The Physical Environment

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The first part of this Product examines the potential physical and environmental impacts of sea-level rise on the coastal environments of the mid-Atlantic region. Rising sea level over the next century will have a range of effects on coastal regions, including land loss and shoreline retreat from erosion and inundation, an increase in the frequency of storm-related flooding, and intrusion of salt water into coastal freshwater aquifers. The sensitivity of a coastal region to sea-level rise depends both on the physical aspects (shape and composition) of a coastal landscape and its ecological setting. One of the most obvious impacts is that there will be land loss as coastal areas are inundated and eroded. Rising sea level will not only inundate the landscape but will also be a driver of change for the coastal landscape. These impacts will have large effects on natural environments such as coastal wetland ecosystems, as well as effects on human development in coastal regions (see Part II of this Product). Making long-term projections of coastal change is difficult because of the multiple, interacting factors that contribute to that change. Given the large potential impacts to human and natural environments, there is a need to improve our ability to conduct long-term projections.

Part I describes the physical settings of the mid-Atlantic coast as well as the processes that influence shoreline change and land loss in response to sea-level rise. Part I also provides an assessment of coastal changes that may occur over the twenty-first century, as well as the consequences of those changes for coastal habitats and the flora and fauna they support.

Chapter 1 provides an overview of the current understanding of climate change and sea-level rise and their potential effects on both natural environments and society, and summarizes the background information that was used to develop this Product. Sea-level rise will have a range of impacts to both natural systems and human development and infrastructure in coastal regions. A major challenge is to understand the extent of these impacts and how to develop planning and adaptation strategies that address both the quality of the natural environment and human interests.

Chapter 2 highlights the important issues in analysis of sea-level rise vulnerability based on coastal elevation data. Elevation is a critical factor in determining vulnerability to inundation, which will be the primary response to sea-level rise for only some locations in the mid-Atlantic region. Because sea-level rise impact assessments often rely on elevation data, it is important to understand the inherent accuracy of the underlying data and its effects on the uncertainty of any resulting vulnerability maps and statistical summaries. The existing studies of sea-level rise vulnerability in the Mid-Atlantic based on currently available elevation data do not provide the level of confidence that is optimal for local decision making. However, recent research using newer high-resolution, high-accuracy elevation data is leading toward development of improved capabilities for vulnerability assessments.

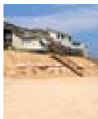
Chapter 3 summarizes the factors and processes controlling the dynamics of ocean coasts. The major factor affecting the location and shape of coasts at centennial and longer time scales is global sea-level change, which is linked to the Earth's climate. These close linkages are well documented in the scientific literature from field studies conducted over the past few decades. The details of the process-response relationships, however, are the subject of active, ongoing research. The general characteristics and shape of the coast (coastal morphology) reflects complex and ongoing interactions between changes in sea level, the physical processes that act on the coast (hydrodynamic regime, *e.g.*, waves and tidal characteristics), the availability of sediment (sediment supply) transported by waves and tidal currents at the shore, and underlying geology (the structure and composition of the landscape which is often referred to as the geologic framework). Variations in these three factors are responsible for the different coastal landforms and environments occurring in the coastal regions of the United States. Chapter 3 presents a synthesis and assessment of the potential changes that can be expected for the mid-Atlantic shores of the United States, which are primarily comprised of beaches and barrier islands.

Chapter 4 describes the vulnerability of coastal wetlands in the mid-Atlantic region to current and future sea-level rise. The fate of coastal wetlands is determined in large part by the way in which wetland vertical development processes change with climate drivers. In addition, the processes by which wetlands build vertically vary by geomorphic setting. Chapter 4 identifies those important climate drivers affecting wetland vertical development in the geomorphic settings of the mid-Atlantic region. The information on climate drivers, wetland vertical development, geomorphic settings, and local sea-level rise trends was synthesized and assessed using an expert decision process to determine wetland vulnerability for each geomorphic setting in each subregion of the mid-Atlantic region.

Chapter 5 summarizes the potential impacts to biota as a result of habitat change or loss driven by sea-level rise. Habitat quality, extent, and spatial distribution will change as a result of shore erosion, wetland loss, and shifts in estuarine salinity gradients. Of particular concern is the loss of wetland habitats and the important ecosystem functions they provide, which include critical habitat for wildlife; the trapping of sediments, nutrients, and pollutants; the cycling of nutrients and minerals; the buffering of storm impacts on coastal environments; and the exchange of materials with adjacent ecosystems.

CHAPTER 1

Sea-Level Rise and Its Effects on the Coast



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KEY FINDINGS

- Consensus in the climate science community is that the global climate is changing, mostly due to mankind's increased emissions of greenhouse gases such as carbon dioxide, methane, and nitrous oxide, from burning of fossil fuels and land-use change (measurements show a 25 percent increase in the last century). Warming of the climate system is unequivocal, but the effects of climate change are highly variable across regions and difficult to predict with high confidence based on limited observations over time and space. Two effects of atmospheric warming on coasts, which are relevant at regional, national, and global scales, are sea-level rise and an increase in major cyclone intensity.

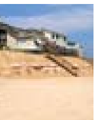
- Global sea level has risen about 120 meters (at highly variable rates) due to natural processes since the end of the Last Glacial Maximum (*i.e.*, last Ice Age). More recently, the sea-level rise rate has increased over natural rise due to an increase in the burning of fossil fuels. In some regions, such as the Mid-Atlantic and much of the Gulf of Mexico, sea-level rise is significantly greater than the observed global sea-level rise due to localized sinking of the land surface. The sinking has been attributed to ongoing adjustment of the Earth's crust due to the melting of former ice sheets, sediment compaction and consolidation, and withdrawal of hydrocarbons from underground.

- Instrumental observations over the past 15 years show that global mean sea level has been highly variable at regional scales around the world and, on average, the rate of rise appears to have accelerated over twentieth century rates, possibly due to atmospheric warming causing expansion of ocean water and ice-sheet melting.

- Results of climate model studies suggest sea-level rise in the twenty-first century will significantly exceed rates over the past century. Rates and the magnitude of rise could be much greater if warming affects dynamical processes that determine ice flow and losses in Greenland and Antarctica.

- Beyond the scope of this Product but important to consider, global sea-level elevations at the peak of the last interglacial warm cycle were 4 to 6 meters (13 to 20 feet) above present, and could be realized within the next several hundred years if warming and glacier and ice-sheet melting continue.

- Coastal regions are characterized by dynamic landforms and processes because they are the juncture between the land, oceans, and atmosphere. Features such as barrier islands, bluffs, dunes, and wetlands constantly undergo change due to driving processes such as storms, sediment supply, and sea-level change. Based on surveys over the past century, all U.S. coastal states are experiencing overall erosion at highly variable rates. Sea-level rise will have profound effects by increasing flooding frequency and inundating low-lying coastal areas, but other processes such as erosion and accretion will have cumulative effects that are profound but not yet predictable with high reliability. There is some recent scientific opinion that coastal landforms such as barrier islands and wetlands may have thresholds or tipping points with sea-level rise and storms, leading to rapid and irreversible change.



- Nearly one-half of the 6.7 billion people around the world live near the coast and are highly vulnerable to storms and sea-level rise. In the United States, coastal populations have doubled over the past 50 years, greatly increasing exposure to risk from storms and sea-level rise. Continued population growth in low-lying coastal regions worldwide and in the United States will increase vulnerability to these hazards as the effects of climate change become more pronounced.

- Most coastal regions are currently managed under the premise that sea-level rise is not significant and that shorelines are static or can be fixed in place by engineering structures. The new reality of sea-level rise due to climate change requires new considerations in managing areas to protect resources and reduce risk to humans. Long-term climate change impact data are essential for adaptation plans to climate change and coastal zone plans are most useful if they have the premise that coasts are dynamic and highly variable.

1.1 INTRODUCTION

The main objective of this Product is to review and assess the potential impacts of sea-level rise on U.S. coastal regions. Careful review and critique of sea-level and climate change science is beyond the scope of this Product; however, that information is central in assessing coastal impacts. Climate and coastal scientific disciplines are relatively recent, and while uncertainty exists in predicting quantitatively the magnitude and rates of change in sea level, a solid body of scientific evidence exists that sea level has risen over the recent geologic past, is currently rising and contributing to various effects such as coastal erosion, and has the potential to rise at an accelerated rate this century and beyond. Worldwide data also show that rates of global sea-level rise are consistent with increasing greenhouse gas concentrations and global warming (IPCC, 2001, 2007; Hansen *et al*., 2007; Broecker and Kunzig, 2008). Global climate change is already having significant and wide ranging effects on the Earth's ecosystems and human populations (Nicholls *et al*., 2007).

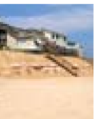
In recognition of the influence of humans on the Earth, including the global climate, the time period since the nineteenth century is being referred to by scientists as the Anthropocene Era (Pearce, 2007; Zalasiewicz, 2008). Changes to the global climate have been dramatic and the rapid rate of climate change observed over the past two decades is an increasing challenge for adaptation, by humans and animals and plants alike.

