

Causes of Sea Level Rise

What the Science Tells Us

HIGHLIGHTS

Roughly a third of the nation's population lives in coastal counties. Several million of those live at elevations that could be flooded by rising seas this century, scientific projections show. These cities and towns—home to tourist destinations, fisheries, natural landscapes, military bases, financial centers, and beaches and boardwalks—face a growing risk from sea level rise.

The choices we make today are critical to protecting coastal communities. While it will be necessary to adapt to rising seas by, for example, making buildings and infrastructure more resilient, reducing our heat-trapping emissions is one of the best ways to limit the magnitude and pace of sea level rise over the long term.

From the rocky shoreline of Maine to the busy trading port of New Orleans, from historic Golden Gate Park in San Francisco to the golden sands of Miami Beach, our coasts are an integral part of American life. Where the sea meets land sit some of our most densely populated cities, most popular tourist destinations, bountiful fisheries, unique natural landscapes, strategic military bases, financial centers, and beaches and boardwalks where memories are created. Yet many of these iconic places face a growing risk from sea level rise.

Global sea level is rising—and at an accelerating rate—largely in response to global warming. The global average rise has been about eight inches since the Industrial Revolution. However, many U.S. cities have seen much higher increases in sea level (NOAA 2012a; NOAA 2012b). Portions of the East and Gulf coasts have faced some of the world's fastest rates of sea level rise (NOAA 2012b). These trends have contributed to loss of life, billions of dollars in damage to coastal property and infrastructure, massive taxpayer funding for recovery and rebuilding, and degradation of our prized shores.

Scientific projections show that global sea level will continue to rise over the course of this century, transforming our coasts. Meeting the challenge of rising seas and coastal storm surges will require immense efforts to build the resilience of our treasured coastal communities. We also need to make ambitious cuts in our heat-trapping emissions, to slow the pace and magnitude of change in sea level and gain time to plan and prepare for its effects.

What Is Causing Sea Level Rise?

Global warming is the main contributor to the rise in global sea level since the Industrial Revolution. Human activities such as burning coal and oil and cutting



Sea level rise, combined with worsening storm surge, threatens to harm people, property, and ecosystems in coastal communities around the country.

down tropical forests increase atmospheric concentrations of heat-trapping gases. The result is that the planet has already warmed by 1.4°F since 1880 (Hansen et al. 2010).

These rising air temperatures are also warming ocean waters. Indeed, the oceans have absorbed 85 percent of the excess heat trapped by the atmosphere since 1880 (Cazenave and Llovel 2010; Levitus et al. 2009; Levitus et al. 2005; Levitus et al. 2001). As ocean water warms, it expands. This thermal expansion was the main driver of global sea level rise for 75 to 100 years after the start of the Industrial Revolution. However, the share of thermal expansion in global sea level rise has declined in recent decades as the shrinking of land ice has accelerated (Cazenave and Llovel 2010; Lombard et al. 2005).¹

Land ice—glaciers, ice caps, and ice sheets—stores nearly two-thirds of the world’s freshwater and is shrinking in response to higher temperatures (Trenberth et al. 2007). Glaciers partially melt each summer and grow again each winter. However, as temperatures rise, ice growth in winter is often less than ice melt in summer. The result is that nearly all the world’s surveyed glaciers, ice caps, and the Greenland ice sheet are losing ice, adding water to the oceans and causing global sea level to rise (EPA 2012; Cogley 2009; Meier et al. 2007; Kaser et al. 2006). Shrinking land ice added about one inch to global sea level from 1993 to 2008—accounting for

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more than half of the increase during that period (Church et al. 2011).

Indeed, the pace of ice loss from both small glaciers and large ice sheets has accelerated (EPA 2012; NRC 2012; Cazenave and Llovel 2010; Witze 2008; Howat, Joughin, and Scambos 2007; Meier et al. 2007; Kaser et al. 2006). Recent studies suggest that ice loss added nearly half an inch to global sea level from 2003 to 2007, contributing 75 percent to 80 percent of the total increase (Cazenave and Llovel 2010).

