermal expansion<br>• Melting of glaciers and ice sheets<br>• Glacial isostatic adjustment<br>• Plate tectonics<br>• Natural compaction of |

[29] This phenomenon is referred to as *glacial isostatic rebound*, or *glacial isostatic adjustment*. This phenomenon occurs because the land surface underneath the continental ice sheets was depressed downward due to the weight of the ice. Since the ice melted, the land has slowly rebounded upward. That process continues today and is the primary reason why portions of the Alaska coast, and portions of Scandinavian countries' coastlines, are experiencing a decrease in their RSLs because the land is rebounding upward faster than GSL is rising. Although portions of Alaska's coast are not experiencing sea-level rise, Alaska's low-lying coastal communities are at risk from coastal erosion and flooding; some of these threats are resulting in relocation of villages. For more details on Alaska's coastal erosion flood risks, see GAO, *Alaska Native Villages: Limited Progress Has Been Made on Relocating Villages Threatened by Flooding and Erosion*, GAO-09-551, June 2009, at http://www.gao.gov/new.items/d09551.pdf.

| GSL | RSL |
|---|---|
| | sediments<br>• Groundwater extraction<br>• Oil and gas extraction<br>• Draining of organic-rich soils |

**Source:** Congressional Research Service (CRS).

**Note**: Other factors may also influence RSL rise, such as water impoundments on land and groundwater depletion, but those listed in **Table 2** are likely the largest contributors.

## Global Sea-Level Rise

According to some studies, precise satellite measurements of the Earth's energy budget and other global measurements since 1970 indicate that the net energy inflow to the climate system has increased and that the oceans have stored more than 90% of the increase in recent decades.[30] These studies also indicate that the expansion of seawater associated with this energy storage has contributed about 40% of the associated GSL rise since 1971.[31] Melting glaciers, combined with seawater expansion, explains about 75% of the rise in GSL over that period.[32] The contribution to GSL rise from the Greenland and Antarctic ice sheets is considered to have increased since the early 1990s, although the precise amounts are not well understood.[33]

### Greenhouse Gas Emissions and Natural Variability

Global GHG emissions have increased significantly since the late 19th century, and there is broad scientific agreement that the increased concentration of GHG in the atmosphere has exerted a discernible warming influence on both air and ocean temperatures, at least since the 1970s.[34] Global atmospheric temperatures have risen since the late 1800s, but what portion of warming can be attributed to human activities over that time period is not precisely known. GSL has risen at an average of 1.7 mm per year since about 1880, as shown in **Figure 2**. As with atmospheric temperatures, it is difficult to precisely attribute what proportion of GSL rise stems from human activities and what has been driven by natural influences (this is discussed further below in "Uncertainties in Future Global Sea-Level Rise Projections").

The three different studies of GSL rise plotted in **Figure 2** show variations at the interannual and decadal-scale time spans, but overall all three studies indicate a fairly similar upward slope over the century. As mentioned above, satellite measurements show that GSL rise has averaged about 3.2 mm per year since the early 1990s, an increase compared with the 100+ year average of 1.7 mm per year. The current average rate of GSL probably is not unprecedented; studies indicate that a similar rate of GSL rise likely also occurred from 1920 to 1950.

30 IPCC, The Physical Science Basis, Working Group I, 2013, pp. 1159-1160. The net energy inflow to the climate system (referred to often as the effective radiative forcing) has increased since 1970 as a result of increased concentrations of greenhouse gases. That means that the amount of energy received by the sun and stored in the Earth's climate system exceeds the amount of energy leaving the Earth.

31 Ibid., p. 1161.

32 Ibid., p. 1139.

33 Ibid.

34 For more on greenhouse gases and climate, see CRS Report R43229, *Climate Change Science: Key Points*, by Jane A. Leggett.

A challenge for policymakers and coastal communities is how to anticipate, plan for, and mitigate the effects of a longer-term overall rise in sea levels. The significant variations in sea-level rise occurring regionally and at the decadal time scale, such as those influenced by El Niño or the PDO, are superimposed on and may temporarily mask long-term trends of GSL rise.

## Uncertainties in Future Global Sea-Level Rise Projections

Policymakers may contend with a pattern of GSL rise that could look very different in the 21st century compared to what **Figure 2** shows, as the longer-term trends accumulate over time and regional trends change.[35] The IPCC, for example, concludes that it is *very likely* that the rate of GSL rise in the 21st century will exceed the rate observed in the 20th century.[36] Further, the IPCC states that sea level will continue to rise for centuries, with the amount dependent on future GHG emissions. In its assessment of future GSL rise, the U.S. National Climate Assessment expressed *very high confidence* that GSL will rise at least 0.2 meters but no more than 2.0 meters by 2100 (i.e., at least 8 inches to as much as 6.6 feet).[37] For coastal communities, highly confident assertions that sea level will rise are significant for planning. However, the difference between a rise of 0.2 meters and a rise of 2.0 meters between now and the year 2100 could signify different approaches to planning for, mitigating, and responding to the effects of sea-level rise.[38] This is discussed in more detail below in "Part II. Sea-Level Rise and U.S. Coasts."

Both the rate of future global sea-level rise and its exact dependence on future GHG emissions appear uncertain for several reasons. Probably the biggest uncertainty is the future behavior of the Greenland and Antarctic ice sheets.[39]

Estimates of the Antarctic ice sheet contributions to GSL rise between now and 2100 vary widely.[40] Continued GHG-driven warming in the future could create instability in the large ice sheets of West and East Antarctica and lead to collapse.[41] The collapse of large Antarctic ice sheets presents the largest potential for sudden GSL rise, but current scientific understanding of ice sheet dynamics does not identify what factor or factors would unambiguously lead to a rapid and unstable ice sheet retreat.[42]

In Greenland, melting has exceeded snow accumulation over the last few decades, so its ice sheet appears to have contributed to GSL rise.[43] This trend is expected to continue and even increase in

[35] IPCC, The Physical Science Basis, Working Group I, 2013, p. 1149.

[36] Ibid., p. 1205.

[37] Adam Parris et al., *Global Sea Level Rise Scenarios for the United States National Climate Assessment*, NOAA, NOAA Technical Report OAR CPO-1, December 6, 2012, p. 1, at http://scenarios.globalchange.gov/sites/default/files/NOAA_SLR_r3_0.pdf. Hereinafter referred to as Parris, 2012.

[38] Other studies give different ranges for projected sea-level rise in the 21st century, but the ranges are generally similar. For example, one study gave an upper limit of 1.9 meters of GSL rise by 2100 with only a 5% probability of occurring; see S. Jevrejeva, A. Grinsted, and J.C. Moore, "Upper Limit for Sea Level Projections by 2100," *Environmental Research Letters*, vol. 9, no. 10 (October 10, 2014), at http://iopscience.iop.org/article/10.1088/1748-9326/9/10/104008.

[39] Parris, 2012, p. 2.

[40] IPCC, The Physical Science Basis, Working Group I, 2013, p. 1177.

[41] Ibid., p. 1178.

[42] Ibid.

[43] Ibid. p. 1179.

the next century. Unlike Antarctica, however, Greenland does not appear to be at risk of sudden ice sheet collapse.[44]

Because the future behavior of both the Greenland and Antarctic ice sheets is relatively uncertain, an additional GSL rise of a few tenths of a meter on top of current projections is possible in the latter half of this century. GHG-driven climate forcing appears to be the main driver for future GSL rise. This implies that policies directed toward reducing sea-level rise would need to address the issue of global GHG emissions as a long-term approach to mitigating the effects of GSL rise.[45] However, many scientists conclude that GSL will continue to rise for centuries even if GHG concentrations in the atmosphere are stabilized and that other measures may be needed to address the consequences of such rise.[46]

## Relative Sea-Level Rise

In many locations along the U.S. coastline, the elevation of the land surface near the shore is changing in a vertical direction. Where the land is moving down, the rate of RSL rise increases; where the land is moving up, the rate of RSL rise decreases.

Several natural and human-caused factors influence RSL rise locally. Many of these factors could be amenable to regional and local policy alternatives to mitigate risks to communities and ecosystems. Some of these factors are discussed below.

### Natural Forces Influencing Relative Sea Level

Some of the changes in land elevation are caused by natural forces, such as post-glacial rebound (also called glacial isostatic adjustment, or GIA). GIA raising land elevation is occurring most rapidly where the ice was thickest in North America about 20,000 years ago, during the peak of the last ice age, in the region around Hudson Bay and in parts of the southern Alaskan coastline (see **Figure 4**). However, as the land previously buried under thick ice is now rising, land in most of the contiguous United States is sinking. This land is sinking in response to GIA because as the ice pressed down on the crust in the north 20,000 years ago, the land not buried under ice tilted up. Now the reverse is happening, and land previously tilted up is tilting back down, like a continent-sized seesaw. For much of the U.S. coastline, downward tilting is occurring at rates between 0.5 mm and 2 mm per year.[47] For the U.S. East Coast, land subsidence from GIA is about 1 mm-2 mm per year.[48] Policymakers cannot change GIA, but coastal communities could account for its contribution to RSL in their planning, mitigation, and response activities.

Plate tectonics and natural compaction of sedimentary layers in places such as river deltas are two other naturally occurring processes that cause vertical land movement. Regional uplift in parts of the Pacific Northwest coastline is likely occurring in response to tectonic activity associated with the Cascadia subduction zone (see **Figure 4**).[49] Loading of sediments from the Mississippi River,

[44] Ibid. For comparison, if the Greenland ice sheet melted completely, global sea levels would rise about 20 feet. If the Antarctic ice sheet melted completely, global sea levels would rise about 200 feet. See National Snow & Ice Data Center, *Quick Facts on Ice Sheets*, at http://nsidc.org/cryosphere/quickfacts/icesheets.html.

[45] For more information about global agreements on GHG emissions, see CRS Report R44092, *Greenhouse Gas Pledges by Parties to the United Nations Framework Convention on Climate Change*, by Jane A. Leggett.

[46] IPCC, The Physical Science Basis, Working Group I, 2013, p. 1205.

[47] Parris, 2012, p. 16.

[48] Ibid.

[49] S. Mazzotti et al., "Crustal Uplift and Sea Level Rise in Northern Cascadia from GPS, Absolute Gravity, and Tide (continued...)

shallow and deep compaction of sediments, and possibly faulting are likely responsible for some of the high rates of land subsidence in southern Louisiana, including the New Orleans area.[50]

## Human Activities That Affect Relative Sea Level

Despite the contributions from natural forces, most land subsidence in the United States is caused by human activities.[51] (See **Table 2**.) Groundwater withdrawals in excess of recharge to the aquifer from precipitation are responsible for about 80% of land subsidence in the United States.[52] Groundwater pumped to the surface decreases pressure in the aquifer, and the aquifer system compacts, resulting in land subsidence. For example, groundwater withdrawals in the southern Chesapeake Bay region have accounted for more than half of overall land subsidence in the region—about 1 mm-5 mm per year. Combined with GIA, these withdrawals have resulted in the region having the highest rate of RSL rise on the U.S. East Coast (**Figure 6**).[53] On the West Coast, land subsidence due to groundwater pumping was first recognized in the Santa Clara Valley in California.[54] At the northern end of the valley, land adjacent to San Francisco Bay dropped 2 feet-8 feet in elevation by 1969 since groundwater pumping began in the early 20th century, resulting in 17 square miles of formerly dry land sinking below high-tide level.[55]

(...continued)

Gauge Data," *Geophysical Research Letters*, vol. 34, no. 15 (August 14, 2007).