Effects from climate change are not uniform, but vary considerably from region to region and over a range of time scales (Nicholls *et al*., 2007). These variations occur due to regional and local differences in atmospheric, terrestrial, and oceanographic processes. The processes driving climate change are complex and so-called feedback interactions between the processes can both enhance and diminish sea-level rise impacts, making prediction of long-term effects difficult. Accelerated global sea-level rise, a likely major long-term outcome of climate change, will have increasingly far-reaching impacts on coastal regions of the United States and around the world (Nicholls *et al*., 2007). Relative sea-level rise impacts are already evident for many coastal regions and will increase significantly during this century and beyond (FitzGerald *et al*, 2008; IPCC, 2007; Nicholls *et al*., 2007). Sea-level rise will cause significant and often dramatic changes to coastal landforms (*e.g.*, barrier islands, beaches, dunes, marshes), as well as ecosystems, estuaries, waterways, and human populations and development in the coastal zone (Nicholls *et al*., 2007; Rosenzweig *et al*., 2008; FitzGerald *et al*., 2008). Low-lying coastal plain regions, particularly those that are densely populated (*e.g.*, the Mid-Atlantic, the north central Gulf of Mexico), are especially vulnerable to sea-level rise and land subsidence and their combined impacts to the coast and to development in the coastal zone (*e.g.*, McGranahan *et al*., 2007; Day *et al*., 2007a).

The effects of sea-level rise are not necessarily obvious in the short term, but are evident over the longer term in many ways. Arguably, the most visible effect is seen in changing coastal landscapes, which are altered through more frequent flooding, inundation, and coastal erosion as barrier islands, beaches, and sand dunes change shape and move landward in concert with sea-level rise and storm effects. In addition, the alteration or loss of coastal habitats such as wetlands, bays, and estuaries has negative impacts on many animal and plant species that depend on these coastal ecosystems.

Understanding how sea-level rise is likely to affect coastal regions and, consequently, how society will choose to address this issue in the short term in ways that are sustainable for the long term, is a major challenge for both scientists and coastal policy makers and managers. While human populations in high-risk coastal areas continue to expand rapidly, the analyses of long-term sea-level measurements show that sea level rose on average 19 centimeters (cm) (7.5 inches [in]) globally during the twentieth century (Jevrejeva *et al*., 2008). In addition, satellite data show global sea-level rise has accelerated over the past 15 years, but at highly variable rates on regional scales. Analyses indicate that the magnitude and rate of sea-level rise for this century and beyond is likely to exceed that of the past century (Meehl *et al*., 2007; Rahmstorf, 2007; Jevrejeva *et al*., 2008).

Over the last century, humans have generally responded to eroding shorelines and flooding landscapes by using engineering measures to protect threatened property or by relocating development inland to higher ground. In the future, these responses will become more widespread and more expensive for society as sea-level rise accelerates (Nicholls *et al*., 2007). Currently, the world population is 6.7 billion people and is predicted to expand to 9.1 billion by the year 2042 (UN, 2005). Globally, 44 percent of the world's population lives within 150 kilometers (km) (93 miles [mi]) of the ocean (<http://www.oceansatlas.org/index.jsp>) and more than 600 million people live in low elevation coastal zone areas that are less than 10 meters (m) (33 feet [ft]) above sea level (McGranahan *et al*., 2007), putting them at significant risk to the effects of sea-level rise. McGranahan *et al*. (2007) chose the 10-m elevation to delineate the low elevation coastal zone in recognition of the limits imposed by the vertical accuracy of the best available global elevation datasets. Eight of the 10 largest cities in the world are sited on the ocean coast. In the United States, 14 of the 20 largest urban centers are located within 100 km of the coast and less than 10 m above sea level. Using the year 2000 census data for U.S. coastal counties as defined by the National Oceanic



and Atmospheric Administration (NOAA) and excluding the Great Lakes states, approximately 126 million people resided in coastal areas (Crossett *et al*., 2004). The Federal Emergency Management Agency (FEMA), using the same 2000 census data but different criteria for defining coastal counties, estimated the coastal population to be 86 million people (Crowell, *et al*., 2007). Regardless, U.S. coastal populations have expanded greatly over the past 50 years, increasing exposure to risk from storms and sea-level rise. Continued population growth in low-lying coastal regions worldwide and in the United States will increase vulnerability to these hazards.

Modern societies around the world have developed and populations have expanded over the past several thousand years under a relatively mild and stable world climate and relatively stable sea level (Stanley and Warne, 1993; Day *et al*., 2007b). However, with continued population growth, particularly in coastal areas, and the probability of accelerated sea-level rise and increased storminess, adaptation to expected changes will become increasingly challenging.

This Product reviews available scientific literature through late 2008 and assesses the likely effects of sea-level rise on the coast of the United States, with a focus on the mid-Atlantic region. An important point to emphasize is that sea-level rise impacts will be far-reaching. Coastal lands will not simply be flooded by rising seas, but will be modified by a variety of processes (*e.g.*, erosion, accretion) whose impacts will vary greatly by location and geologic setting. For example, the frequency and magnitude of flooding may change, and sea-level rise can also affect water table elevations, impacting fresh water supplies. These changes will have a broad range of human and environmental impacts. To effectively cope with sea-level rise and its impacts, current policies and economic considerations should be examined, and possible options for changing planning and management activities are warranted so that society and the environment are better able to adapt to potential accelerated rise in sea level. This Product examines the potential coastal impacts for three different plausible scenarios of future sea-level rise, and focuses on the potential effects to the year 2100. The effects, of course, will extend well beyond 2100, but detailed discussion of effects farther into the future is outside the scope of this Product.

1.1.1 Climate Change Basis for this Product

The scientific study of climate change and associated global sea-level rise is complicated due to differences in observations, data quality, cumulative effects, and many other factors. Both direct and indirect methods are useful for studying past climate change. Instrument records and historical documents are most accurate, but are limited to the past 100 to 150 years in the United States. Geological information from analyses of continuous cores sampled from ice sheets and glaciers, sea and lake sediments, and sea corals provide useful proxies that have allowed researchers to decipher past climate conditions and a record of climate and sea-level changes stretching back millions of years before recorded history (Miller *et al*., 2005; Jansen *et al*., 2007). The most precise methods have provided accurate high-resolution data on the climate (*e.g.*, global temperature, atmospheric composition) dating back more than 400,000 years.

The Intergovernmental Panel on Climate Change (IPCC) 2007 Fourth Assessment Report provides a comprehensive review and assessment of global climate change trends, expected changes over the next century, and the impacts and challenges that both humans and the natural world are likely to be confronted with during the next century (IPCC, 2007). Some key findings from this Report are summarized in Box 1.1. A 2008 U.S. Climate Change Science Program (CCSP) report provides a general assessment of current scientific understanding of climate change impacts to the United States (CENR, 2008) and the recent CCSP Synthesis and Assessment Product (SAP) 3.4 on Abrupt Climate Change discusses the effects of complex changes in ice sheets and glaciers on sea level (Steffen *et al*., 2008). CCSP SAP 4.1 provides more specific information and scientific consensus on the likely effects and implications of future sea-level rise on coasts and wetlands of the United States and also includes a science strategy for improving the understanding of sea-level rise, documenting its effects, and devising robust models and methods for reliably predicting future changes and impacts to coastal regions.

1.2 WHY IS GLOBAL SEA LEVEL RISING?

The elevation of global sea level is determined by the dynamic balance between the mass of ice on land (in glaciers and ice sheets) and the mass of water in ocean basins. Both of these factors are highly influenced by the Earth's atmospheric temperature. During the last 800,000 years, global sea level has risen and fallen about 120 m (400 ft) in response to the alternating accumulation and decline of large continental ice sheets about 2 to 3 km (1 to 2 mi) thick as climate warmed and cooled in naturally occurring 100,000 year astronomical cycles (Imbrie and Imbrie, 1986; Lambeck *et al*., 2002). Figure 1.1 shows a record of large global sea-level change over the past 400,000 years during the last four cycles, consisting of glacial maximums with low sea levels and interglacial warm periods with high sea levels. The last interglacial period, about 125,000 years ago, lasted about 10,000 to 12,000 years, with average temperatures warmer than today but close to those predicted for the next century, and global sea level was 4 to 6 m (13 to 20 ft) higher than present (Imbrie and Imbrie, 1986). Following the peak of the last Ice Age about 21,000 years ago, the

BOX 1.1: Selected Findings of the Intergovernmental Panel on Climate Change (2007) on Climate Change and Sea-Level Rise

Recent Global Climate Change:

Note: The likelihood scale, established by the IPCC and used throughout SAP 4.1, is described in the Preface (page XV). The terms used in that scale will be italicized when used as such in this Product.

Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level.

Human-induced increase in atmospheric carbon dioxide is the most important factor affecting the warming of the Earth's climate since the start of the Industrial Era. The atmospheric concentration of carbon dioxide in 2005 exceeds by far the natural range over the last 650,000 years.

Most of the observed increase in global average temperatures since the mid-twentieth century is very likely due to the observed increase in human-caused greenhouse gas concentrations. Discernible human influences now extend to other aspects of climate, including ocean warming, continental-average temperatures, temperature extremes, and wind patterns.

Recent Global Sea-Level Rise:

Observations since 1961 show that the average temperature of the global ocean has increased to depths of at least 3,000 meters (m) and that the ocean has been absorbing more than 80 percent of the heat added to the climate system. Such warming causes seawater to expand, contributing to global sea-level rise.

Mountain glaciers and snow cover have declined on average in both hemispheres. Widespread decreases in glaciers and ice caps have contributed to global sea-level rise.

New data show that losses from the ice sheets of Greenland and Antarctica have very likely contributed to global sea-level rise between 1993 and 2003.

Global average sea level rose at an average rate of 1.8 (1.3 to 2.3) millimeters (mm) per year between 1961 and 2003. The rate was faster between 1993 and 2003: about 3.1 (2.4 to 3.8) mm per year. Whether the faster rate for 1993 to 2003 reflects decadal variability or an increase in the longer term trend is unclear (see Figure 1.3).

Global average sea level in the last interglacial period (about 125,000 years ago) was likely 4 to 6 m higher than during the twentieth century, mainly due to the retreat of polar ice. Ice core data indicate that average polar temperatures at that time were 3 to 5°C higher than present, because of differences in the Earth's orbit. The Greenland ice sheet and other arctic ice fields likely contributed no more than 4 m of the observed global sea-level rise. There may also have been contributions from Antarctica ice sheet melting.