Other factors—from local sinking of land to changing regional ocean currents—also can play a role in sea level rise.² These influences are contributing to “hot spots” that are facing higher-than-average local sea level rise, such as the East and Gulf coasts of the United States (Sallenger, Doran, and Howd 2012; Milne 2008).³

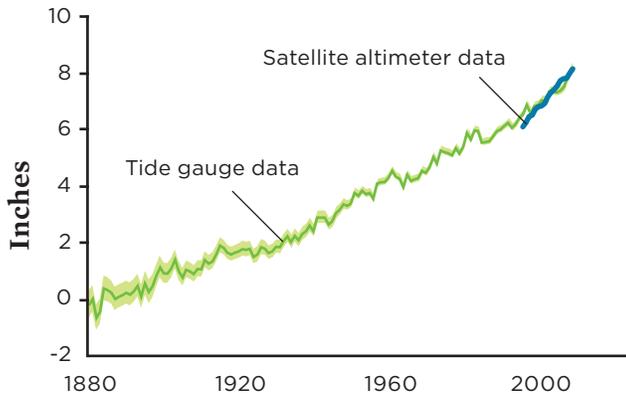


More than 5 million people along the Eastern Seaboard live in areas at risk of coastal flooding,⁴ and population density in coastal counties is projected to grow at more than three times the national pace over the next 10 years. Coastal communities, including in New Jersey (above), have seen severe damage from storms—most recently from Hurricane Sandy.

U.S. Air Force/Master Sgt. Mark C. Olsen

FIGURE 1. Global Sea Level Rise and Recent Causes

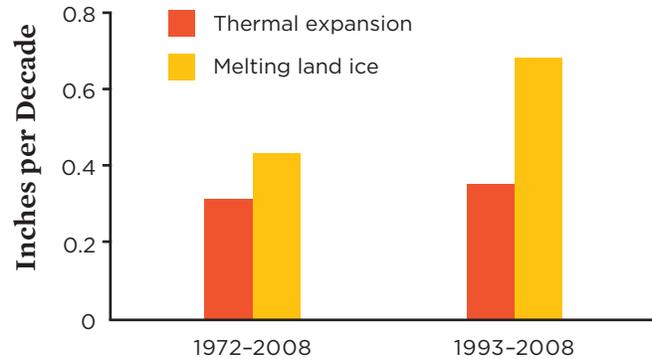
Average Global Sea Level Rise since the Industrial Revolution



Loss of ice on land and thermal expansion of seawater—both primarily caused by global warming—have been the key drivers of an average global sea level rise of about eight inches since 1880. Tide gauges around the world have recorded the long-term rise in sea level since 1870 (green line with shaded error range). Satellite observations since 1993 (blue line) have confirmed the trend.

SOURCES: NRC 2012; CHURCH ET AL. 2011; CAZENAVE AND LLOVEL 2010.

Climate-related Contributions to Global Sea Level Rise



From 1972 to 2008, melting land ice—glaciers, ice caps, and ice sheets—accounted for 52 percent of sea level rise, while warmer oceans contributed 38 percent. Groundwater withdrawal and other factors, both known and unknown, contributed the remaining 10 percent. Ice loss has accelerated since the early 1990s, and has accounted for 75 percent to 80 percent of sea level rise since 2003.

SOURCES: NRC 2012; CHURCH AND WHITE 2011; CAZENAVE AND LLOVEL 2010; NICHOLLS AND CAZENAVE 2010.

Measuring Global Sea Level Rise

Global sea level rose roughly eight inches from 1880 to 2009, and about 0.8 inch per decade from 1972 to 2008 (Figure 1) (Church and White 2011; Church et al. 2011).⁵ Tide gauges, land benchmarks, and other methods can be consulted in specific coastal areas to determine how much the location differs from the global average rate of sea level rise. Local sea level is influenced by many factors including meteorological events, ocean currents, geologic factors, groundwater flow, river dams, drilling, dredging, and construction.

The rise in sea level is accelerating both globally and regionally in many places. From 1993 to 2008, the global rate has risen to 0.11 to 0.13 inch per year—a 65 percent to 90 percent increase above the twentieth-century average (Church and White 2011; Ablain et al. 2009; Leuliette, Nerem, and Mitchum 2004). Scientists attribute this acceleration mainly to ocean warming, a quickening pace of land ice loss, and a net transfer of groundwater from the land into the sea (Konikow 2011; Domingues et al. 2008; Witze 2008; Howat, Joughin, and Scambos 2007).⁶ The stretch of coastline from Nova Scotia to the Gulf of Mexico faced some of the world’s fastest rates of sea level rise in the twentieth century—from 0.10 inch per year in Boston to 0.38 inch per year in Louisiana (NOAA 2012b).⁷

PROJECTING FUTURE SEA LEVEL RISE

Our past heat-trapping emissions have committed us to continued sea level rise, because oceans and land ice are still adjusting to the changes we have already made to the atmosphere. Even if global emissions were to drop to zero by 2016, scientists project another 1.2 to 2.6 feet of sea level rise by 2100 (Schaeffer et al. 2012; Zecca and Chiari 2012; Meehl et al. 2007).