[50] Roy K. Dokka, "The Role of Deep Processes in Late 20th Century Subsidence of New Orleans and Coastal Areas of Southern Louisiana and Mississippi," *Journal of Geophysical Research-Solid Earth*, vol. 116, no. B6 (June 22, 2011). The coastline of southern Louisiana also has been affected by changes to the load of sediment carried downriver by the Mississippi River each year, due primarily to engineered changes, land use, and changes in river management along the river course over the past century or longer. For example, the sediment load carried downriver decreased markedly between 1950 and 1966. See the Coastal Wetlands Planning, Protection and Restoration Act website, "the Mississippi River Basin," at http://lacoast.gov/new/About/Basin_data/mr/.

[51] Devin Galloway, David R. Jones, and S. E. Ingebritsen, *Land Subsidence in the United States*, U.S. Geological Survey, U.S. Geological Survey Circular 1182, 1999, p. 1, at http://pubs.usgs.gov/circ/circ1182/pdf/circ1182_intro.pdf. Hereinafter referred to as Galloway, 1999.

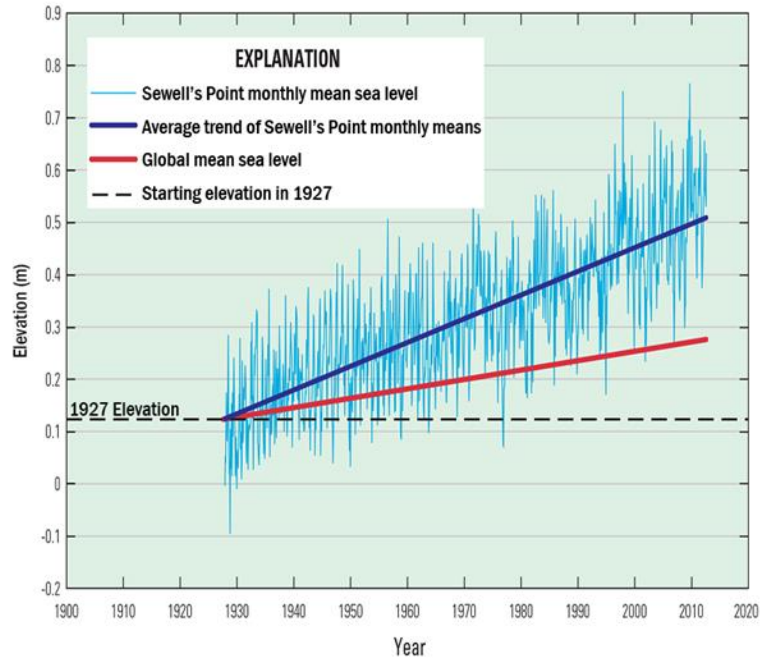
[52] Jack Eggleston and Jason Pope, *Land Subsidence and Relative Sea-Level Rise in the Southern Chesapeake Bay Region*, U.S. Geological Survey, U.S. Geological Survey Circular 1392, 2013, at http://pubs.usgs.gov/circ/1392/pdf/circ1392.pdf.

[53] Ibid., p. 2.

[54] Galloway, 1999, p. 16.

[55] Ibid., p. 18.

**Figure 6. Monthly Average Sea-Level Elevation at Sewell's Point, Norfolk, VA**




**Source:** Jack Eggleston and Jason Pope, *Land Subsidence and Relative Sea-Level Rise in the Southern Chesapeake Bay Region*, U.S. Geological Survey, U.S. Geological Survey Circular 1392, 2013, p. 18, at http://pubs.usgs.gov/circ/1392/pdf/circ1392.pdf.

**Notes:** Relative sea-level rise at Sewell's Point, located in southern Chesapeake Bay averaged 4.4 mm per year (+/-0.27 mm per year) from 1927 to 2006. Most of the difference between the dark blue line, showing relative sea-level rise, and the red line, showing global mean sea-level rise, is due to land subsidence at Sewell's Point.

In some locations, oil and gas extraction also causes land subsidence. Oil and gas pumped to the surface decreases pressure in the reservoir, and the reservoir system compacts, resulting in land subsidence. Land subsidence in the Houston-Galveston area in Texas from both groundwater and oil and gas extraction has resulted in RSL rates exceeding 25 mm per year in some locations at different times in the 20th century.[56] Oil and gas pumping-induced subsidence is largely restricted to the production field, whereas subsidence from groundwater pumping may have a more regional effect. Land subsidence in the Houston-Galveston area and the high rates of RSL rise likely have increased the frequency and severity of flooding in the region.[57]

Land subsidence also occurs when organic rich soils (often called *peats*) are drained of water for agricultural or other purposes. Organic rich soils can be up to 80%-90% water by volume. When these soils are drained, the effects of compaction, desiccation, and oxidation can result in subsidence. Reclamation of organic rich soils mainly for agricultural purposes in the Sacramento-San Joaquin Delta in California led to land subsidence of up to 25 mm-75 mm per year in places, resulting in some Delta islands subsiding as much as 15 feet below sea level.[58]

[56] Ibid., p. 37.

[57] Ibid., p. 37.

[58] Ibid., p. 86. "Islands" in the Sacramento-San Joaquin Delta are actually low-lying agricultural lands that are below the delta's surface level. The water is kept out by levees.

### Addressing Activities Contributing to Relative Sea-Level Rise

Groundwater withdrawal, oil and gas extraction, and draining of organic soils have long been recognized as factors leading to land subsidence. Land subsidence along the coastline exacerbates sea-level rise and increases the risks of flooding, seawater intrusion, and other impacts. Unlike for GIA or tectonic movements, policymakers could enact policies that mitigate land subsidence and potentially alter the rate of RSL rise along the coastlines. For example, some conclude that subsidence in the Houston-Galveston region led the Texas legislature to create the Harris-Galveston Subsidence District, which has the authority to restrict groundwater withdrawal.[59] In the Santa Clara Valley, local management of groundwater resources reduced land subsidence that had dropped 2 feet-8 feet in elevation by 1969 caused by groundwater pumping since the beginning of the century.

# Part II. Sea-Level Rise and U.S. Coasts

After a brief introduction to the effects of sea-level rise on U.S. coasts, Part II of the report is divided into the following three sections:

- effects on shorelines and ecosystems, which discusses how coastal processes and topography influence how U.S. shorelines and ecosystems may change with sea-level rise;
- effects on development and society, which describes U.S. coastal development and its coastal storm and nuisance flooding risks; and
- actions addressing the impacts of sea-level rise, which describes the activities of various federal agencies, existing federal coastal management statutes, and the role of public and private actions.

## Introduction to Effects of Sea-Level Rise on Coasts

The effects of sea-level rise on U.S. coasts can be broadly categorized as

- permanent or episodic inundation of low-lying lands,
- increased erosion and shoreline change (e.g., barrier island migration),
- increased impacts and damages from coastal storms, and
- saltwater intrusion of estuaries and aquifers.

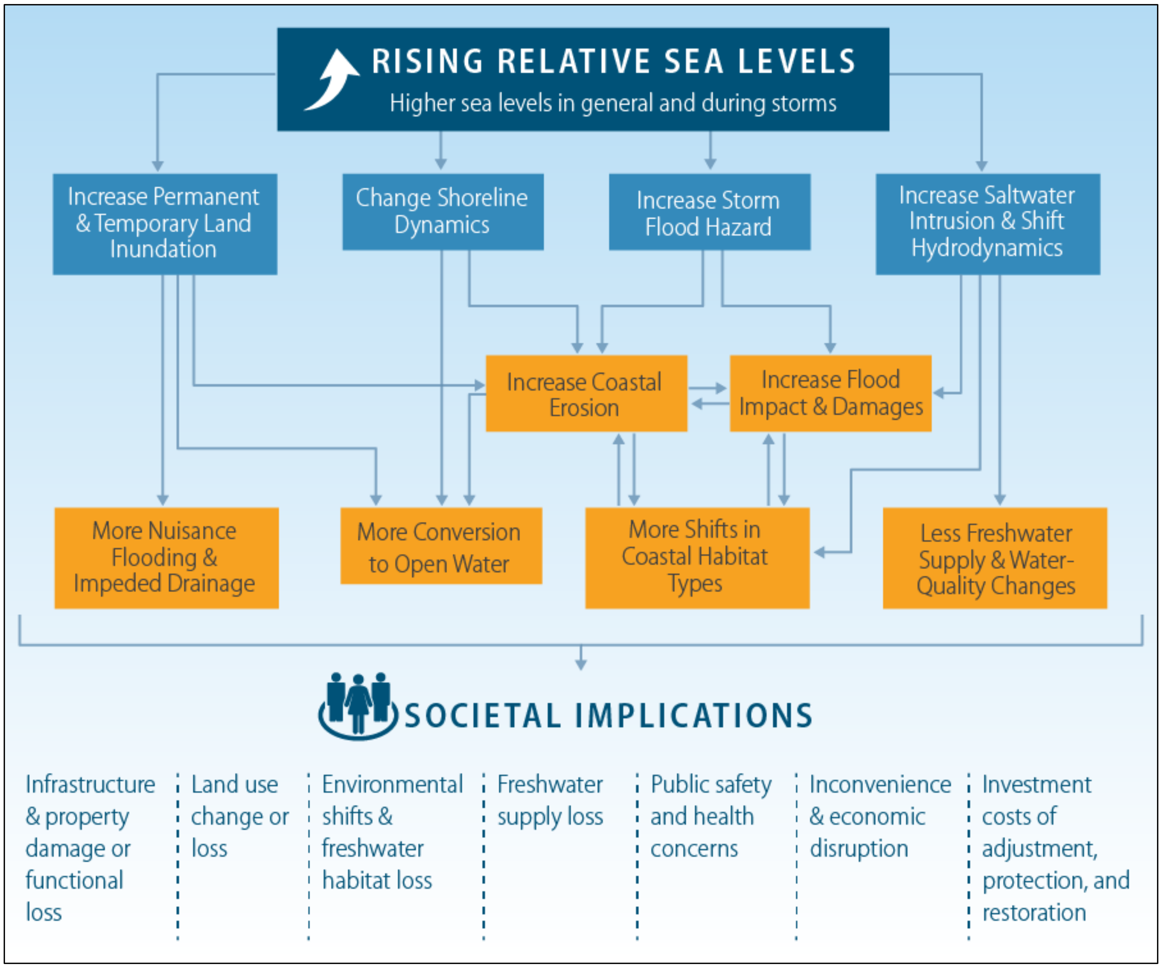
These physical effects have both environmental and societal consequences. **Figure 7** illustrates how a rising sea level influences coastal processes and resources and shows some of the societal implications.