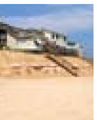
Projections of the Future:

Continued greenhouse gas emissions at or above current rates would cause further warming and induce many changes in the global climate system during the twenty-first century that would very likely be larger than those observed during the twentieth century.

Based on a range of possible greenhouse gas emissions scenarios for the next century, the IPCC estimates the global increase in temperature will likely be between 1.1 and 6.4°C. Estimates of sea-level rise for the same scenarios are 0.18 m to 0.59 m, excluding the contribution from accelerated ice discharges from the Greenland and Antarctica ice sheets.

Extrapolating the recent acceleration of ice discharges from the polar ice sheets would imply an additional contribution up to 0.20 m. If melting of these ice caps increases, larger values of sea-level rise cannot be excluded.

In addition to global sea-level rise, the storms that lead to coastal storm surges could become more intense. The IPCC indicates that, based on a range of computer models, it is likely that hurricanes will become more intense, with larger peak wind speeds and more heavy precipitation associated with ongoing increases of tropical sea surface temperatures, while the tracks of "winter" or extratropical cyclones are projected to shift towards the poles along with some indications of an increase in intensity in the North Atlantic.



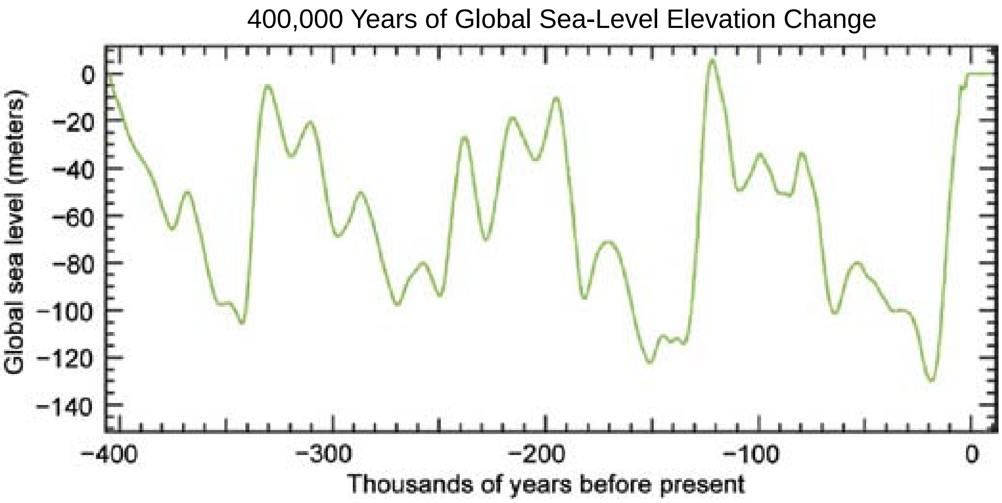


Figure 1.1 Plot of large variations in global sea-level elevation over the last 400,000 years resulting from four natural glacial and interglacial cycles. Evidence suggests that sea level was about 4 to 6 meters (m) higher than present during the last interglacial warm period 125,000 years ago and 120 m lower during the last Ice Age, about 21,000 years ago (see reviews in Muhs *et al.*, 2004 and Overpeck *et al.*, 2006). (Reprinted from Quaternary Science Reviews, 21/1-3, Phillippe Huybrechts, Sea-level changes at the LGM from ice-dynamic reconstructions of the Greenland and Antarctic ice sheets during the glacial cycles, 203-231, Copyright [2002], with permission from Elsevier).

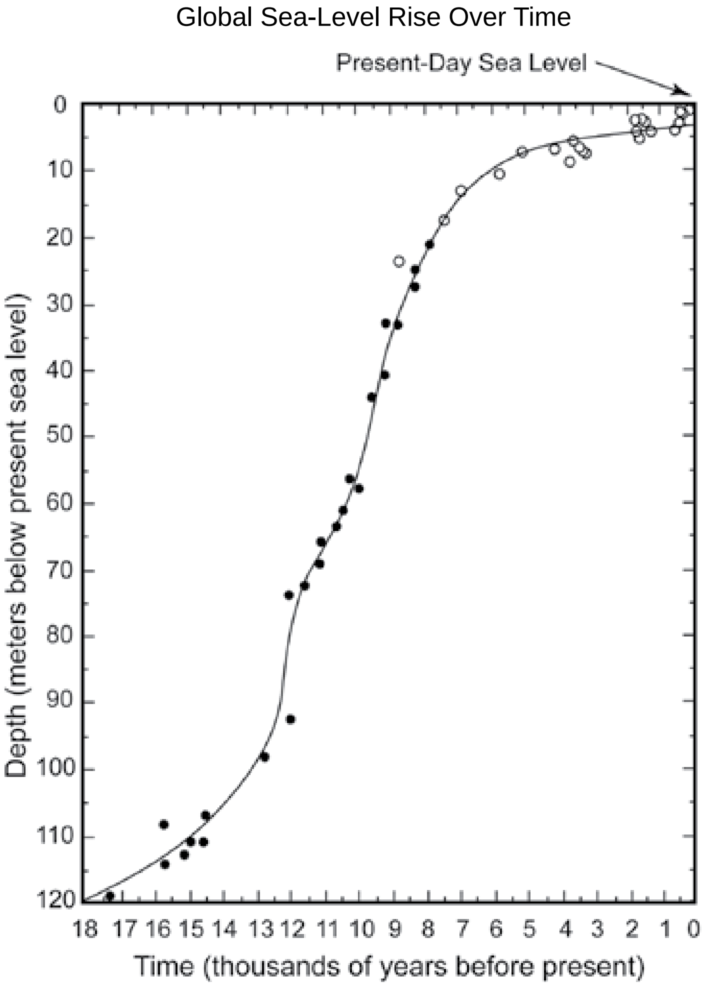


Figure 1.2 Generalized plot of the rise in global sea level at variable rates over the last 18,000 years as the Earth moved from a glacial period to the present interglacial warm period. This curve is reconstructed from radiocarbon-dated corals from Barbados (filled circles) and four other Caribbean island locations (open circles). The radiocarbon age (not calendar years) and depth of each sample from present mean sea level is plotted. Modified and reprinted by permission from Macmillan Publishers Ltd: Nature (Fairbanks, R.G., A 17,000-year glacio-eustatic sea level record–influence of glacial melting rates on the Younger Dryas event and deep-sea circulation, 349[6250], 637-642, ©1989).

Earth entered the present interglacial warm period. Global sea level rose very rapidly at average rates of 10 to 20 mm per year punctuated with periodic large “meltwater pulses” with rates of more than 50 mm per year from about 21,000 to 6,000 years ago. Sea-level rise then slowed to a rate of about 0.5 mm per year from 6,000 to 3,000 years ago (Fairbanks, 1989; Rohling *et al.*, 2008). During the past 2,000 to 3,000 years, the rate slowed to approximately 0.1 to 0.2 mm per

year until an acceleration occurred in the late nineteenth century (Lambeck and Bard, 2000; IPCC, 2001).

There is growing scientific evidence that, at the onset of the present interglacial warm period, the Earth underwent abrupt changes when the climate system crossed several thresholds or tipping points (points or levels in the evolution of the Earth's climate leading to irreversible change) that triggered dramatic changes in temperature, precipitation, ice cover, and sea level. These changes are thought to have occurred over a few decades to a century and the causes are not well understood (NRC, 2002; Alley *et al.*, 2003). One cause is thought to be disruption of major ocean currents by influxes of fresh water from glacial melt. It is not known with any confidence how anthropogenic climate change might alter the natural glacial-interglacial cycle or the forcings that drive abrupt change in the Earth's climate system. Imbrie and Imbrie (1986) surmise that the world might experience a "super-interglacial" period with mean temperatures higher than past warm periods.

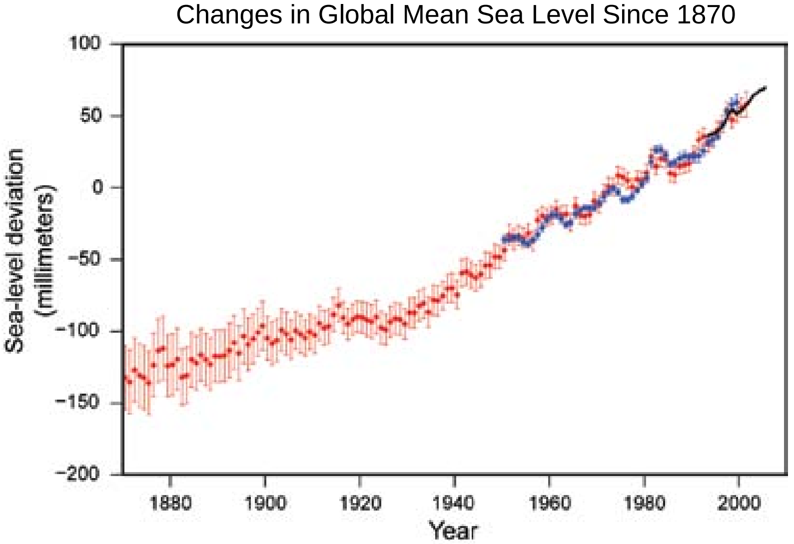


Figure 1.3 Annual averages of global mean sea level in millimeters from IPCC (2007). The red curve shows sea-level fields since 1870 (updated from Church and White, 2006); the blue curve displays tide gauge data from Holgate and Woodworth (2004), and the black curve is based on satellite observations from Leuliette *et al.* (2004). The red and blue curves are deviations from their averages for 1961 to 1990, and the black curve is the deviation from the average of the red curve for the period 1993 to 2001. Vertical error bars show 90 percent confidence intervals for the data points. (Adapted from *Climate Change 2007: The Physical Science Basis*. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Figure 5.13. Cambridge University Press.)