However, while past emissions will largely dictate sea level rise through 2050, our present and future emissions will have great bearing on sea level rise from 2050 to 2100 and beyond (Schaeffer et al. 2012; Zecca and Chiari 2012; Jevrejeva, Moore, and Grinsted 2010). Land ice, in particular, can respond very rapidly to changes in climate (Joughin 2006). Scientists have developed a range of scenarios for future sea level rise based on estimates of growth in heat-trapping emissions and the potential responses of oceans and ice. The latest scenarios suggest a 90 percent certainty that the increase in global sea level will range from 8 inches to 6.6 feet above 1992 levels by 2100 (NOAA 2012a).

The lowest end of this range is a simple extension of historic sea level rise—and recent data indicate that this rate has nearly doubled in recent years.⁸ Three other scenarios show a more likely range of 1.6 to 6.6 feet of sea level rise by 2100.⁹ The rate and magnitude of the loss of ice sheets—primarily

in Greenland and West Antarctica—account for much of the difference in the projections of sea level rise by the end of the century (NOAA 2012a).¹⁰

Our Coasts at Risk

Roughly a third of the nation’s population—more than 100 million people—lives in coastal counties.¹¹ These counties account for 42 percent of the U.S. gross domestic product.¹² Coastal states with low-lying land are especially vulnerable to rising seas and coastal storm surges. Louisiana, Florida, North Carolina, California, and South Carolina top the list of exposed states, based on the amount of dry land less than 3.3 feet above high-tide levels (Strauss et al. 2012).

That 3.3 feet of global sea level rise is likely to occur by the end of the century under a scenario with continued high global warming emissions and active loss of land ice (“intermediate-high projection” in Figure 2)—and could occur even earlier under a scenario with a more accelerated rate of shrinking of land ice (“highest projection” in Figure 2). Local factors make it likely that parts of the East and Gulf coasts will see an even faster pace of local sea level rise than the global average, putting large populations at risk (Boon 2012).

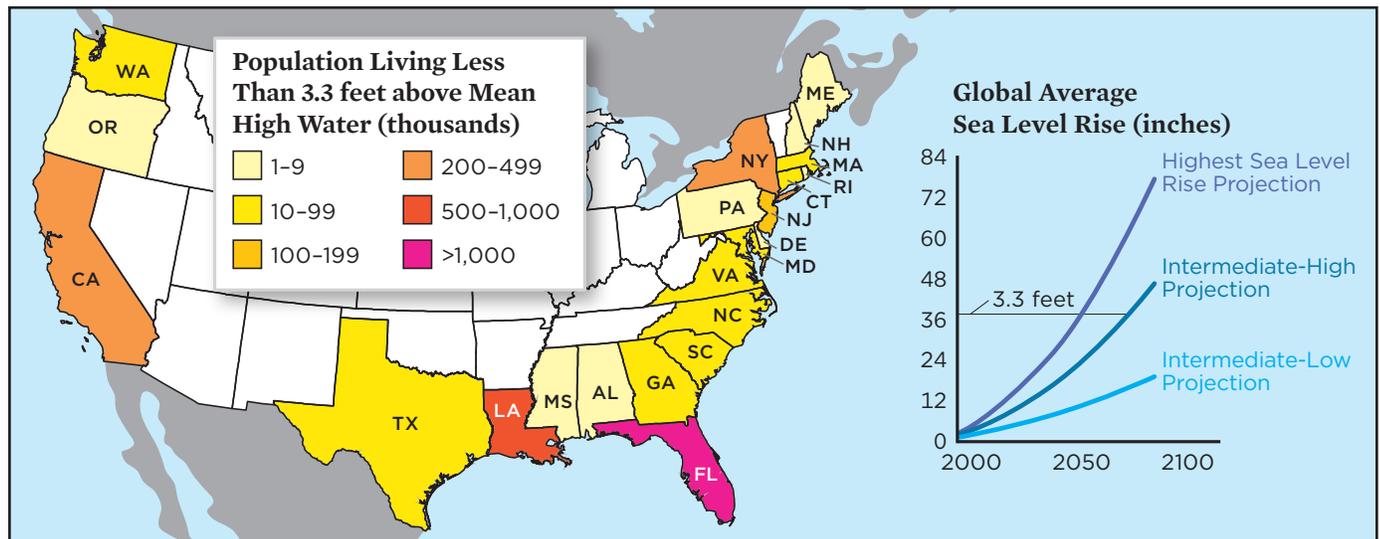
Roughly a third of the nation’s population lives in coastal counties and is especially vulnerable to rising seas and storm surges in low-lying areas.