A suite of potential policy response options exists for each effect. Policy choices on how to respond to sea-level rise may influence not only human behavior and investments along the coast but also what types of physical response (e.g., hard or nature-based shoreline stabilization) are undertaken to manage the impacts for undeveloped, somewhat developed, and extensively developed coastlines. For policymakers, choosing a response is challenging because of the difficult tradeoffs that each response represents (e.g., short- versus long-term costs and benefits, environmental or development losses or benefits). As previously noted, uncertainty in future rates

[59] Galloway, 1999, pp. 45-46.

of sea-level rise also complicates the decision context; for example, the estimated range of 0.2 meter (8 inches) to 2.0 meter (6.6 feet) of sea-level rise by 2100 makes it challenging to agree upon how to evaluate and compare the costs and benefits of alternative responses, policies, and investments.[60]

**Figure 7. Selected Coastal Effects of Relative Sea-Level Rise**




**Source:** CRS.

**Notes:** This illustration depicts how rising higher sea levels may influence a number of coastal processes and affect coastal terrestrial and estuarine ecosystems and society. Each process and impact shown also is affected by other factors in addition to sea-level rise. For example, coastal shoreline dynamics are influenced not only by sea-level rise but also by climate and weather patterns; nearshore hydrodynamics and geomorphology; coastal land development and use; infrastructure projects such as seawalls and dredging; and other factors.

[60] For example, one element of the analyses of benefits and costs that can become difficult to agree upon for long-lived infrastructure is the discount rate. The discount rate is the rate used to convert future costs and benefits into present values. Whether the rate should represent the opportunity cost of private capital or the social rate of time preference remains a topic of significant debate and disagreement among economists, decisionmakers, and other stakeholders. For more on the debate related to discount rates in the economic evaluation of federal water resources projects, including coastal flood risk reduction projects, see CRS Report R44594, *Discount Rates in the Economic Evaluation of U.S. Army Corps of Engineers Projects*, by Nicole T. Carter and Adam C. Nesbitt.

## Effects on Shorelines and Ecosystems

The effects of sea-level rise are dependent on a shoreline's topography and hydrodynamics. Coastal topography varies dramatically across the United States. Shorelines have varied forms—marsh, rocks, bluffs, beach, forest, and developed areas and infrastructure; each is affected differently by rising sea levels.[61] Some shorelines are directly exposed to wave action, whereas others are sheltered.[62] Some shorelines are highly erodible; others are resistant to erosion.

Because of natural coastal processes, some less-developed and undeveloped coastal areas may not necessarily be inundated by sea-level rise; instead, these areas may adapt to rising sea levels. Recent research suggests that 70% of the coastal landscape of the northeastern United States may have some capacity to adapt to sea-level rise—that is, many low-lying areas may be able to adapt rather than be inundated (e.g., marshes may build vertically in response to sea-level rise).[63] For example, unconsolidated sandy coasts have the capacity to adjust to changing conditions if nearby sand sources are available.[64] The availability of sand can be influenced by forces and events that shape coastal sediment transport and dispersion. For developed and rocky areas, a direct relationship between sea-level rise and inundation is likely. This diversity in vulnerability to sea-level rise is captured by the U.S. Geological Survey's effort to assess the U.S. Atlantic, Pacific, and Gulf of Mexico coasts, as shown in **Figure 8**.

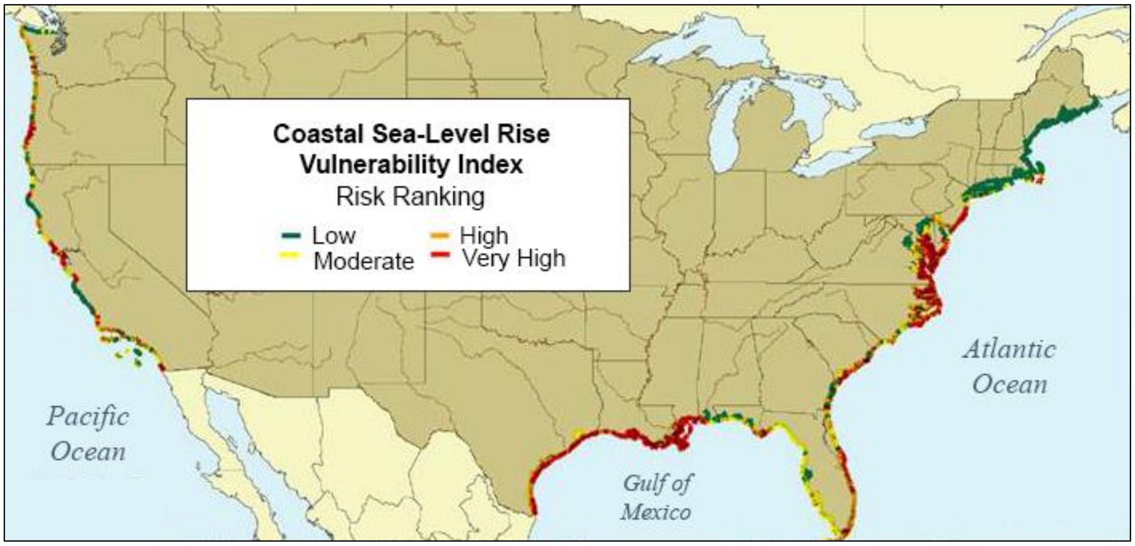
[61] Sandy areas may be reconfigured and become saturated without necessarily being submerged. Rocks and harder land forms are often most susceptible to inundation.

[62] Many sheltered shorelines are river valleys that have been drowned over the centuries or drainage features that are protected by headlands or islands. Many semi-protected sheltered shorelines border estuaries. A 2007 National Academy of Sciences report estimated that the United States has 850 estuaries representing over 80% the Atlantic and Gulf of Mexico coastal areas and more than 98% of the Virginia and Maryland coastlines (National Academy of Sciences, *Mitigating Shore Erosion Along Sheltered Coasts*, 2007, at http://www.nap.edu/download/11764).

[63] E. E. Lentz et al., "Evaluation of dynamic coastal response to sea-level rise modifies inundation likelihood," *Nature Climate Change*, March 14, 2016.

[64] The benefits of maintaining sediment within the near-shore coastal context for sea-level rise adaptation have been noted (J. G. Titus et al., *Coastal Sensitivity to Sea-Level Rise: A Focus on the Mid-Atlantic Region*, U.S. Climate Change Science Program and the Subcommittee on Global Change Research, Synthesis and Assessment Product 4.1, 2009). The federal agency most involved in actively managing sediments is the U.S. Army Corps of Engineers, as part of its navigation and coastal flood risk reduction projects.

**Figure 8. U.S. Coastal Vulnerability Index for the Atlantic, Pacific, and Gulf of Mexico**




**Source:** U.S. Geological Survey, National Assessment of Coastal Vulnerability to Sea Level Rise, at http://woodshole.er.usgs.gov/project-pages/cvi/images/largenat.jpg. Full 2001 data series available at http://pubs.usgs.gov/dds/dds68/. Figure modified by CRS.

**Notes:** Although the USGS assessment did not analyze the coastal vulnerability of the Alaska, Hawaii, territories, or insular areas, the USGS analyzed some portions of those coasts. For example, a USGS-National Park Service collaboration provides information on some coastal shorelines in Alaska, Hawaii, Virgin Islands, American Samoa, and Guam at http://woodshole.er.usgs.gov/project-pages/nps-cvi/parks/parklist.html.

For small islands and their populations, the options for adjustment to higher sea levels are particularly constrained. Understanding where inundation and dynamic coastal responses may occur is significant for understanding how coasts may evolve. How coasts evolve may determine which policies and investments are likely to be most effective for adjusting to higher sea levels.

In addition to sea-level rise, other local physical factors shape how higher sea levels affect shorelines. These factors include coastal slope, tidal range, wave height, sediment availability, and other geomorphic characteristics.[65] Short-term events, such as a large storm with intense surge and wave action, may contribute to rapid and concentrated coastal land loss or, in some other cases, cause land growth through accretion. Discerning where and under what climate conditions coastal processes are dominated by short-term events, such as storms, rather than long-term processes, such as sea-level rise, is part of the challenge of anticipating the evolution of U.S. coasts.

Assessing the potential effects of sea-level rise depends in part on the accuracy of coastal data and mapping, especially elevation information. Advances in research, monitoring, and data analyses—combined with greater incorporation of morphologic, ecologic, and anthropogenic factors—are anticipated to improve understanding of coastal dynamics and to enhance the efficacy of sea-level rise planning efforts.[66] Some effects of sea-level rise are particularly hard to

[65] Many current models and tools used to estimate and visualize the impacts of sea-level rise on U.S. coastal areas show inundation as a relatively simple function of elevation. These approaches are known as *bathtub models*. Although these models provide a first-order assessment of potential impacts, they fail to account for the complex and dynamic nature of coasts. Outputs of bathtub models are helpful (especially for developed coasts and fixed coastal infrastructure) but likely insufficient for understanding how coasts and coastal habitats evolve and change with changing sea levels.

[66] For example, a better understanding of how sea-level rise may affect artificial beach nourishment frequency and sand requirements would help federal, state, and local agencies to develop estimates of the potential long-term costs and (continued...)

predict. For example, complex interactions may influence the extent to which sea-level rise contributes to coastal lagoons experiencing changes in circulation, tidal exchange, and turbidity. How coastal changes may ultimately affect societal concerns, such as commercial fishing harvests, is challenging to predict. Moreover, fisheries changes may be more influenced by factors other than sea-level rise, such as higher water temperatures, coastal development impacts on habitat, and mortality from fishing activities.

## Coastal Wetlands and Habitats

Wetlands' ability to adjust to higher sea levels may depend in part on their ability to adjust vertically and to migrate inland.[67] Inland migration is partially determined by topography, as well as by the presence or absence of human settlements and coastal flood defenses.[68] For undeveloped coasts, the types of habitat and species in wetlands, bays, and estuaries may change with higher sea levels due to alterations in inundation frequency, salinity, and shoreline dynamics. For example, parts of a low-lying terrestrial ecosystem, such as the Florida Everglades, may transition from freshwater-dependent species to salt-tolerant species.

To illustrate variation in the effects of sea-level rise, one study attempted to identify how six coastal estuaries in Florida would lose or gain certain coastal terrestrial ecosystems under a 1-meter sea-level rise scenario.[69] Certain coastal habitat types—most notably coastal forest and undeveloped dry land—are likely to be lost, whereas other coastal habitats, such as mangroves, transitional saltmarsh, and saltmarsh, may become more common. Habitat transitions may take decades depending on the plant species involved. Changes in estuaries are of particular interest because of estuaries' productivity and value. Estuarine fish and shellfish species comprise a substantial portion of commercial and recreational catch.[70]

The rate of sea-level rise also may determine whether the coasts experience rapid and irreversible change or whether marshes, beaches, and barrier islands are able to adapt. For example, slower

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(...continued)

resource challenges for shoreline management (Coastal States Organization, *The Role of Coastal Zone Management Programs in Adaptation to Climate Change*, Final Report of the CSO Climate Change Work Group, September 2007).

[67] The primary processes associated with sea-level rise that influence wetlands are inundation, erosion, overwash, saturation, and accretion (L. L. Geselbracht et al., "Modeled Sea Level Rise Impacts on Coastal Ecosystems at Six Major Estuaries on Florida's Gulf Coast: Implications for Adaptation Planning," *PLoS ONE*, vol. 10, no. 7 (July 24, 2015)).