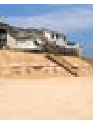
At the peak of the last Ice Age, sea level was approximately 120 m lower than today and the shoreline was far seaward of its present location, at the margins of the continental shelf (Figure 1.2). As the climate warmed and ice sheets melted, sea level rose rapidly but at highly variable rates, eroding and submerging the coastal plain to create the continental shelves, drowning ancestral river valleys, and creating major estuaries such as Long Island Sound, Delaware Bay, Chesapeake Bay, Tampa Bay, Galveston Bay, and San Francisco Bay.

A few investigators have found that global sea level was relatively stable over the last 400 to 2,000 years, with rates averaging 0 to 0.3 mm per year until the late nineteenth or early twentieth centuries (Lambeck and Bard, 2000; Lambeck *et al.*, 2004; Gehrels *et al.*, 2008). Some studies indicate that acceleration in sea-level rise may have begun earlier, in the late eighteenth century (Jevrejeva *et al.*, 2008). Analyses of tide-gauge data indicate that the twentieth century rate of sea-level rise averaged 1.7 mm per year on a global scale (Figure 1.3) (Bindoff *et al.*, 2007), but that the rate fluctuated over decadal periods throughout the century (Church and White, 2006; Jevrejeva *et al.*, 2006, 2008). Between 1993 and 2003, both satellite altimeter and tide-gauge observations indicate that the rate of sea-level rise increased to 3.1 mm per year (Bindoff *et al.*, 2007); however, with such a short record, it is not yet possible to determine with certainty whether this is a natural decadal variation or due to human-induced climate warming (Bindoff *et al.*, 2007).

1.3 RELATIVE SEA-LEVEL RISE AROUND THE UNITED STATES

Geologic data from radiocarbon age-dating organic sediments in cores and coral reefs are indirect methods used for determining sea-level elevations over the past 40,000 years, but the records from long-term (more than 50 years) tide-gauge stations have been the primary direct measurements of relative sea-level trends over the past century (Douglas, 2001). Figure 1.4 shows the large variations in relative sea level for U.S. coastal regions. The majority of the Atlantic Coast and Gulf of Mexico Coast experience higher rates of sea-level rise (2 to 4 mm per year and 2 to 10 mm per year, respectively) than the current global average (1.7 mm per year).

There are large variations for relative sea-level rise (and fall) around the United States, ranging from a fall of 16.68 mm per year at Skagway in southeast Alaska due to tectonic processes and land rebound upward as a result of glacier melting (Zervas, 2001), to a rise of 9.85 mm per year at Grand Isle, Louisiana, due to land subsidence downward from natural causes and possibly oil and gas extraction.



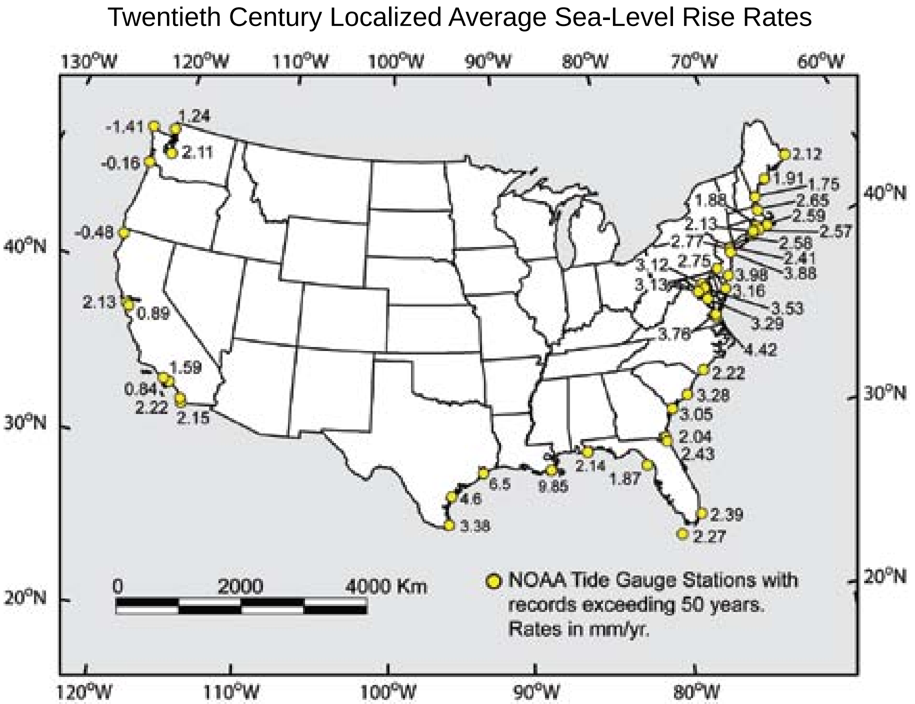


Figure 1.4 Map of twentieth century annual relative sea-level rise rates around the U.S. coast. The higher rates for Louisiana (9.85 millimeters [mm] per year) and the mid-Atlantic region (1.75 to 4.42 mm per year) are due to land subsidence. Sea level is stable or dropping relative to the land in the Pacific Northwest, as indicated by the negative values, where the land is tectonically active or rebounding upward in response to the melting of ice sheets since the last Ice Age (data from Zervas, 2001).

The rate of relative sea-level rise (see Box 1.2 for definition) measured by tide gauges at specific locations along the Atlantic coast of the United States varies from 1.75 mm to as much as 4.42 mm per year (Table 1.1; Figure 1.4; Zervas, 2001). The lower rates, which occur along New England and from Georgia to northern Florida, are close to the global rate of 1.7 (±0.5) mm per year (Bindoff *et al.*, 2007). The highest rates are in the mid-Atlantic region between northern New Jersey and southern Virginia. Figure 1.5 is an example of the monthly average (mean) sea-level record and the observed relative sea-level rise trend at Baltimore, Maryland. At this location, the relative sea-level trend is 3.12 (±0.08) mm per year, almost twice the present rate of global sea-level rise. Subsidence of the land surface, attributed mainly to adjustments of the

BOX 1.2: Relative Sea Level

"Global sea-level rise" results mainly from the worldwide increase in the volume of the world's oceans that occurs as a result of thermal expansion of warming ocean water and the addition of water to the ocean from melting ice sheets and glaciers (ice masses on land). "Relative sea-level rise" is measured directly by coastal tide gauges, which record both the movement of the land to which they are attached and changes in global sea level. Global sea-level rise can be estimated from tide gauge data by subtracting the land elevation change component. Thus, tide gauges are important observation instruments for measuring sea-level change trends. However, because variations in climate and ocean circulation can cause fluctuations over 10-year time periods, the most reliable sea level data are from tide gauges having records 50 years or longer and for which the rates have been adjusted using a global isostatic adjustment model (Douglas, 2001).

At regional and local scales along the coast, vertical movements of the land surface can also contribute significantly to sea-level change and the combination of global sea-level and land-level change is referred to as "relative sea level" (Douglas, 2001). Thus, "relative sea-level rise" refers to the change in sea level relative to the elevation of the land, which includes both global sea-level rise and vertical movements of the land. Both terms, global sea level and relative sea level, are used throughout this Product.

Vertical changes of the land surface result from many factors including tectonic processes and subsidence (sinking of the land) due to compaction of sediments and extraction of subsurface fluids such as oil, gas, and water. A principal contributor to this change along the Atlantic Coast of North America is the vertical relaxation adjustments of the Earth's crust to reduced ice loading due to climate warming since the last Ice Age. In addition to glacial adjustments, sediment loading also contributes to regional subsidence of the land surface. Subsidence contributes to high rates of relative sea-level rise (9.9 millimeters per year) in the Mississippi River delta where thick sediments have accumulated and are compacting. Likewise, fluid withdrawal from coastal aquifers causes the sediments to compact locally as the water is extracted. In Louisiana, Texas, and Southern California, oil, gas, and ground-water extraction have contributed markedly to subsidence and relative sea-level rise (Gornitz and Lebedeff, 1987; Emery and Aubrey, 1991; Nicholls and Leatherman, 1996; Galloway *et al.*, 1999; Morton *et al.*, 2004). In locations where the land surface is subsiding, rates of relative sea-level rise exceed the average rate of global rise (*e.g.*, the north central Gulf of Mexico Coast and mid-Atlantic coast).

Table 1.1 Rates of Relative Sea-Level Rise for Selected Long-Term Tide Gauges on the Atlantic Coast of the United States (Zervas, 2001). For comparison, the global average rate is 1.7 millimeters (mm) per year.