HOW SEA LEVEL RISE AFFECTS OUR COASTS

Ocean waves, currents, and tides constantly reshape shorelines. Coastal storms such as Hurricane Sandy provide stark evidence of how dramatic and rapid these changes can be. Sea level rise is changing the dynamics at play along our coasts—and with them our coastal communities, economies, and ecosystems. These dynamics include:

Amplified storm surge. Coastal storms often cause storm surge, where high winds push water inland (Figure 3, p. 5). With rising seas, storm surge occurs on top of an elevated water level. That means a storm today could create more

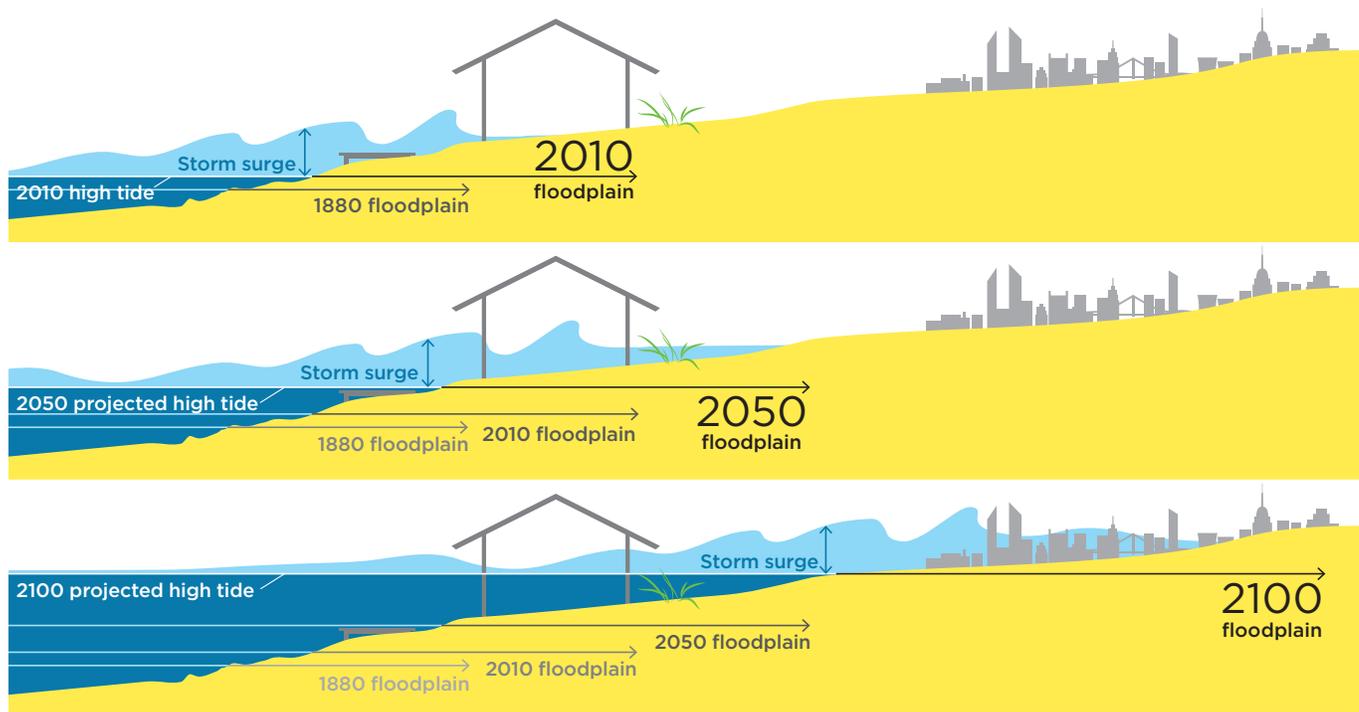
FIGURE 2. Coastal States at Risk from Global Sea Level Rise



People in states with low-lying coastlines have been subject to severe flooding and damage from coastal storms in recent years. Although all coastal states are vulnerable, Florida, Louisiana, New York, and California have the most residents living on land less than 3.3 feet above high tide. Depending on our future emissions—and the resulting ocean warming and land ice loss—global average sea level could rise to the 3.3-foot mark within this century.