[68] Another consideration is the type of wetland. Wetland types identified in the continental United States include open coast, back-barrier lagoon marsh, estuarine embayment, estuarine brackish marsh, tidal fresh marsh, tidal fresh forest, nontidal brackish marsh, nontidal forest, and delta (Titus, *Coastal Sensitivity to Sea-Level Rise: A Focus on the Mid-Atlantic Region*, 2009) An example of planning for the movement of wetlands is at the Chesapeake Bay's Blackwater National Wildlife Refuge. Managers there designed corridors for the landward migration of habitat through the acquisition of easement and land (B. D. DeJong et al., "Pleistocene relative sea levels in the Chesapeake Bay region and their implications for the next century," *GSA Today*, vol. 25 [August 2015]). Other low-ling national wildlife refuges include Chincoteague (VA), Ding Darling (FL), Delta (LA), and Humboldt Bay (CA)

[69] L. L. Geselbracht et al., "Modeled Sea Level Rise Impacts on Coastal Ecosystems at Six Major Estuaries on Florida's Gulf Coast: Implications for Adaptation Planning," *PLoS ONE*, vol. 10, no. 7 (July 24, 2015).

[70] An analysis of data from 2000 to 2004 estimated that estuarine species comprised 46% by weight and 68% by value of the total U.S. commercial landings with considerable regional variation. For example, estuarine species represented more than 97% of the landings by weight in the Chesapeake and Gulf of Mexico, 77% in the North Atlantic, 76% for the Pacific Northwest, and 15% in Alaska. For recreational landings during the same period, estuarine species comprised approximately 80% of the U.S. harvest. (K. A. Lellis-Dibble, K. E. McGlynn, and T. E. Bigford, *Estuarine Fish and Shellfish Species in U.S. Commercial and Recreational Fisheries*, NOAA, NOAA Technical Memorandum NMFS-F/SPO-90, November 2008, http://www.habitat.noaa.gov/pdf/publications_general_estuarinefishshellfish.pdf).

rates of sea-level rise may allow for some coastal ecosystems (mangroves, estuarine beach, and ocean beach) to adjust and persist. However, these ecosystems types may convert into open water with faster rates of sea-level rise. The relatively rapid rate of RSL rise in portions of Louisiana and the low-elevation of coastal lands make portions of the state particularly susceptible to the conversion of land into open water.

## Coastal Erosion

How sea-level rise may alter coastal erosion is a function of the land forms and the nearshore hydrodynamics (e.g., the changing role of reefs and wetlands in dampening wave energy as the result of higher water levels and potential changes in storm surges). The extent to which erosion can be attributed to sea-level rise versus other human activities (e.g., dredged navigation channels, shoreline armoring,[71] inland dams' capture of sediment) is often difficult to distinguish. For the mid-Atlantic, erosion is anticipated to dominate changes in shoreline position in response to sea-level rise and storms over the next century. For some higher sea-level rise scenarios, some barrier islands may undergo significant changes, such as segmentation or rapid island migration.[72] Research on coastal erosion in Hawaii found that shoreline change rates varied greatly around each island; the study estimated that the average shoreline recession in 2050 would be nearly twice the historical extrapolation of past recession rates.[73]

[71] Shoreline armoring is the practice of using physical structures to protect shorelines from coastal erosion. For example, groins are structures built typically perpendicular to the shore that interrupt water flow and limit the movement of sediment, and jetties are hardened structures built at inlets to manage the sediment entering the inlet's channel. Other types of shoreline armoring include seawalls and engineered offshore breakwaters.

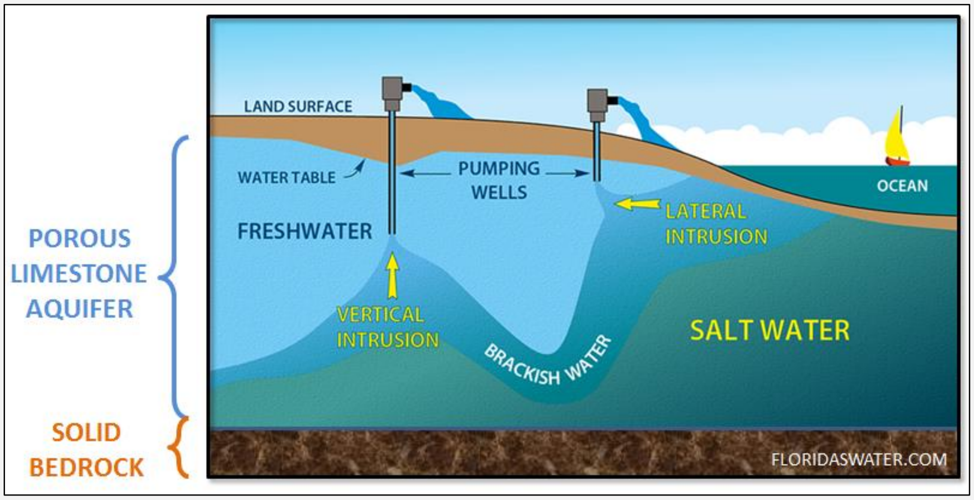
[72] J. G. Titus et al., *Coastal Sensitivity to Sea-Level Rise: A Focus on the Mid-Atlantic Region*, U.S. Climate Change Science Program and the Subcommittee on Global Change Research, Synthesis and Assessment Product 4.1, 2009.

[73] T. R. Anderson et al., "Doubling of coastal erosion under rising sea level by mid-century in Hawaii," *Nat Hazards*, March 18, 2015. Barrier islands are elongated, shore-parallel accumulations of unconsolidated materials; they are typically made primarily of sand and are separated from the mainland by water (e.g., bays, lagoons, or wetlands). Data from the 2000 census were used to estimate the barrier island population of the Atlantic and Gulf Coasts. The estimate was 1.4 million people; the barrier island population increased 14% from 1990 to 2000, with Delaware's barrier islands almost doubling during those ten years (K. Zhang and S. Leatherman, "Barrier Island Population along the U.S. Atlantic and Gulf Coasts," *Journal of Coastal Research*, vol. 27 (2010), pp. 356-363). Half of the estimated barrier island population in 2000 was in Florida, while New York's barrier islands had the highest population density.

## Sea-Level Rise and Groundwater

Rising sea levels have the potential to affect groundwater at the coastline and further inshore. For the coastal plains, which include some of the world's most prolific aquifers (such as the Atlantic and Gulf Coastal Plains of North America), the most characteristic type of water-quality degradation is saline-water intrusion (i.e., seawater entering the freshwater aquifer). At the seaward edge of a coastal plain aquifer, the relatively denser subsurface seawater lies beneath the less dense freshwater aquifer as a "wedge." Under natural conditions, groundwater in the aquifer—recharged by rainfall events—flows toward the sea and prevents the saltwater wedge from growing inland. However, human actions, such as groundwater pumping, may reduce groundwater flow toward the coastline, which often results in saline-water *encroachment*. In some cases, when freshwater wells are contaminated with saline water, they must be abandoned. For example, groundwater pumping in the 1930s lowered the water table under Brooklyn, NY, by 30 feet-50 feet, allowing saline-water encroachment and contamination of the aquifer.

**Figure 9. Groundwater Pumping and Saltwater Intrusion in Coastal Aquifers**




**Source**: Brian McNoldy, *Water, Water, Everywhere: Sea Level Rise in Miami*, University of Miami, Rosenstiel School of Marine & Atmospheric Science, October 3, 2014, at http://www.rsmas.miami.edu/blog/category/meteorology-physical-oceanography/.

Sea-level rise is expected to change the dynamics between the overlying freshwater aquifer and the underlying saline water wedge, which, in some scenarios, would grow inland and upward as sea levels rise. Several studies have examined possible scenarios in which sea-level rise would result in some saline-water encroachment and have an adverse effect on freshwater supplies, particularly for wells that are close to the coastline. The effects of sea-level rise are complicated by human activities, such as groundwater pumping, paving of the land surface (thus reducing the amount of recharge), the installation of surface water drains, and other types of development. Several studies indicate that if the amount of groundwater flow toward the coastline is not altered, then the saline-water intrusion may not change substantially even with rising sea levels under certain conditions. If sea levels are rising, however, and the amount of groundwater flow is altered by increased groundwater pumping, drainage, or runoff from surface water bodies, then the saline-water wedge may intrude inland substantially.

Under the scenario described above in which groundwater flow to the coastline is not altered, sea-level rise may cause a different problem that could affect groundwater tables and may even cause flooding further inshore of the coastline. One study refers to this scenario as the *lifting process,* whereby rising sea levels would cause the water table to rise in the coastal plain aquifer. A rising water table would mean that the amount of storage capacity in the aquifer would decrease because the distance between the land surface and the top of the water table would shrink, reducing the volume available to store rainwater infiltrating down during a storm. In some cases, that shift may induce flooding during high-rainfall events in which the amount of precipitation would exceed the amount of storage capacity in the aquifer. The combination of a rising water table due to sea-level rise and potentially more intense precipitation during severe storms due to climate change may result in an increased risk of inland flooding.

The scenarios described here would also apply to islands, such as Long Island, NY, or barrier islands along the Atlantic or Gulf coastlines, which depend at least in part on aquifers for their freshwater supplies. The complexity of the aquifers, combined with the different levels of coastal development along U.S. coastlines, complicates broad generalizations regarding how rising sea levels would affect particular coastal communities. However, continued sea-level rise likely will have some effect on those coastline and island communities that pump groundwater for their freshwater supplies.

**Sources**: C. W. Fetter, "Coastal Plain Aquifers," in *Applied Hydrology*, 2nd ed. (Columbus, OH: Merrill Publishing Company, 1988), pp. 305-306; Sun Woo Chang et al., "Does Sea-Level Rise Have an Impact on Saltwater Intrusion?" *Advances in Water Resources*, vol. 34 (June 22, 2011); Adrian D. Werner and Craig T. Simmons, "Impact of Sea-Level Rise on Sea Water Intrusion in Coastal Aquifers," *Ground Water*, vol. 47, no. 2 (2009), pp. 197-204; F. Bloetscher et al., "Assessing Potential Impacts of Sea Level Rise on Public Health and Vulnerable Populations in Southeast Florida and Providing a Framework to Improve Outcomes," *Sustainability*, vol. 8, no. 4 (March 2016).

## Effects on Coastal Development and Society

In addition to the anticipated effects of sea-level rise on shorelines and coastal ecosystems, sea-level rise may have broader societal implications through its effects on developed areas of the U.S. coast. For developed coastal areas, higher relative sea levels can increase the frequency and duration of nuisance flooding,[74] as well as contribute to the risk associated with coastal storms. Saltwater intrusion into estuaries and aquifers may also affect freshwater availability for coastal communities. (For more, see the box "Sea-Level Rise and Groundwater.") Sea-level rise may pose particular physical, economic, and cultural challenges for islands and their economies (e.g., Hawaiian islands, Florida Keys) as well as the islands of U.S. territories and freely associated states.[75]

### Coastal Development

Some U.S. coastal activities and developments are located at the coast due to necessity, such as ports and fishing operations and certain military installations, or for cultural reasons, such as communities of indigenous coastal peoples. Other investors and households choose to locate on the coast. The recreational, aesthetic, and lifestyle amenities of the coasts often are a particular attraction. Some coastal areas are known for high property values and incomes. Other coastal areas have populations with more limited economic means or are otherwise considered to be socially vulnerable; these groups may have fewer resources available to prepare for sea-level rise or to cope with some of the consequences.