Station	Rate of Sea-Level Rise (mm per year)	Time Span of Record	Station	Rate of Sea-Level Rise (mm per year)	Time Span of Record
Eastport, ME	2.12 ±0.13	1929-1999	Lewes, DE	3.16 ±0.16	1919-1999
Portland, ME	1.91 ±0.09	1912-1999	Baltimore, MD	3.12 ±0.16	1902-1999
Seavey Island, ME	1.75 ±0.17	1926-1999	Annapolis, MD	3.53 ±0.13	1928-1999
Boston, MA	2.65 ±0.1	1921-1999	Solomons Island, MD	3.29 ±0.17	1937-1999
Woods Hole, MA	2.59 ±0.12	1932-1999	Washington, DC	3.13 ±0.21	1931-1999
Providence, RI	1.88 ±0.17	1938-1999	Hampton Roads, VA	4.42 ±0.16	1927-1999
Newport, RI	2.57 ±0.11	1930-1999	Portsmouth, VA	3.76 ±0.23	1935-1999
New London, CT	2.13 ±0.15	1938-1999	Wilmington, NC	2.22 ±0.25	1935-1999
Montauk, NY	2.58 ±0.19	1947-1999	Charleston, SC	3.28 ±0.14	1921-1999
Willets Point, NY	2.41 ±0.15	1931-1999	Fort Pulaski, GA	3.05 ±0.20	1935-1999
The Battery, NY	2.77 ±0.05	1905-1999	Fernandina Beach, FL	2.04 ±0.12	1897-1999
Sandy Hook, NJ	3.88 ±0.15	1932-1999	Mayport, FL	2.43 ±0.18	1928-1999
Atlantic City, NJ	3.98 ±0.11	1911-1999	Miami, FL	2.39 ±0.22	1931-1999
Philadelphia, PA	2.75 ±0.12	1900-1999	Key West, FL	2.27 ±0.09	1913-1999

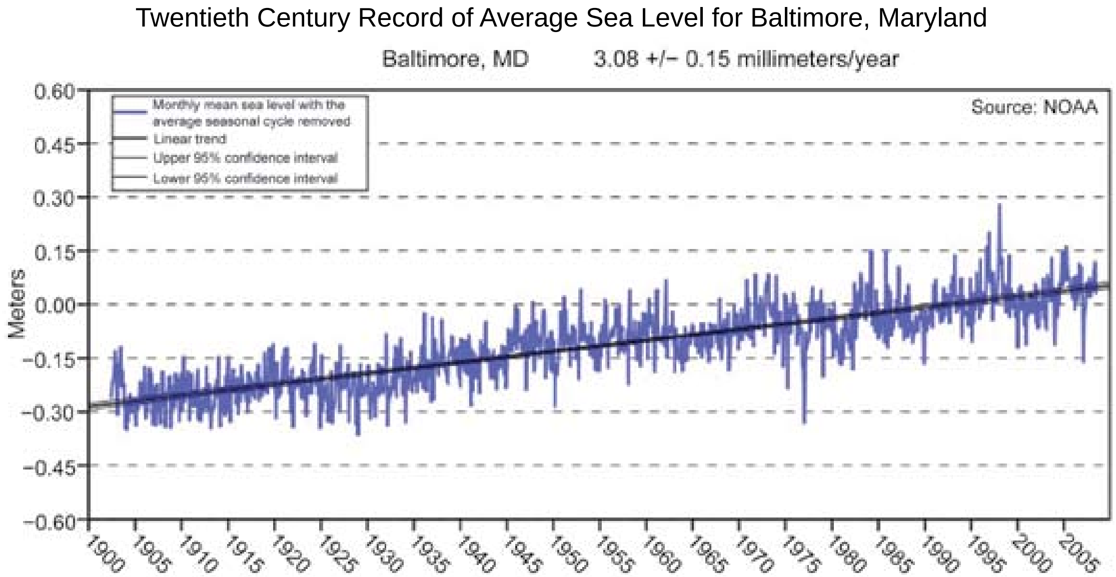
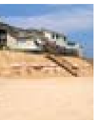

Twentieth Century Record of Average Sea Level for Baltimore, Maryland

Figure 1.5 The monthly computed average sea-level record (black line) from 1900 to 2006 from the Baltimore, Maryland tide gauge. Blue line is the observed data. The zero line is the latest 19-year National Tidal Datum Epoch mean value. The rate, 3.12 millimeters (mm) per year, is nearly double the present rate (1.7 mm per year) of global sea-level rise due to land subsidence (based on Zervas, 2001).

Earth's crust in response to the melting of the Laurentide ice sheet and to the compaction of sediments due to freshwater withdrawal from coastal aquifers, contributes to the high rates of relative sea-level rise observed in this region (Gornitz and Lebedeff, 1987; Emery and Aubrey, 1991; Kearney and Stevenson, 1991; Douglas, 2001; Peltier, 2001).

While measuring and dealing with longer-term global averages of sea-level change is useful in understanding effects on coasts, shorter-term and regional-scale variations due primarily to warming and oceanographic processes can be quite different from long-term averages, and equally important for management and planning. As shown in Figure 1.6, from Bindoff *et al.* (2007) based on a decade of data, some of the highest rates of rise are off the U.S. Mid-Atlantic and the western Pacific, while an apparent drop occurred off the North and South American Pacific Coast.

Recently, the IPCC Fourth Assessment Report (IPCC, 2007) estimated that global sea level is likely to rise 18 to 59 cm (7



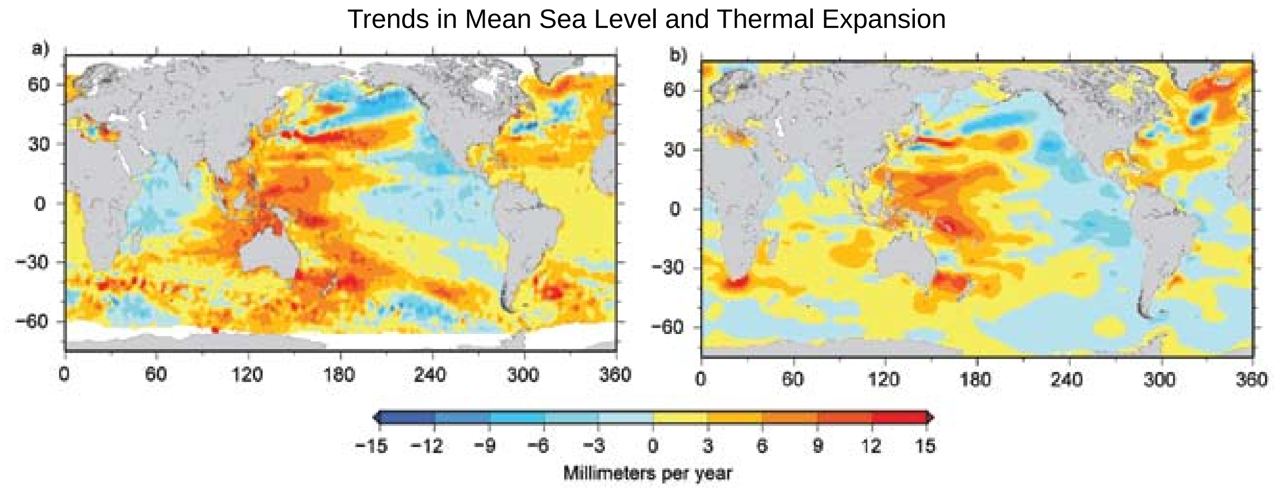


Figure 1.6 (a) Geographic distribution of short-term linear trends in mean sea level (millimeters per year) for 1993 to 2003 based on TOPEX/Poseidon satellite altimetry (updated from Cazenave and Nerem, 2004) and (b) geographic distribution of linear trends in thermal expansion (millimeters per year) for 1993 to 2003 (based on temperature data down to 700 meters [from Ishii *et al.*, 2006]). (Adapted from *Climate Change 2007: The Physical Science Basis*. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Figure 5.15. Cambridge University Press).

to 23 in) over the next century; however, possible increased meltwater contributions from Greenland and Antarctica were excluded (Meehl *et al.*, 2007; IPCC, 2007). The IPCC projections (Figure 1.7) represent a "likely range" which inherently allows for the possibility that the actual rise may be higher or lower. Recent observations suggest that sea-level rise rates may already be approaching the higher end of the IPCC estimates (Rahmstorf *et al.*, 2007; Jevrejeva *et al.*, 2008). This is because potentially important meltwater contributions from Greenland and Antarctica were excluded due to limited data and an inability at that time to adequately model ice flow processes. It has been suggested by Rahmstorf (2007) and other climate scientists that a global sea-level rise of 1 m (3 ft) is plausible within this century if increased melting of ice sheets in Greenland and Antarctica is added to the factors included in the IPCC estimates. Therefore, thoughtful precaution suggests that a global sea-level rise of 1 m to the year 2100 should be considered for future planning and policy discussions.

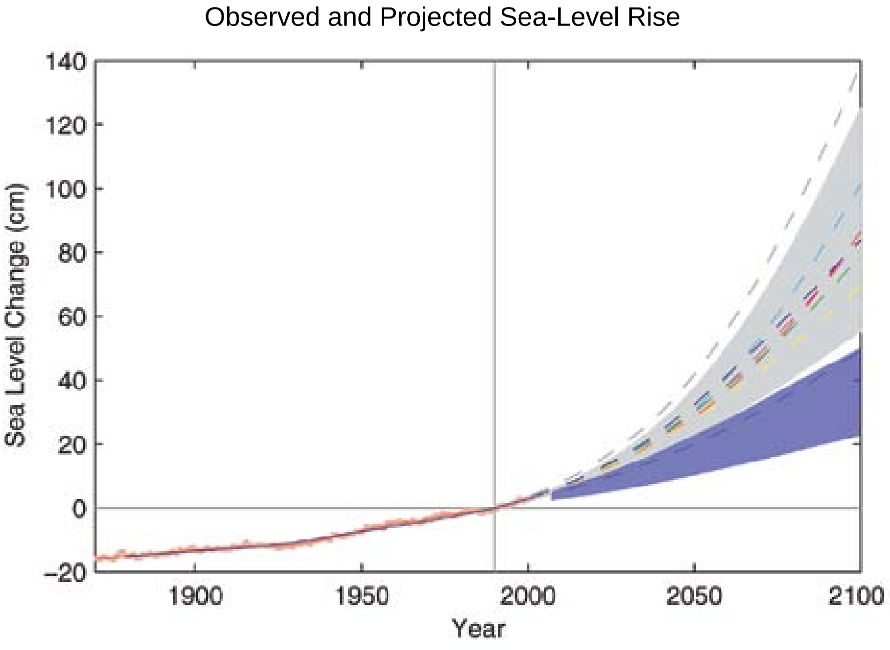


Figure 1.7 Plot in centimeters (cm) rise over time of past sea-level observations and several future sea-level projections to the year 2100. The blue shaded area is the sea-level rise projection by Meehl *et al.* (2007) corresponding to the A1B emissions scenario which forms part of the basis for the IPCC (2007) estimates. The higher gray and dash line projections are from Rahmstorf (2007). (Modified from: Rahmstorf, S., 2007: A semi-empirical approach to projecting future sea-level rise. Science, 315(5810), 368-370. Reprinted with permission from AAAS.)