SOURCES: NOAA 2012A; STRAUSS ET AL. 2012.

FIGURE 3. Storm Surge and High Tides Magnify the Risks of Local Sea Level Rise



Sea level sets a baseline for storm surge—the potentially destructive rise in sea height that occurs during a coastal storm. As local sea level rises, so does that baseline, allowing coastal storm surges to penetrate farther inland. With higher global sea levels in 2050 and 2100, areas much farther inland would be at risk of being flooded. The extent of local flooding also depends on factors like tides, natural and artificial barriers, and the contours of coastal land.

Note: Local factors such as tides and coastal profile will influence extent of floodplain.

extensive flooding than an identical storm in 1900, with sometimes catastrophic damage to our homes and critical infrastructure—as recent events have shown. In the future, with even higher sea levels, storm surges could reach even further inland.

More shoreline erosion and degradation. Sea level rise increases the potential for erosion by allowing waves to penetrate further inland, even during calm weather (Zhang et al. 2004). Indeed, the rate of land loss from erosion can be 100 times greater—or more—than the rise in sea level itself (Cooper et al. 2008; Zhang et al. 2004).¹³ In many parts of the United States, erosion and development have already lowered natural coastal defenses. These changes have left us more vulnerable to storms, and forced investments in expensive measures such as repeated beach replenishment and construction of artificial barriers (Moser, Williams, and Boesch 2012).

Permanent inundation. As sea level rises, the ocean is poised to gradually claim low-lying coastal lands; small increases in sea level can produce significant inundation in these areas

(Cooper et al. 2008). Some coastal wetlands and populated areas already flood regularly during particularly high tides (Brinkmann 2012). A rise of two feet above today’s sea level would put more than \$1 trillion of property and structures in the United States at risk of inundation, with roughly half of that value concentrated in Florida (Moser et al. 2013). With these changes, saltwater could also reach further into coastal groundwater, increasing the salinity of freshwater used for drinking and agriculture.¹⁴

Responding to Sea Level Rise: Choices, Opportunities, and Risks

With sea level rise well under way, coastal communities from Alaska to the Florida Keys are grappling with difficult choices on how to respond to this growing threat. More and more communities will need to weigh the costs and risks of accommodating the rising seas, retreating from them, or trying to defend coastal properties and infrastructure with a variety of protective measures.

Making deep reductions in global warming emissions is one of the best ways to limit the magnitude and pace of sea level rise, and the costs of adapting to it.

Traditional defensive approaches—such as building seawalls and levees, or replenishing sand along eroded beaches—can help protect against flooding and damage but may not provide adequate or sustainable protection over the long term (Moser, Williams, and Boesch 2012). Maintaining or restoring natural buffers, such as barrier islands, tidal wetlands, and mangroves, can also help defend coastlines, while providing additional ecosystem services (Jones, Hole, and Zavaleta 2012; Colls, Ash, and Ikkala 2009). Elevating and flood-proofing structures, using land for temporary purposes when it is not flooded, and constructing channels are examples of measures that can help accommodate both temporary flooding and gradual inundation of low-lying areas (Kimmelman 2013). Some of the most vulnerable coastal communities may increasingly need to consider the stark option of some form of retreat from the rising seas.

Over time our choices may change as sea level rise forecloses certain options, or new solutions for building resilience



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Florida is already experiencing local sea level rise and worsening storm surge. Homes, businesses, and vital infrastructure along many parts of its Atlantic coast, including Fort Lauderdale (above), regularly face flooding during high tides. Local sea level rise is damaging unique ecosystems and will also increase the risk of saltwater entering groundwater aquifers.

emerge. We will also develop a deeper understanding of the risks and tradeoffs we face in confronting climate change. In weighing the best options for each unique coastal community, we will also need to share experiences and coordinate policies and actions across local, state, regional, and national jurisdictions.