U.S. states vary in how much of their coasts are developed, intermediately developed, undeveloped, or actively conserved. For example, along the Atlantic coast, the jurisdictions (including areas that are tidally influenced) with the highest percentage of developed lands within 1 meter of sea level are the District of Columbia (82%), Connecticut (80%), and New York

[74] W. Sweet et al., *Sea Level Rise and Nuisance Flood Frequency Changes around the United States*, NOAA, June 2014. Studies that provide estimates of the potential value of infrastructure at risk often use the elevation of coastal properties. These studies often do not account for natural or man-made defenses or for the complexity of coastal processes. For example, according to one 2014 study, $1.6 trillion in coastal property is located between mean sea level and the high-tide levels (Rhodium Group, *American Climate Prospectus: Economic Risks in the United States*, prepared as input to the Risky Business Project, June 2014). Determining the extent to which this inventory is at risk and how that risk may evolve over time and for different rates of sea-level rise as the result of changes in defenses and coastal processes, however, requires more data and complex modeling.

[75] For more on sea-level rise impacts associated with Hawaii and U.S. Affiliated Pacific Islands, see J. -A. Leong et al., Ch. 23 Hawai'i and U.S. Affiliated Pacific Islands, in *U.S. Global Change Research Program, Climate Change Impacts in the United States: The Third National Climate Assessment*, J. M. Melillo, T.C. Richmond, and G. W. Yohe, eds., 2014, pp. 537-556. For more on cultural issues, see T. M. Bennett et al., Ch. 12 Indigenous People, Land, and Resources, in *U.S. Global Change Research Program, Climate Change Impacts in the United States: The Third National Climate Assessment*, J. M. Melillo, T.C. Richmond, and G. W. Yohe, eds., 2014, pp. 297-317.

(73%). The Atlantic coastal states with the most land within 1 meter of sea level that is either undeveloped or conserved are Maryland (65%), North Carolina (58%) and Georgia (57%).[76]

Many factors shape development patterns, including state and local restrictions on land use and coastal structures, as well as demand and financing for such development. Land use in the United States, other than federal lands, is the jurisdiction of state and local governments. Similarly, state and local entities adopt building requirements and building codes (although some federal programs may require compliance with certain standards and requirements). Some states have considerably more assets, people, and businesses at risk than others. For example, many of Florida's coastal counties have vulnerable roads, ports, airports, and energy facilities and a significant coastal recreation economy, as well as significant population centers and private property, which may be impacted by rising sea levels.[77] For a discussion of the implications of sea-level rise for California's shorelines and the state's water supply system, see "California and Sea-Level Rise" box.

**California and Sea-Level Rise**

According to a National Academy of Sciences 2012 report, *Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future*, higher sea levels magnify the adverse impact of storm surges and high waves on the coast. The authors of the report derived relative sea-level rise estimates for California. For the San Francisco Bay Delta specifically, relative sea level was estimated to increase from 2000 levels by roughly 0.5 feet by 2030, 1 foot by 2050, and 3 feet by 2100. The report also stated that the incidence of extreme high-water events in the San Francisco Bay area would increase from less than 10 hours per decade (from 1970-1999) to several thousand hours per decade by 2100. Earthquake-induced changes were not factored into these estimates.

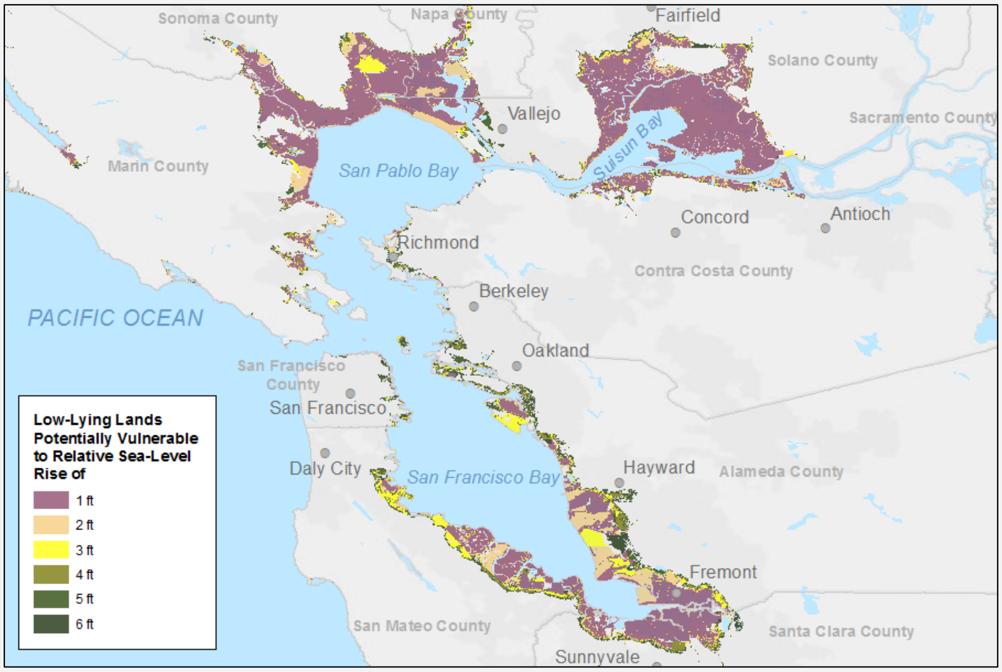
**Figure 10** illustrates low-lying lands near San Francisco that are vulnerable to higher sea levels. Significant development and infrastructure along the edge of central and southern San Francisco Bay—such as two international airports, a naval air station, freeways, housing developments, and sports stadiums—have been built on fill that raised the land level a few feet above the current high tides. A significant amount of the lands in the illustration are undeveloped (e.g., tidal mudflats and wetlands). To what extent these undeveloped lands and their habitats would adjust to higher sea levels or be inundated would depend on complex coastal and estuarine processes (e.g., sediment deposition). While generally not captured by the low-lying lands illustration below, the region's coastal cliffs (and the infrastructure and development associated with them) also may be affected by higher sea levels. Roughly 70% of the California's coastline (790 miles) is characterized by steep, actively eroding sea cliffs. Cliffs are altered by a combination of short-term events such as storms, nearby faults that shift terrain up or down, and long-term processes such as global sea-level rise. Another complicating factor is the apparent shift in the Pacific Decadal Oscillation (PDO, discussed above in **Figure 3**). The apparent shift in the PDO since 2012 may lead to higher sea levels in the eastern Pacific Ocean and lower sea levels in the western Pacific, the reverse of what occurred from 1993 to 2012. This shift to higher sea levels in the eastern Pacific could exacerbate the adverse impact of sea-level rise, storm surges, and high waves on the California coastline.

The San Francisco Bay and San Joaquin and Sacramento Rivers Delta (Bay-Delta), the western portion of which is shown in **Figure 10**, has a significant role in California's water supply system. Freshwater from the Sacramento and San Joaquin Rivers flows into the Bay-Delta and is pumped to users south of the Bay-Delta; some water users also pull water directly from the Bay-Delta. A September 2014 Bureau of Reclamation report, *Sacramento and San Joaquin Basins Climate Impact Assessment*, noted that sea-level rise could contribute to future challenges associated with managing salinity. The report states that future sea-level rise may result in management decisions to allow more freshwater to flow toward the ocean to temper saline water intrusion into the Bay-Delta. If such a management decision were to be made, it could result in less water available for delivery to water contractors, according to the Bureau of Reclamation report.

[76] J. G. Titus, et al., "State and local governments plan for development of most land vulnerable to rising sea level along the US Atlantic coast," *Environ. Res. Lett.*, 2009.

[77] According to some estimates, up to $15 billion in coastal property in Florida could be inundated by sea-level rise by 2030 and $23 billion by 2050 (Risky Business, *Come Heat and High Water: Climate Risk in the Southeastern U.S. and Texas*, July 2015, at http://riskybusiness.org/site/assets/uploads/2015/09/Climate-Risk-in-Southeast-and-Texas.pdf).

**Figure 10. Low-Lying Lands near San Francisco, CA**




**Source:** CRS using data from NOAA, Vital Signs, and Esri.

**Notes:** Illustration is based largely on elevation data. It does not account for potential dynamic responses (e.g., marshes that may build vertically in response to sea-level rise) and other processes (e.g., erosion) that may alter the spatial extent of terrestrial effects. NOAA elevation data for other coastal areas can be accessed at https://coast.noaa.gov/dataviewer/#/lidar/search/.

## Coastal Storm Risk

Sea-level rise exacerbates the risks associated with flooding from coastal storms and precipitation. The extent to which sea-level rise may increase the risk of flooding from coastal storms to developed areas depends on the specifics of the storm (e.g., occurrence during high or low tide) as well as on the local characteristics of the coast. In some locations, new coastal and tidal areas may be at risk of coastal storm flooding due to higher seas allowing storm surge and floodwaters to penetrate further inland.[78] Sea-level rise also may increase flood damages by inhibiting drainage of precipitation and floodwaters in low-lying areas.

Coastal storms can result in some of the most expensive natural disasters in the United States; therefore, potential increases in damages may raise federal, state, and local financial concerns related to disaster response and recovery.[79] A U.S. Environmental Protection Agency report using

[78] An illustration of how the New York City 100-year flood zone may change under sea-level rise scenarios is included in the New York City Panel on Climate Change's report on *Climate Risk Information 2013: Observations, Climate Change, Projections, and Maps*, June 2013, at http://www.nyc.gov/html/planyc2030/downloads/pdf/ npcc_climate_risk_information_2013_report.pdf. The report also states that based on its projections for sea-level rise in 2050, the current 100-year flood (1% probability) flood would be roughly five times more likely by 2050.