This Product focuses on the effects of sea-level rise on U.S. coasts over the next century, but climate warming and its effects are likely to continue well beyond that due to the amount of greenhouse gases already in the atmosphere. Currently, the amount of potential melting from land-based ice masses (primarily Greenland and West Antarctica) is uncertain and is therefore not fully incorporated into all sea-level rise model projections. Recent observations of changes in ice cover and glacial melting on Greenland, West Antarctica, and smaller glaciers and ice caps around the world indicate that ice loss could be more rapid than the trends evaluated for the IPCC (2007) report (Chen *et al.*, 2006;

Shepherd and Wingham, 2007; Meier *et al*., 2007; Fettweis *et al*., 2007). The science needed to assign probability to these high scenarios is not yet well established, but scientists agree that this topic is worthy of continued study because of the grave implications for coastal areas in the United States and around the world.

1.4 IMPACTS OF SEA-LEVEL RISE FOR THE UNITED STATES

1.4.1 Coastal Vulnerability for the United States

Coastal communities and habitats will be increasingly stressed by climate change impacts due to sea-level rise and storms (Field *et al*., 2007). To varying degrees over decades, rising sea level will affect entire coastal systems from the ocean shoreline well landward. The physical and ecological changes that occur in the near future will impact people and coastal development. Impacts from sea-level rise include: land loss through submergence and erosion of lands in coastal areas; migration of coastal landforms and habitats; increased frequency and extent of storm-related flooding; wetland losses; and increased salinity in estuaries and coastal freshwater aquifers. Each of these effects can have impacts on both natural ecosystems and human developments. Often the impacts act together and the effects are cumulative. Other impacts of climate change, such as increasingly severe droughts and storm intensity—combined with continued rapid coastal development—could increase the magnitude and extent of sea-level rise impacts (Nicholls, *et al*., 2007). To deal with these impacts, new practices in managing coasts and the combined impacts of mitigating changes to the physical system (*e.g.*, coastal erosion or migration, wetland losses) and impacts to human populations (*e.g.*, property losses, more frequent flood damage) should be considered.

Global sea-level rise, in combination with the factors above, is already having significant effects on many U.S. coastal areas. Flooding of low-lying regions by storm surges and spring tides is becoming more frequent. In certain areas, wetland losses are occurring, fringe forests are dying and being converted to marsh, farmland and lawns are being converted to marsh (*e.g.*, see Riggs and Ames, 2003, 2007), and some roads and urban centers in low elevation areas are more frequently flooded during spring high tides (Douglas, 2001). In addition, "ghost forests" of standing dead trees killed by saltwater intrusion are becoming increasingly common in southern New Jersey, Maryland, Virginia, Louisiana, and North Carolina (Riggs and Ames, 2003). Relative sea-level rise is causing saltwater intrusion into estuaries and threatening freshwater resources in some parts of the mid-Atlantic region (Barlow, 2003).

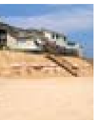
Continued rapid coastal development exacerbates both the environmental and the human impact of rising sea level. Due to the increased human population in coastal areas, once sparsely developed coastal areas have been transformed into high-density year-round urban complexes (*e.g.*, Ocean City, Maryland; Virginia Beach, Virginia; Myrtle Beach, South Carolina). With accelerated rise in sea level and increased intensity of storms, the vulnerability of development at the coast and risks to people will increase dramatically unless new and innovative coastal zone management and planning approaches are employed.

1.4.2 Climate Change, Sea-Level Rise, and Storms

Although storms occur episodically, they can have long-term impacts to the physical environment and human populations. Coupled with rise in sea level, the effects of storms could be more extensive in the future due to changes in storm character, such as intensity, frequency, and storm tracking. In addition to higher sea level, coastal storm surge from hurricanes could become higher and more intense rainfall could raise the potential for flooding from land runoff. Recent studies (*e.g.*, Emanuel, *et al*., 2004, 2008; Emanuel, 2005; Komar and Allen, 2008; Elsner *et al*., 2008) have concluded that there is evidence that hurricane intensity has increased during the past 30 years over the Atlantic Ocean; however, it is unknown whether these trends will continue. A recent evaluation of climate extremes concluded that it is presently unknown whether the global frequency of hurricanes will change (Karl *et al*., 2008).

Land-falling Atlantic coast hurricanes can produce storm surges of 5 m (16 ft) or more (Karl *et al*., 2008). The power and frequency of Atlantic hurricanes has increased substantially in recent decades, though North American mainland land-falling hurricanes do not appear to have increased over the past century (Karl *et al*., 2008). The IPCC (2007) and Karl *et al*. (2008) indicate that, based on computer models, it is likely that hurricanes will become more intense, with increases in tropical sea surface temperatures. Although hurricane intensity is expected to increase on average, the effects on hurricane frequency in the Atlantic are still not certain and are the topic of considerable scientific study (Elsner *et al*., 2008; Emanuel *et al*., 2008; see also review in Karl *et al*., 2008).

Extratropical cyclones can also produce significant storm surges. These storms have undergone a northward shift in track over the last 50 years (Karl *et al*., 2008). This has reduced storm frequencies and intensities in the mid-latitudes and increased storm frequencies and intensities at high latitudes (Gutowski *et al*., 2008). Karl *et al*. (2008) conclude that future intense extratropical cyclones will become more frequent with stronger winds and more extreme wave heights though the overall number of storms may decrease. So, while



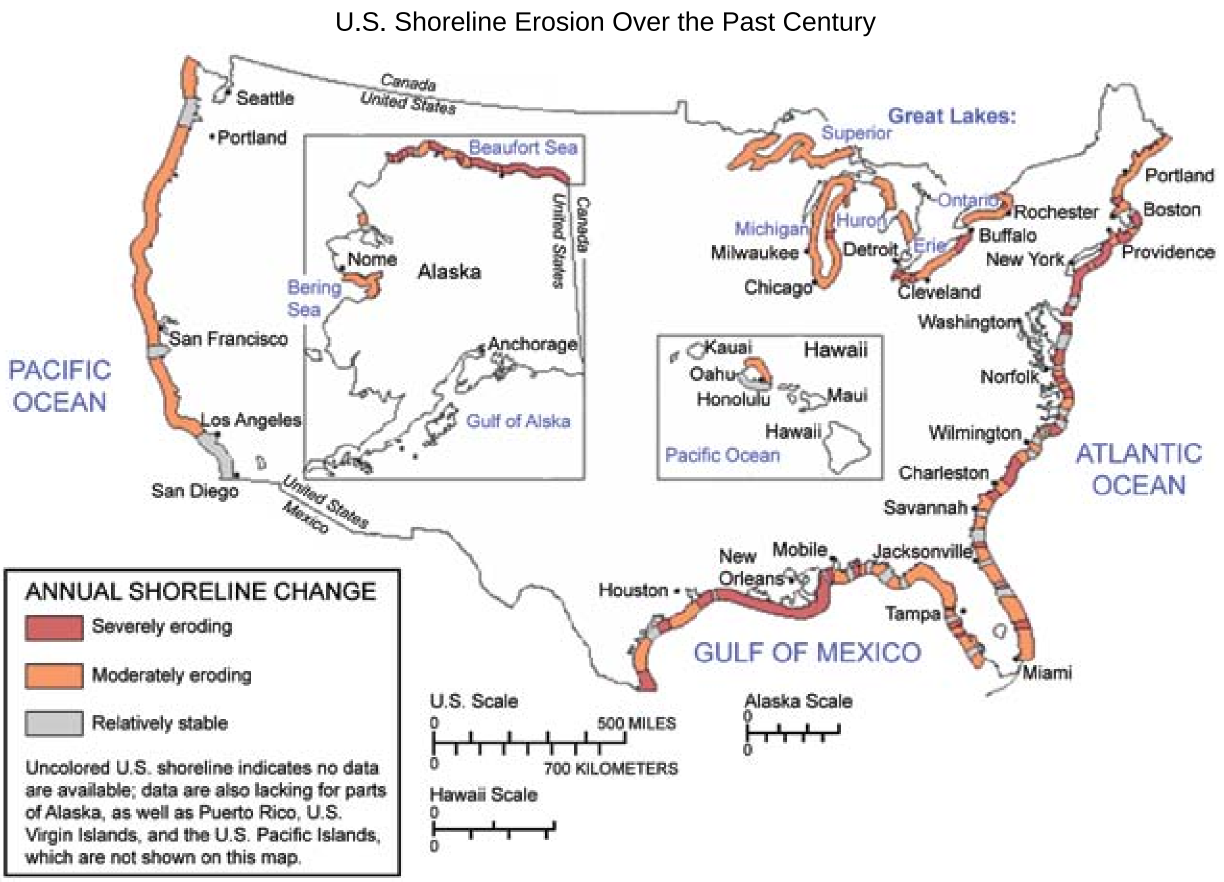

U.S. Shoreline Erosion Over the Past Century

Figure 1.8 Shoreline change around the United States based on surveys over the past century. All 30 coastal states are experiencing overall erosion at highly variable rates due to natural processes (*e.g.*, storms, sea-level rise) and human activity (From USGS, 1985).

general storm projections are possible, specific projections for regional changes in extratropical cyclone activity, such as for the mid-Atlantic coast, are not yet available. Thus, while increased storm intensity is a serious risk in concert with sea-level rise, specific storm predictions are not so well established that planners can yet rely on them.