However, even as we work to adapt to unfolding climate change, deep reductions in our global warming emissions remain one of the best ways to limit the magnitude and pace of sea level rise and cut the costs of these adaptations.

ENDNOTES

1. For much of the twentieth century, thermal expansion accounted for the majority of global sea level rise. However, from 1993 to 2007, that share dropped to about 30 percent.
2. Local sea level is a combination of global sea level and other factors. These factors include sinking or rising of land and changing regional ocean currents.
3. A range of factors beyond thermal expansion and the shrinking of land ice can contribute to sea level rise, though their significance varies by location. These factors include:
 - Groundwater depletion, which reduces the amount of water stored below the land surface and results in a net transfer of water into the oceans (Konikow 2011).
 - Decreasing ocean salinity, which causes seawater to expand (Ishii et al. 2006; Antonov, Levitus, and Boyer 2002).
 - Geological uplift or subsidence of coastal areas, which can affect local rates of sea level change dramatically (Anderson, Milliken, and Wallace 2010).
 - Changes in the path or strength of ocean currents (Ezer et al. 2013; Sallenger, Doran, and Howd 2012).
 - Volcanic eruptions, which tend to cool the oceans and slow thermal expansion (Church and White 2006; Church, White, and Arblaster 2005).
4. These areas have a 1 percent annual chance of flooding (that is, a 100-year flood) (Crowell et al. 2010).
5. Since 1900, global sea level has risen by an average of 0.07 inch per year (Church and White 2011). Most U.S. coastlines have seen rising sea levels since the 1950s (NOAA 2012a).
6. As part of the water cycle, rainwater that percolates into underground aquifers slowly flows into rivers or the ocean over the course of thousands or, in some cases, millions of years (Bentley et al. 1986; Castro and Goblet 2003). When we pump groundwater out of aquifers for human uses, some of that ancient water quickly ends up in rivers and reaches the ocean much more rapidly than it would naturally. The cumulative effect of this enhanced flow is a rise in global sea level (Konikow 2011; Domingues et al. 2008; Witze 2008; Howat, Joughin, and Scambos 2007).
7. Sea level rise along much of the eastern North American coast has exceeded the global average since 1955. Rates of change are highest along the Gulf Coast.
8. Satellite altimetry recorded a global sea level rise of 0.13 inch per year from 1993 to 2009—nearly twice the twentieth-century average rate measured by tide gauges (Church and White 2011). The National Oceanic and Atmospheric Administration (NOAA) recommends using the lowest scenario only where there is a “great tolerance for risk” (NOAA 2012a).
9. The highest end of the range assumes a more accelerated rate of ice melt. An intermediate-high scenario (four feet by 2100) assumes continued high global warming emissions and active loss of land ice. An intermediate-low scenario assumes aggressive cuts in emissions and limited loss of ice sheets. Studies that apply information on the relationship between global temperature and sea level to a future with higher emissions project a rise in the range of 3.9 feet by 2100—the intermediate-high scenario (Jevrejeva, Moore, and Grinsted 2010; Vermeer and Rahmstorf 2009; Horton et al. 2008). These models were run using a range of scenarios from the Intergovernmental Panel on Climate Change. The figure of 3.9 feet is based on the A1B scenario.
10. NOAA has recommended incorporating local and regional factors into projections of global sea level rise to assess risk and make coastal planning decisions. The agency recommends using a lower-risk scenario to evaluate short-term, low-cost projects, such as whether to pursue seasonal construc-

tion, while using a higher-risk scenario to evaluate new long-term infrastructure projects such as power plants (NOAA 2012a).

11. Coastal shoreline counties are defined in NOAA 2012c. We exclude counties bordering the Great Lakes from our population analysis (U.S. Bureau of the Census 2010).
12. Data are available from NOAA's State of the Coast website: http://stateofthecoast.noaa.gov/coastal_economy/welcome.html. Economic data include activity along the Great Lakes shorelines of Pennsylvania and New York but not along other Great Lakes shorelines.
13. In parts of New Jersey, for example, the shoreline has retreated by nearly 120 feet for each foot of sea level rise over the past century, because of the combined effects of erosion and sea level rise.
14. Saltwater intrusion into coastal aquifers can render them unusable and require costly remedial measures (Barlow and Reichard 2009; Stanton and Ackerman 2007). Salinization can also degrade coastal wetland ecosystems, as is occurring in the Florida Everglades (Ross et al. 2000).

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