[79] Congressional Budget Office (CBO) presented its analysis of the future significance of hurricane damages for the federal budget in its June 2016 report, *Potential Increases in Hurricane Damage in the United States: Implications for the Federal Budget*, at https://www.cbo.gov/sites/default/files/114th-congress-2015-2016/reports/51518-Hurricane- (continued...)

climate change projections estimated the potential future economic impacts of combined storm surge and sea-level rise on U.S. coastal property. The report estimated that cumulatively during this century (2000-2100), adaptation to and damages from the combined coastal flood hazard to infrastructure and property could cost $0.8 trillion in the United States; these costs represent investments in cost-effective protective measures, storm damages (not addressed by the protective measures), and abandoned property.[80]

Sea-level rise increases flood risk by increasing the flood hazard from storms and precipitation; the higher hazard means that more coastal areas are more vulnerable. Flood and other types of natural-disaster risk are often expressed as a probabilistic function of

- a hazard, which is the local threat of an event (e.g., probability of a Category 5 hurricane storm surge);
- vulnerability, which allows a threat to cause consequences (e.g., level of protection and performance of shore-protection measures); and
- consequences of an event (e.g., loss of life, property damage, economic loss, environmental damage, reduced health and safety, and social disruption).[81]

For sea-level rise, some stakeholders promote policies to reduce the hazard (e.g., climate change mitigation, reduced groundwater withdrawal). Others are interested in reducing vulnerability (e.g., shore-protection measures, storm-surge gates). Other stakeholders support policies to reduce consequences through hazard-mitigation measures, such as development restrictions, building codes, flood-proofing of structures, buyouts of vulnerable properties, and improved evacuation routes.[82]

## Coastal Nuisance Flooding

Relative sea-level rise contributes not only to flooding from large storms but also to the incidence and duration of lesser flood events (e.g., regular flooding during high tides); these events are known as nuisance flooding, because a main impact is public inconvenience, or sometimes referred to as "sunny day" flooding because the flooding often is not associated with a storm or precipitation. Nuisance flooding often consists of shallow flooding of infrastructure and buildings, as shown in **Figure 11**. According to NOAA's 2014 report, *Sea Level Rise and Nuisance Flood Frequency Changes around the United States*, nuisance flooding has increased

(...continued)

Damage.pdf. (Hereinafter referred to as CBO 2016.) CBO estimated the current federal spending associated with hurricanes at $18 billion, and stated that the federal spending has recently covered about 60% of the economic damage from hurricanes. CBO's analysis indicates that federal spending as a percentage of a hurricane's economic damage has been increasing since the early 2000s but that the percentage varies considerably from hurricane to hurricane. Since 2005, federal spending for some hurricanes has been less than 25% of the economic damage (e.g., Hurricane Dolly in 2008) and exceeded 70% for other hurricanes (e.g., Hurricanes Katrina and Sandy). Of the 16 hurricanes that CBO analyzed, the two storms with the highest percentages of federal spending were the two storms causing the largest economic damage.

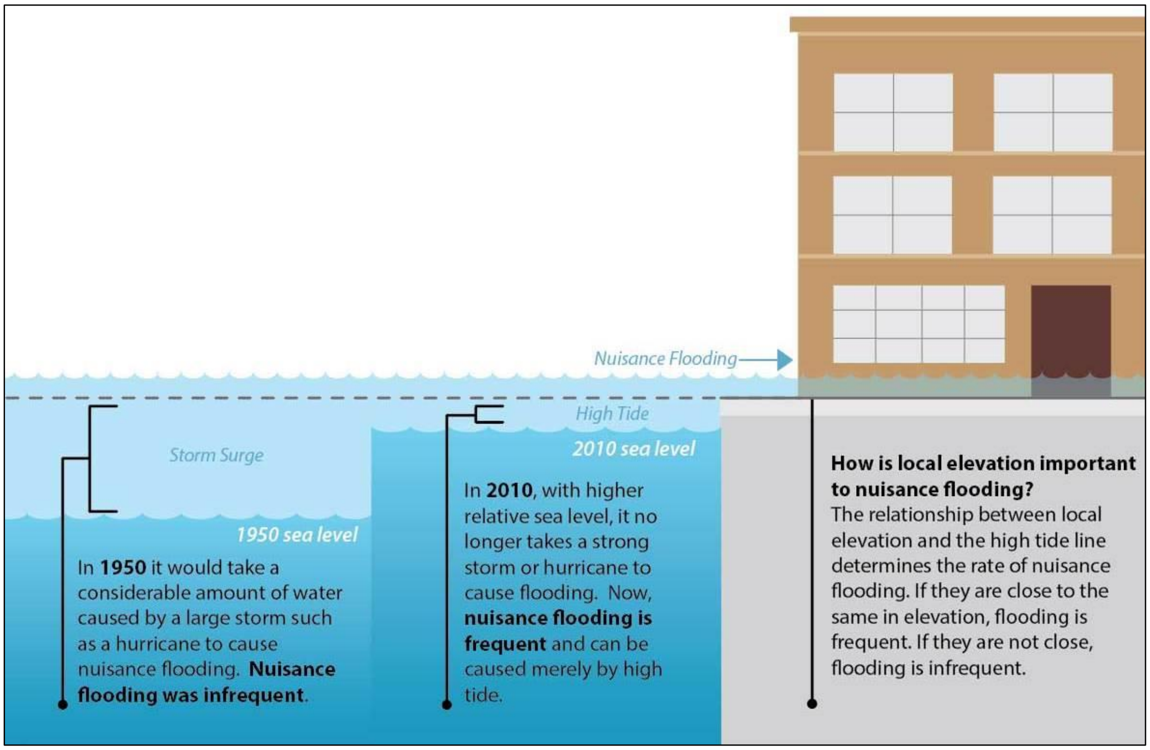
[80] U.S. Environmental Protection Agency, *Climate Change in the United States: Benefits of Global Action*, 2015, at https://www.epa.gov/sites/production/files/2015-06/documents/cirareport.pdf. These estimates are 2014 dollars discounted at 3%.

[81] For an introduction to federal coastal flood risk activities, see CRS In Focus IF10225, *Coastal Flood Resilience: Policy, Roles, and Funds*, by Nicole T. Carter, Harold F. Upton, and Francis X. McCarthy.

[82] For more on federal hazard mitigation activities, see CRS Report RL34537, *FEMA's Pre-Disaster Mitigation Program: Overview and Issues*, by Francis X. McCarthy.

dramatically in many U.S. coastal regions since the mid-20th century.[83] Some scholars argue that the widespread, cumulative annualized costs associated with regular nuisance flooding may be much greater than the costs associated with the annual average flood damages from larger storms.[84] Nuisance or minor flooding can also contribute to environmental change in affected areas. Nuisance flooding, when considered as a single event, is high probability but relatively low consequence; its full impacts are often due to the cumulative damages from repeated nuisance flooding. Although this flooding may be regularly repeated, it often may fall outside the purview or priorities of many federal disaster programs and efforts, which target their efforts on events that overwhelm local and state emergency response resources or on more disruptive and costly events.

**Figure 11. Illustration of Increase in Coastal Nuisance Flood Hazard**




**Source:** Adapted from NOAA, *NOAA: El Niño may accelerate nuisance flooding*, 2015.

Decisionmakers in developed areas subject to nuisance flooding and other persistent sea-level rise impacts are turning to a variety of engineering solutions to cope with the near-term impacts. These solutions include adding pumping capacity and control valves to storm sewers; armoring sewer systems to keep storm water out; raising roadways; using gravity, injection wells, and trenches to drain neighborhoods; adding salinity control structures; and injecting water into aquifers to retard salinity intrusion.[85] Decisionmakers in these areas also are employing public

[83] NOAA, *Sea Level Rise and Nuisance Flood Frequency Changes around the United States*, NOAA Technical Report NOS CO-OPS 073, June 2014

[84] J.A. Michael, "Episodic flooding and the cost of sea-level rise," *Ecological Economics*, 2007, pp. 149-159;

[85] F. Bloetscher et al., "Assessing Potential Impacts of Sea Level Rise on Public Health and Vulnerable Populations in Southeast Florida and Providing a Framework to Improve Outcomes," *Sustainability*, vol. 8, no. 4 (March 2016).

communication campaigns and developing public health efforts, as well as using public acquisition of at-risk properties in some instances.[86]

## Actions Addressing the Effects of Sea-Level Rise

Adjusting to sea-level rise presents an array of policy challenges and raises federalism questions regarding decisionmaking and responsibility. Part of the reason that the federal response to sea-level rise is particularly challenging is that regulations for coastal land use and requirements for coastal buildings and developments often are central to adjustment choices. According to a 2009 report by the U.S. Climate Change Science Program,

> Key opportunities for preparing for sea level rise include: provisions for preserving public access along the shore; land-use planning to ensure that wetlands, beaches, and associated coastal ecosystem services are preserved; siting and design decisions such as retrofitting (e.g., elevating buildings and homes); and examining whether and how changing risk due to sea-level rise is reflected in flood insurance rate maps.[87]

For coastal developments, the fundamental question for public and private decisionmakers is under what circumstances to protect, accommodate, or retreat in light of sea-level rise and other coastal hazards and their risks. In general, restrictions on private land-use decisions are largely the domain of local and state governments. Similarly, the requirements for coastal developments (e.g., required coastal setbacks) and buildings (e.g., building codes related to elevation of structures and equipment) have been set by local and state governments. The federal government, however, bears part of the financial burden associated with the consequences of coastal flooding through its disaster assistance and the National Flood Insurance Program (NFIP).[88]

A challenge will be that the options some local stakeholders may want to pursue may not be affordable or sustainable in the long run or when evaluated from a national perspective. That is, local stakeholders may make decisions that produce benefits for them if they anticipate being protected from negative outcomes; this is known as a "moral hazard" problem. For example, local entities may approve coastal developments that are at risk and make related public infrastructure investments in roads, schools, water systems, and the like, if the local entities believe federal disaster assistance (and related federal tax treatment of disasters losses) would be available when a coastal disaster occurs. This is also the case for decisionmaking by private interests. Some of the burden of the risk is transferred from the private interest and local government to the federal taxpayers. Another aspect that may be shaping decisionmaking behavior is a decision bias to underrate the risks, especially related to low-probability, high-consequence events such as large coastal storm surges.[89]

A public policy challenge related to sea-level rise is the intergenerational transfer of risk. Sea-level rise trends indicate that the coastal community will likely be at more risk in 25 years and 50

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[86] Ibid.

[87] J. G. Titus et al., *Coastal Sensitivity to Sea-Level Rise: A Focus on the Mid-Atlantic Region*, U.S. Climate Change Science Program and the Subcommittee on Global Change Research, Synthesis and Assessment Product 4.1, 2009. References to subsequent chapter numbers that were included in parentheses were removed from the quote.

[88] See footnote 79.

[89] "While decision-makers are quick to see the potential short-term gains that can be obtained from investing in development in such areas, they display less skill at comprehending the long-term risks of such development or of seeing the benefits of long-term investments in protection." H. Kunreuther, R. Meyer, and E. Michel-Kerjan, "Overcoming Decision Biases to Reduce Losses from Natural Catastrophes," in *The Behavioral Foundations of Public Policy*, 2013, ed. E. Shafir, pp. 398-412. Arguably, some interests also may benefit from the underrating of risks and may oppose more accurate risk disclosure.

years. To not develop because of those future risks would represent a decision to forgo current use and enjoyment benefits to avoid future costs. Some view this as an unnecessary sacrifice given the uncertainty related to sea-level rise at the end of the 21st century and the ability to adapt to some sea-level rise. For others, this choice would be altering current practices to reduce the potential consequences of sea-level rise for future generations.

## Federal Actions and Agencies

For Congress, a related policy question is to what extent federal programs, regulations, and funding influence how coasts develop, redevelop after extreme events, and respond to coastal erosion and shoreline dynamics. For example, most communities in the United States adopt minimum floodplain management standards as a condition of their participation in the NFIP. Other examples of how federal programs are directly involved in preparing for sea-level rise are described in the box "Selected Examples of Sea-Level Rise-Related Federal Action Since 2012" and the later box on the "Proposed 'Living Shoreline' General Permit." In addition to federal agencies that are directly involved in sea-level rise science and research and coastal regulatory activities, several federal agencies are indirectly involved in coastal projects and programs that address or could respond to, be affected by, or be exacerbated by sea-level rise.[90] The effect of these federal actions will be determined as they are implemented.