1.4.3 Shoreline Change and Coastal Erosion

The diverse landforms comprising more than 152,750 km (95,471 mi) of U.S. tidal coastline (<http://shoreline.noaa.gov/faqs.html>) reflect a dynamic interaction between: (1) natural factors and physical processes that act on the coast (*e.g.*, storms, waves, currents, sand sources and sinks, relative sea level), (2) human activity (*e.g.*, dredging, dams, coastal engineering), and (3) the geological character of the coast and nearshore. Variations of these physical processes in both location and time, and the local geology along the coast, result in the majority of the U.S. coastlines undergoing overall long-term erosion at highly varying rates, as shown in Figure 1.8.

The complex interactions between these factors make it difficult to relate sea-level rise and shoreline change and to reach agreement among coastal scientists on approaches to predict how shorelines will change in response to sea-level rise. The difficulty in linking sea-level rise to coastal change stems from the fact that shoreline change is not driven solely by sea-level rise. Instead, coasts are in dynamic flux, responding to many driving forces, such as the underlying geological character, changes in tidal flow, and volume of sediment in the coastal system. For example, FitzGerald *et al.* (2008) discuss the dramatic effects that changes in tidal wetland area can have on entire coastal systems by altering tidal flow, which in turn affects the size and shape of tidal inlets, ebb and flood tide deltas, and barrier islands. Consequently, while there is strong scientific consensus that climate change is accelerating sea-level rise and affecting coastal regions, there are still considerable uncertainties predicting in any detail how the coast will respond to future sea-level rise in concert with other driving processes.

There is some scientific opinion that barrier islands, wetlands, and other parts of coastal systems might have tipping points or thresholds, such that when limits are exceeded the landforms become unstable and undergo large irreversible changes (NRC, 2002; Riggs and Ames, 2003; Nicholls *et al.*,

2007). These changes are thought to occur rapidly and are thus far unpredictable. It is possible that this is happening to barrier islands along the Louisiana coast that are subject to high rates of sea-level rise, frequent major storms over the past decade, and limited sediment supply (Sallenger *et al*., 2007). Further deterioration of the barrier islands and wetlands may also occur in the near future along the North Carolina Outer Banks coast as a result of increased sea-level rise and storm activity (Culver *et al*., 2007, 2008; Riggs and Ames, 2003).

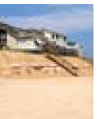
1.4.4 Managing the Coastal Zone as Sea Level Rises

A key issue for coastal zone management is how and where to adapt to the changes that will result from sea-level rise in ways that benefit or minimize impacts to both the natural environment and human populations. Shore protection policies have been developed in response to shoreline retreat problems that affect property or coastal wetland losses. While it is widely recognized that sea-level rise is an underlying cause of these changes, there are few existing policies that explicitly address or incorporate sea-level rise into decision making. Many property owners and government programs engage in coastal engineering activities designed to protect property and beaches such as beach nourishment or seawall or breakwater construction. Some of the current practices affect the natural behavior of coastal landforms and disrupt coastal ecosystems. In the short term, an acceleration of sea-level rise may simply increase the cost of current shore protection practices. In the long term, policy makers might evaluate whether current approaches and justifications for coastal development and protection need to be modified to reflect the increasing vulnerability to accelerating rates of sea-level rise.

To facilitate these decisions, policy makers require credible scientific data and information. Predicting sea-level rise impacts such as shoreline changes or wetland losses with quantitative precision and certainty is often not possible. Related effects of climate change, including increased storms, precipitation, runoff, drought, and sediment supply add to the difficulty of providing accurate reliable information. Predicting future effects is challenging because the ability to accurately map and quantify the physical response of the coast to sea-level rise, in combination with the wide variety of other processes and human engineering activities along the shoreline, has not yet been well developed.

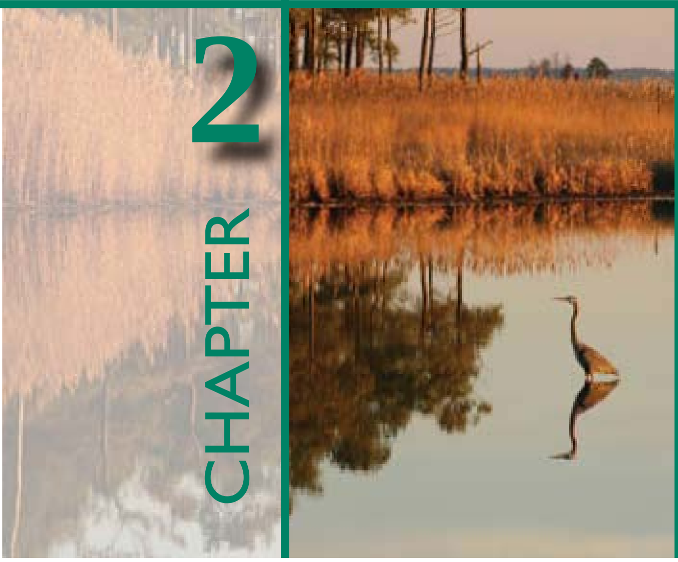
In the United States, coastal regions are generally managed under the premise that sea level is stable, shorelines are static, and storms are regular and predictable. This Product examines how sea-level rise and changes in storm intensity and frequency due to climate change call for new considerations in managing areas to protect resources and reduce risk. This SAP 4.1 also examines possible strategies for coastal planning and management that will be effective as sea-level rise accelerates. For instance, broader recognition is needed that coastal sediments are a valuable resource,

best conserved by implementing Best Coastal Sediment Management practices (see <http://www.wes.army.mil/rsm/>) on local, regional, and national levels in order to conserve sediment resources and maintain natural sediment transport processes.



This Product assesses the current scientific understanding of how sea-level rise can impact the tidal inundation of low-lying lands, ocean shoreline processes, and the vertical accretion of tidal wetlands. It also discusses the challenges that will be present in planning for future sea-level rise and adapting to these impacts. The SAP 4.1 is intended to provide information for coastal decision makers at all levels of government and society so they can better understand this topic and incorporate the effects of accelerating rates of sea-level rise into long-term management and planning.

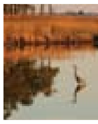
CHAPTER 2



Coastal Elevations

Lead Author: Dean B. Gesch, USGS

Contributing Authors: Benjamin T. Gutierrez, USGS; Stephen K. Gill, NOAA



KEY FINDINGS

- Coastal changes are driven by complex and interrelated processes. Inundation will be the primary response to sea-level rise in some coastal locations; yet there has been little recognition in previous studies that inundation is just one of a number of possible responses to sea-level rise. A challenge remains to quantify the various effects of sea-level rise and to identify the areas and settings along the coast where inundation will be the dominant coastal change process in response to rising seas.

- Sheltered, low-energy coastal areas, where sediment influx is minimal and wetlands are absent or are unable to build vertically in response to rising water levels, may be submerged. In these cases, the extent of inundation is controlled largely by the slope of the land, with a greater degree of inundation occurring in areas with more gentle gradients. In areas that are vulnerable to a simple inundation response to rising seas, elevation is a critical factor in assessing potential impacts.

- Accurate delineations of potential inundation zones are critical for meeting the challenge of fully determining the potential socioeconomic and environmental impacts of predicted sea-level rise.

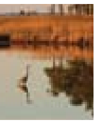
- Coastal elevation data have been widely used to quantify the potential effects of predicted sea-level rise, especially the area of land that could be inundated and the affected population. Because sea-level rise impact assessments often rely on elevation data, it is critical to understand the inherent accuracy of the underlying data and its effects on the uncertainty of any resulting vulnerability maps and statistical summaries.

- The accuracy with which coastal elevations have been mapped directly affects the reliability and usefulness of sea-level rise impact assessments. Although previous studies have raised awareness of the problem of mapping and quantifying sea-level rise impacts, the usefulness and applicability of many results are hindered by the coarse resolution of available input data. In addition, the uncertainty of elevation data is often neglected.

- Existing studies of sea-level rise vulnerability based on currently available elevation data do not provide the degree of confidence that is optimal for local decision making.

- There are important technical considerations that need to be incorporated to improve future sea-level rise impact assessments, especially those with a goal of producing vulnerability maps and statistical summaries that rely on the analysis of elevation data. The primary aspect of these improvements focuses on using high-resolution, high-accuracy elevation data, and consideration and application of elevation uncertainty information in development of vulnerability maps and area statistics.

- Studies that use elevation data as an input for vulnerability maps and/or statistics need to have a clear statement of the absolute vertical accuracy. There are existing national standards for quantifying and reporting elevation data accuracy.



- Currently best available elevation data for the entire mid-Atlantic region do not support an assessment using a sea-level rise increment of 1 meter or less, using national geospatial standards for accuracy assessment and reporting. This is particularly important because the 1-meter scenario is slightly above the range of current sea-level rise estimates for the remainder of this century and slightly above the highest scenario used in this Product.

- High-quality lidar elevation data, such as that which could be obtained from a national lidar data collection program, would be necessary for the entire coastal zone to complete a comprehensive assessment of sea-level rise vulnerability in the mid-Atlantic region. The availability of such elevation data will narrow the uncertainty range of elevation datasets, thus improving the ability to conduct detailed assessments that can be used in local decision making.