### Selected Examples of Sea-Level Rise-Related Federal Actions Since 2012

In recent years, the federal government has become increasingly involved in guiding, shaping, and informing how communities and individuals prepare for and respond to sea-level rise, as well as in preparing federal agencies and programs. Much of the federal influence focuses on activities and decisions with a federal nexus, such as federally funded projects. Below are illustrative examples of roles that federal agencies have played in addressing sea-level rise since 2012. Although some of these examples relate to the Obama Administration's climate change initiatives (e.g., actions pursuant to the 2013 Executive Order 13653 "Preparing the United States for the Impacts of Climate Change"), the drivers of relative sea-level rise are broader than climate forces.

**Flood Resiliency of Structures and Facilities.** The Administration released a Federal Flood Risk Management Standard (FFRMS) in 2015 for federally funded projects. Actions in which federal funds are used for new construction, substantial improvement, or repairs to address substantial damage to a structure or facility are required to meet the requirements of the FFRMS. For areas vulnerable to coastal flood hazards, the FFRMS requires that the funded structure or facility be resilient to coastal flood hazards from relative sea-level rise, storm surge, tides, and waves.

**Coastal Hazard Planning and Communication.** Beginning in 2016 (pursuant to 44 C.F.R. Part 201), FEMA has instructed that state hazard-mitigation plans, as required by 42 U.S.C. §5165, are to account for climate change and consider the probability of future hazard events. The Technical Mapping Advisory Council (TMAC), which is an authorized federal advisory committee that makes recommendations to FEMA related to flood mapping for the National Flood Insurance Program, delivered a report to the FEMA administrator in January 2016. The TMAC report (dated December 2015) entitled *Future Conditions Risk Assessment and Modeling Report* stated on page 3: "The TMAC believes that future conditions flood hazard products, tools, and information can be developed and provided to communities via policy change alone, and that regulatory or legislative changes are not necessary at this time" and on page 5-16: "The end mapping product could be a non-regulatory product.... FEMA should use Parris et. al, 2012, or similar global mean sea level scenarios, adjusted to reflect local conditions, including any regional effects (Local Relative Sea Level) to determine future coastal flood hazard estimates. Communities should be consulted to determine which scenarios and time horizons to map based on risk tolerance and criticality."

Under the 2010 Executive Order 13547, "Stewardship of the Ocean Our Coasts, and the Great Lakes," the National Ocean Council published the National Ocean Policy Implementation Plan in 2013 and has published subsequent annual work plans. Actions associated with coastal resilience identified in the January *2016 Annual Work Plan* included a national coastal mapping strategy and federal agency mapping plans. The 2016 plan also identified efforts to integrate

[90] For more on the actions of selected federal departments and agencies to adapt their own missions, infrastructure, operations, and personnel to projected climate change, see CRS Report R43915, *Climate Change Adaptation by Federal Agencies: An Analysis of Plans and Issues for Congress*, coordinated by Jane A. Leggett.

regional sea-level rise scenarios into coastal risk assessment tools; these tools are shared with stakeholders through the U.S. Climate Resilience Toolkit hosted by NOAA.

**Technical Assistance and Knowledge.** In 2015, NOAA published its *Guidance for Considering the Use of Living Shorelines.* Therein the agency stated its support for "living shoreline" alternatives for shoreline stabilizations for sheltered coasts (e.g., coasts not exposed to open ocean wave energy). The alternatives have a footprint that is largely made up of native material and vegetation or other natural and living elements. The NOAA guidance is in part the result of a multiagency effort called Systems Approach to Geomorphic Engineering to develop knowledge on using nature-based measures with structural measures in coastal contexts.

Municipal water, wastewater, and stormwater systems in low-lying areas have been identified as infrastructure particularly vulnerable to sea-level rise; sea-level rise may reduce the quality and reliability of their services, as well as reduce their useful life and increase their operation and maintenance expenses. Through its Climate Ready Water Utilities Initiative, EPA has developed risk-management software, the Climate Resilience Evaluation and Awareness Tool, that water sector owners and operators can use to identify regional climate change threats, including sea-level rise impacts, and to design adaptation plans. EPA also established a Climate Ready Estuaries program to assess vulnerability, develop adaptation strategies, and educate stakeholders to climate change risks, including sea-level rise and its effects on estuaries.

**Facility Owner and Project Developer.** In 2016, the Department of Defense released *Regional Sea Level Scenarios for Coastal Risk Management* and compiled an accompanying database on regionalized sea level and extreme water level scenarios for 1,774 Department of Defense sites worldwide that are coastal or tidally influenced. The report is part of the department's effort to screen its facilities for vulnerabilities and to assess impacts. The U.S. Army Corps of Engineers updated its 2011 sea-level-rise policy for civil works projects (e.g., storm-damage reduction, navigation) in 2013. The 2013 *Incorporating Sea Level Change in Civil Works Programs (*Engineer Regulation 1100-2-8162) provides guidance for incorporating the direct and indirect physical effects of projected future sea-level change across the project life cycle.

## Existing Federal Coastal Management Statutes

The primary federal statutes that directly address coastal development pressures are the Coastal Zone Management Act of 1972, as amended (CZMA, P.L. 92-532, 16 U.S.C. §1451-1464) and the Coastal Barrier Resources Act of 1982, as amended (CBRA, P.L. 97-348). CBRA designates undeveloped coastal barriers and adjacent areas. Most federal spending that would support additional development is prohibited in the CBRA designated areas. Under the CZMA, NOAA approves the coastal zone management programs developed by participating coastal states and U.S. territories and provides limited funding for coastal zone planning and management.

### *Coastal Zone Management Act*

The CZMA was enacted to encourage planning to protect natural resources while fostering wise development in the coastal zone. The CZMA recognizes that states (and, in some states, local government) have the lead responsibility for planning and managing their coastal zones. The CZMA authorizes grants to states and territories to develop and implement coastal management programs to address competing development, economic, and recreation pressures. Thirty-four of the 35 eligible states and 5 territories participate in CZMA. CZMA grants can be used for numerous CZMA-defined coastal zone enhancement objectives, including managing the effects of sea-level rise and reducing threats to life and property. Participating states and territories have developed widely varying programs that emphasize different elements of coastal management. The state programs are intended to discourage unwise development in flood-prone and exposed areas and to encourage protection of natural protective features along the coast, including beach systems, coastal barriers, and wetlands. For more on the act, see CRS Report RL34339, *Coastal Zone Management: Background and Reauthorization Issues*, by Harold F. Upton.

### *Coastal Barrier Resources Act*

The CBRA and subsequent amendments to it have designated undeveloped or relatively undeveloped coastal barriers and adjacent areas, where most federal spending that would support additional development is prohibited. There are 585 of these "system units" encompassing nearly 1.3 million acres of land and associated aquatic areas. The units are along the Gulf of Mexico, the Atlantic Coast, and the Great Lakes and around Puerto Rico and the U.S. Virgin Islands. Every CBRA unit is identified in law and with a reference to a map. The designation of units and the drawing of boundaries have been contentious for some units. Only Congress can modify the unit boundaries, and it has enacted numerous site-specific amendments. This program does not prohibit or regulate any activity; it merely prohibits the federal government and federal programs from being used to support additional development within any designated unit. Even with the CBRA prohibitions on federal programs, development has occurred at some units, especially along the southeast Atlantic coast. Also, CBRA does not preclude federal expenditures to restore designated units to former levels of development after natural disasters (e.g., reconstruction of roads and water or sewer systems to former dimensions and capacity). In addition to system units, the CBRA system also includes 272 "otherwise protected areas" encompassing 1.9 million acres, which generally coincide with existing conservation or recreation areas, such as state parks and national wildlife refuges. Unlike the broader prohibitions of the system units, the only CBRA spending prohibition in these areas is the prohibition on federal flood insurance.

## Private and Local Actions

Decisions of how to respond to coastal hazards are largely made by individual landowners, communities, and states. The result is a wide variety of responses across the United States. Historically, landowners and communities facing coastal erosion and coastal flood risks have invested in protection, typically using hard coastal defenses, such as seawalls or groins, or nonstructural approaches, such as dune construction and beach replenishment. Some researchers estimate that as much as 14% of the shoreline of the contiguous United States on the Pacific Ocean, Atlantic Ocean, and Gulf of Mexico has hardened infrastructure, such as seawalls, jetties, and groins.[91] Much of this shoreline armoring has occurred along the sheltered shorelines of the Atlantic and Pacific coasts (e.g., estuaries, lagoons, tidally influenced rivers).[92] According to NOAA, if shoreline hardening continues at the current rate of around 200 kilometers per year (125 miles per year), nearly one-third of the contiguous U.S. shoreline may be hardened by 2100.[93]

Hardened shorelines generally support fewer species than the more complex habitats of natural shorelines and may require additional financial investments in operation and maintenance and in rehabilitation and replacement. Given some of the less-desirable unintended effects of coastal armoring (e.g., beach loss following seawall or jetty construction), alternative means to manage erosion and reduce storm-surge impacts are also being pursued, such as protection of natural dunes and bluffs and investments in oyster-reef restoration or marsh creation.[94] Researchers have

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[91] R. K. Gittman et al., "Engineering away our natural defenses: An analysis of shoreline hardening in the US," *Frontiers in Ecology and the Environment,* vol. 13 (August 2015).

[92] Ibid.

[93] NOAA, *Guidance for Considering the Use of Living Shorelines*, 2015, at http://www.habitat.noaa.gov/pdf/noaa_guidance_for_considering_the_use_of_living_shorelines_2015.pdf.

[94] Intact coastal landforms, such as coastal dunes and wetlands, have shown benefits related to reducing the impacts of storm surge. Whether engineered dunes and restored wetlands have similar efficacy is less certain, especially for larger surges and waves.

identified that 50% of the tidal wetlands of the South Atlantic and Gulf of Mexico are threatened by potential future hardening based on population, development, and storm trends.[95] Although softer approaches to shoreline stabilization may require maintenance investments over time (e.g., replantings), they often become more stable as plants, roots, or oyster reefs grow.[96]

Many private and local government efforts to manage erosion require a federal permit under the Clean Water Act. Advocates for nature-based approaches for stabilizing shorelines have argued that the current regulatory programs have favored the use of hard solutions rather than nature-based approaches. In 2016, the Army Corps of Engineers proposed a general permit for "living shorelines" that may facilitate the permitting, and therefore the adoption, of nature-based approaches for managing coastal erosion. (For more on this proposal, see the box "Proposed 'Living Shoreline' General Permit.")

### Proposed "Living Shoreline" General Permit

Permits issued by the Army Corps of Engineers (Army Corps) authorize various types of development projects in wetlands and other waters of the United States. Army Corps' regulatory process involves two types of permits: (1) general permits for actions by private landowners that are similar in nature and will likely have minimal adverse effect on waters and wetlands, individually and cumulatively, and (2) individual permits for actions likely to have more significant environmental impact. Army Corps uses general permits to minimize the burden of its regulatory program; general permits authorize landowners to proceed with a project without the more time-consuming need to obtain standard individual permits in advance. More than 97% of the regulatory workload of the Army Corps—on average, about 61,000 authorized activities each year—is processed through general permits.

Nationwide permits are one type of general permit. Nationwide permits are issued for five-year periods and thereafter must be renewed. On June 1, 2016, in advance of the scheduled expiration of the current permits (March 2017), the Army Corps issued a proposal to reissue and modify the existing nationwide permits. The proposal also includes two new permits.

One of the proposed new permits would authorize the construction of living shorelines for bank-stabilization activities that control erosion. Two existing nationwide permits already authorize some activities to help protect public and private property from erosion. These permits are generally used for hardened structures such as bulkheads and involve substantial amounts of fill materials. In contrast, a living shoreline provides nature-based erosion control by techniques that incorporate vegetation or other natural elements alone or in combination with some type of harder shoreline structure (e.g., oyster reefs) for added stability. Even narrow marshes—a common component of living shoreline designs—have been shown to slow waves and reduce shoreline erosion. Living shorelines are not practical or feasible in all coastal environments, however, as they work best in sheltered coasts typically found in estuaries, bays, lagoons, and coastal deltas, which are not subject to high-energy erosive forces that occur along open coasts.

Constructing living shorelines often requires substantial amount of fill to be discharged into waters and wetlands to achieve appropriate grades to dissipate wave energy. The Army Corps believes that this proposed nationwide permit is needed because the structures, work, and fills associated with constructing living shorelines often do not fall within the terms and conditions of existing nationwide permits and, thus, often require individual Army Corps permits. A 2007 National Academy of Sciences report (*Mitigating Shore Erosion Along Sheltered Coasts*) found that the lack of a general permit to authorize living shorelines is one of the factors that have discouraged the use of that erosion-control technique in sheltered coasts. The new permit would authorize construction of living shorelines, which the Army Corps believes would give landowners flexibility and greater choice in how to protect their property from erosion. Army Corps regulatory officials would review requests to use the permit and make site-specific determinations whether the proposed activities would result in no more than minimal individual and cumulative adverse environmental effects on wetlands and other waters.

For more on the Army Corps' nationwide permits program, see CRS Report 97-223, *The Army Corps of Engineers' Nationwide Permits Program: Issues and Regulatory Developments*, by Claudia Copeland and Jonathan L. Ramseur.

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[95] R. K. Gittman et al., "Engineering away our natural defenses: An analysis of shoreline hardening in the US," *Frontiers in Ecology and the Environment*, vol. 13 (August 2015).

[96] NOAA, *Guidance for Considering the Use of Living Shorelines*, 2015, at http://www.habitat.noaa.gov/pdf/noaa_guidance_for_considering_the_use_of_living_shorelines_2015.pdf.

# Part III. Policy Considerations and Questions

Sea-level rise raises several questions: What does sea-level rise portend for future economic development of U.S. coasts? How does sea-level rise affect the safety and quality of life of coastal residents? How does sea-level rise alter the coastal ecosystems and potentially alter the benefits that society derives from those ecosystems, such as recreation and commercial fisheries? Near-term choices on managing and adapting to sea-level rise have the potential to significantly shape the responses to these questions and the future U.S. coastal development.

General categories of policy options related to sea-level rise include the following:

- **Maintaining the status quo**. Current government programs, policies, and funding would continue.
- **Reducing the global rise in sea level**. Policies for addressing the human activities influencing sea-level rise could include pursuing domestic and international GHG-mitigation efforts.[97]
- **Reducing the relative rise in sea level**. Policies to address the local or regional drivers of sea-level rise could focus on activities that contribute to land subsidence.
- **Reducing vulnerabilities to sea-level rise**. Policies could foster reducing vulnerability to the effects of sea-level rise (e.g., coastal flood risk reduction projects using dunes or storm-surge gates). Policies also could attempt to foster environmental and social resilience; these policies could include protection of certain coastal habitats, including those that contribute to natural coastal flood defenses.
- **Reducing consequences of sea-level rise**. Policies could promote actions that reduce the consequences of the effects of sea-level rise. These actions could include various hazard-mitigation measures, such as development restrictions, building codes, flood-proofing of structures, buyouts of vulnerable properties, and improved evacuation routes.

For all of the policy options, there are the underlying questions of the policies' costs and benefits and of who will bear the costs of not pursuing or pursuing the policies.

## Considerations Related to the Causes of Sea-Level Rise

Future rates and levels of sea-level rise are uncertain and likely will be determined by a complex mix of phenomena and activities. This uncertainty complicates public and private decisionmaking regarding policies and investments related to coastal development and protection. Considerations for Congress related to the causes of sea-level rise include the following:

- How well understood is the current and projected rate of sea-level rise?
- What factors contribute to changes in sea level, and which of these represent natural variability and which may be influenced by human activities?
- How may factors that affect sea level change in the future?

[97] For more on climate change, see CRS Report R43229, *Climate Change Science: Key Points*, by Jane A. Leggett. Many scientists conclude that GSL will continue to rise for centuries even if greenhouse gas concentrations in the atmosphere are stabilized.

- What are the local, state, and federal responsibilities for managing and mitigating activities that may exacerbate the rate of relative sea-level rise?

Policymakers may contend with a pattern of sea-level rise that could look very different in the 21st century compared to the 20th century. Global sea levels may rise at least 0.2 meters (about 8 inches) but could rise 10 times that amount, or even higher, depending on the behavior of the Antarctic and Greenland ice sheets, according to many scientists. A better scientific understanding of how the two large ice sheets will contribute to sea-level rise may assist coastal communities with their approaches to planning for, mitigating, and responding to potential impacts. Further, recognizing the multiple factors that contribute to relative sea-level rise, such as the local and regional activities that exacerbate or mitigate land subsidence, may be of first-order importance.

## Considerations Related to the Effects of Sea-Level Rise

A 2007 report of the National Academy of Sciences entitled *Mitigating Shore Erosion Along Sheltered Coasts* stated that "sea-level rise is chronic and progressive, requiring a response that is correspondingly progressive. Attempts to follow a 'hold the line' mitigation strategy against erosion and sea-level rise by coastal armoring will result in a steady escalation in both the costs of maintenance and the consequences of failure."[98] The report's statement acknowledges that actions may be taken to manage the impacts of sea-level rise and that significant financial investments in protective and stabilization actions may be cost-effective for some developed areas. However, these actions will have costs, and the consequences of failure may be significant. Some responses may work well for a few decades but may eventually lose their utility or efficacy in the face of steadily higher sea levels. Communities and nature, however, have been adjusting to shoreline dynamics and coastal hazards for centuries; the current question is how to respond efficiently and effectively.

Considerations for Congress associated with the impacts of sea-level rise include the following:

- What is the risk of sea-level rise to the nation, its population, federal facilities, federal operations, critical infrastructure and systems, and the national economy?
- What are the guiding principles for the federal role in coastal projects and activities given sea-level rise and other coastal hazards (e.g., what defines the boundaries and nature of the federal role in erosion control, shoreline stabilizations, and nuisance flooding)?
- What is the role for federal funding in adjusting to sea-level rise and its impacts given that coastal development is determined largely by local and state policies and private decisions?
- To what extent do federal regulations, programs, and funding influence the adoption and approaches used for managing coastal sea-level rise impacts or decisions that unintentionally exacerbate the impacts?
- What is the appropriate way to manage risks posed by sea-level rise to existing infrastructure, new infrastructure, and economic and social systems (e.g., multimodal transportation network)?[99]

[98] National Academy of Sciences, *Mitigating Shore Erosion Along Sheltered Coasts*, 2007, at http://www.nap.edu/download/11764.

[99] Although the study was on climate change adaptation more broadly, the GAO found in 2013 that infrastructure decisionmakers have not systematically incorporated potential climate change impacts into planning for roads, bridges, and wastewater-management systems. Instead, efforts to incorporate climate change impacts into planning for (continued...)

## Federalism Considerations

Although most decisions about coastal land development and protection are made by states, localities, and other stakeholders, the federal government has an interest in how coasts are developing and adjusting to sea-level rise. A challenge for federal lawmakers and other policymakers is how to deal with the tension between federal efforts to manage national and federal government risks (e.g., federal disaster costs, coastal ecosystem shifts) related to sea-level rise and the local, state, and private roles in shaping coastal development and ecosystem health. States and local governments have significant discretion in coastal land use and development decisions. At the same time, local adoption of minimum floodplain management standards as a requirement for NFIP participation influences the locations and design of coastal structures. Past and future land-use, development, and building-code choices and the resulting public and private investments are factors shaping the future financial impacts of sea-level rise for the nation. Among the policy questions associated with sea-level rise facing federal policymakers are the following:

- In the U.S. federalist system of shared responsibilities, who is responsible for the costs associated with adjusting to sea-level rise? Is the federal role and responsibility related to coastal flood hazards clearly articulated and consistently applied across federal agencies, programs, projects, and disasters?
- Who is currently bearing the costs associated with sea-level rise and related coastal erosion, coastal storms, and habitat shifts?
- Are local, regional, and state land-use and development decisions and building requirements contributing to or eroding resilience to sea-level rise and coastal hazards, and what are the implications for the federal role in addressing sea-level rise?
- To what extent do federal programs transfer the risk associated with coastal development to the federal taxpayer? How does the suite of federal disaster assistance and coastal programs harm or bolster coastal resilience? Are federal investments in infrastructure and mitigation of flood damages in coastal areas coordinated?

## General Policy Considerations

Various federal agencies are providing guidance and data to inform state, local, and private efforts to prepare for and respond to sea-level rise. Some stakeholders are concerned that insufficient attention is paid to the risk posed by sea-level rise, as well as to the existing risk associated with coastal hazards. Because of the value of coastal developments at risk from coastal flood hazards and how the risk may increase with sea-level rise, decisionmakers may invest in more coastal protections in many locations.[100] What types of protections (hard, soft, hybrid) and policy choices

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infrastructure projects have occurred primarily on a limited, ad hoc basis (GAO, *Climate Change: Future Federal Adaptation Efforts Could Better Support Local Infrastructure Decision Makers*, 13-242, April 2013, at http://www.gao.gov/assets/660/653741.pdf).

[100] Annual appropriations for the Army Corps to construct coastal flood risk reduction projects were $78 million in FY2013, $77 million in FY2014, $45 million in FY2015, and $41 million in FY2016. Much of these appropriations were not used for the initial investment in coastal protective measures; most of the funds were used for the periodic renourishment of sand-depleted beaches and dunes that are part of authorized Army Corps coastal flood risk reduction projects. Since 2005, most funds that the Army Corps has used to construct new coastal flood risk reduction projects (continued...)

(e.g., restricting human activities that exacerbate subsidence) are implemented may determine the future of U.S. coastal communities and coastal habitats. Other stakeholders are concerned that overestimating the risk of sea-level rise could result in overinvesting and overdesigning protections and mitigations to sea-level rise.

Decisions about coastal land use and land protections, coastal development and infrastructure, and building codes and the resulting public and private investments can shape the future financial impacts of sea-level rise for the nation. Future growth in coastal areas may be shaped by the perceived risk from coastal hazards, such as sea-level rise and coastal storms, and by the efficacy of private and public responses to mitigate that risk.

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has been provided to disaster-affected areas (e.g., areas affected by Hurricanes Katrina and Sandy) through supplemental appropriations legislation. For more on Corps supplemental appropriations, see CRS Report R42841, *Army Corps Supplemental Appropriations: Recent History, Trends, and Policy Issues*, by Charles V. Stern and Nicole T. Carter.