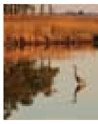
2.1 INTRODUCTION

Sea-level rise is a coastal hazard that can exacerbate the problems posed by waves, storm surges, shoreline erosion, wetland loss, and saltwater intrusion (NRC, 2004). The ability to identify low-lying lands is one of the key elements needed to assess the vulnerability of coastal regions to these impacts. For nearly three decades, a number of large area sea-level rise vulnerability assessments have focused mainly on identifying land located below elevations that would be affected by a given sea-level rise scenario (Schneider and Chen, 1980; U.S. EPA, 1989; Najjar *et al.*, 2000; Titus and Richman, 2001; Ericson *et al.*, 2006; Rowley *et al.*, 2007). These analyses require use of elevation data from topographic maps or digital elevation models (DEMs) to identify low-lying land in coastal regions. Recent reports have stressed that sea-level rise impact assessments need to continue to include maps of these areas subject to inundation based on measurements of coastal elevations (Coastal States Organization, 2007; Seiden, 2008). Accurate mapping of the zones of potential inundation is critical for meeting the challenge of determining the potential socioeconomic and environmental impacts of predicted sea-level rise (FitzGerald *et al*., 2008).

Identification of the socioeconomic impacts of projected sea-level rise on vulnerable lands and populations is an important initial step for the nation in meeting the challenge of reducing the effects of natural disasters in the coastal zone (Subcommittee on Disaster Reduction, 2008). A number of state coastal programs are using sea-level rise inundation models (including linked storm surge/sea-level rise models) to provide a basis for coastal vulnerability and socioeconomic analyses (Coastal States Organization, 2007). State coastal managers are concerned that these research efforts and those of the federal government should be well coordinated, complementary, and not redundant. Despite the common usage of elevation datasets to investigate sea-level rise vulnerability, there are limitations to elevation-based analyses. These limitations are related to the relevance of this approach in a variety of settings and to the data sources and methodologies used to conduct these analyses. Thus, an important objective of this Chapter is to review the available data and techniques, as well as the suitability of elevation-based analyses for informing sea-level rise assessments, to provide guidance for both scientists and coastal managers.

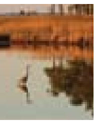
While elevation-based analyses are a critical component of sea-level rise assessments, this approach only addresses a portion of the vulnerability in coastal regions. Coastal changes are driven by complex and interrelated processes such as storms, biological processes, sea-level rise, and sediment transport, which operate over a range of time scales (Carter and Woodroffe, 1994; Brinson *et al.*, 1995; Eisma, 1995; Pilkey and Cooper, 2004; FitzGerald *et al.*, 2008). The response of a coastal region to sea-level rise can be characterized by one or more of the processes in the following broad categories (Leatherman, 2001; Valiela, 2006; FitzGerald *et al.*, 2008):

- land loss by inundation of low-lying lands;
- land loss due to erosion (removal of material from beaches, dunes, and cliffs);
- barrier island migration, breaching, and segmentation;
- wetland accretion and migration;
- wetland drowning (deterioration and conversion to open water);
- expansion of estuaries;
- saltwater intrusion (into freshwater aquifers and surface waters); and
- increased frequency of storm flooding (especially of uplands and developed coastal lands).



Because large portions of the population (both in the United States and worldwide) are located in coastal regions, each of these impacts has consequences for the natural environment as well as human populations. Using elevation datasets to identify and quantify low-lying lands is only one of many aspects that need to be considered in these assessments. Nonetheless, analyses based on using elevation data to identify low-lying lands provide an important foundation for sea-level rise impact studies.

There is a large body of literature on coastal processes and their role in both shoreline and environmental change in coastal regions (Johnson, 1919; Curray, 1964; Komar, 1983; Swift *et al.*, 1985; Leatherman, 1990; Carter and Woodroffe, 1994; Brinson, 1995; Eisma, 1995; Wright, 1995; Komar, 1998; Dean and Dalrymple, 2002; FitzGerald *et al.*, 2008). However, there is generally little discussion of the suitability of using elevation data to identify the vulnerability of coastal regions to sea-level rise. While it is straightforward to reason that low-lying lands occurring below a future sea-level rise scenario are vulnerable, it is often generally assumed that these lands will be inundated. Instead, inundation is likely only one part of the response out of a number of possible sea-level rise impacts. Despite this, some assessments have opted for inundation-based assessments due to the lack of any clear alternatives and the difficulty in accounting for complex processes such as sedimentation (Najjar *et al.*, 2000). It is plausible that extreme rates of sea-level rise (*e.g.*, 1 meter or more in a single year) could result in widespread simple coastal inundation. However, in the more common and likely case of much lower sea-level rise rates, the physical processes are more complex and rising seas do not simply flood the coastal landscape below a given elevation contour (Pilkey and Thieler, 1992). Instead, waves and currents will modify the landscape as sea level rises (Bird, 1995; Wells, 1995). Still, inundation is an important component of coastal change (Leatherman, 2001), especially in very low gradient regions such as North Carolina. However, due to the complexity of the interrelated processes of erosion and sediment redistribution, it is difficult to distinguish and quantify the individual contributions from inundation and erosion (Pilkey and Cooper, 2004).



Inundation will be the primary response to sea-level rise only in some coastal locations. In many other coastal settings, long-term erosion of beaches and cliffs or wetland deterioration will alter the coastal landscape leading to land loss. To distinguish the term inundation from other processes, especially erosion, Leatherman (2001) offered the following important distinction:

- *erosion* involves the physical removal of sedimentary material
- *inundation* involves the permanent submergence of land.

Another term that can confuse the discussion of sea-level rise and submergence is the term *flooding* (Wells, 1995; Najjar *et al*., 2000), which in some cases has been used interchangeably with *inundation*. *Flooding* often connotes temporary, irregular high-water conditions. The term *inundation* is used in this Chapter (but not throughout the entire Product) to refer to the permanent submergence of land by rising seas.

It is unclear whether simply modeling the inundation of the land surface provides a useful approximation of potential land areas at risk from sea-level rise. In many settings, the presence of beaches, barrier islands, or wetlands indicates that sedimentary processes (erosion, transport, or accumulation of material) are active in both the formation of and/or retreat of the coastal landscape. Sheltered, low-energy coastal areas, where sediment influx is minimal and wetlands are absent or are unable to build vertically in response to rising water levels, may be submerged. In these cases, the extent of inundation is controlled by the slope of the land, with a greater degree of inundation occurring in the areas with more gentle gradients (Leatherman, 2001). In addition, inundation is a likely response in heavily developed regions with hardened shores. The construction of extensive seawalls, bulkheads, and revetments to armor the shores of developed coasts and waterways have formed nearly immovable shorelines that may become submerged. However, the challenge remains to quantify the various effects of sea-level rise and to identify the areas and settings along the coast where inundation will be the dominant coastal change process from sea-level rise.

Despite several decades of research, previous studies do not provide the full answers about sea-level rise impacts for the mid-Atlantic region with the degree of confidence that is optimal for local decision making. Although these studies have illuminated the challenges of mapping and quantifying sea-level rise impacts, the usefulness and applicability of many results are hindered by the quality of the available input data. In addition, many of these studies have not adequately reported the uncertainty in the underlying elevation data and how that uncertainty affects the derived vulnerability maps and statistics. The accuracy with which coastal elevations have been mapped directly affects the reliability and usefulness of sea-level rise impact assessments. Elevation datasets often incorporate a range of data sources, and some studies have had to rely on elevation datasets that are poorly suited for detailed inundation mapping in coastal regions, many of which are gently sloping landscapes (Ericson *et al*., 2006; Rowley *et al*., 2007; McGranahan *et al*., 2007). In addition to the limited spatial detail, these datasets have elevation values quantized only to whole meter intervals, and their overall vertical accuracy is poor when compared to the intervals of predicted sea-level rise over the next century. These limitations can undermine attempts to achieve high-quality assessments of land areas below a given sea-level rise scenario and, consequently, all subsequent analyses that rely on this foundation.

Due to numerous studies that used elevation data, but have lacked general recognition of data and methodology constraints, this Chapter provides a review of data sources and methodologies that have been used to conduct sea-level rise vulnerability assessments. New high-resolution, high-accuracy elevation data, especially lidar (light detection and ranging) data, are becoming more readily available and are being integrated into national datasets (Gesch, 2007) as well as being used in sea-level rise applications (Coastal States Organization, 2007). Research is also progressing on how to take advantage of the increased spatial resolution and vertical accuracy of the new data (Poulter and Halpin, 2007; Gesch, 2009). Still, there is a critical need to thoroughly evaluate the elevation data, determine how to appropriately utilize the data to deliver well-founded results, and accurately communicate the associated uncertainty.

The widespread use of vulnerability assessments, and the attention they receive, is likely an indication of the broad public interest in sea-level rise issues. Because of this extensive exposure, it is important for the coastal science community to be fully engaged in the technical development of elevation-based analyses. Many recent reports have been motivated and pursued from an economic or public policy context rather than a geosciences perspective. It is important for scientists to communicate and collaborate with coastal managers to actively identify and explain the applications and limitations of sea-level rise impact assessments. Arguably, sea-level rise is one of the most visible and understandable consequences of climate change for the general public, and the coastal science community needs to ensure that appropriate methodologies are developed to meet the needs for reliable information. This Chapter reviews the various data sources that are available to support inundation vulnerability assessments. In addition, it outlines what is needed to conduct and appropriately report results from elevation-based sea-level rise vulnerability analyses and discusses the context in which these analyses need to be applied.

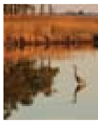
2.2 ELEVATION DATA

Measurement and representation of coastal topography in the form of elevation data provide critical information for research on sea-level rise impacts. Elevation data in its various forms have been used extensively for sea-level rise studies. This section reviews elevation data sources in order to provide a technical basis for understanding the limitations of past sea-level rise impact analyses that have relied on elevation data. While use of coastal elevation data is relatively straightforward, there are technical aspects that are important considerations for conducting valid quantitative analyses.

2.2.1 Topographic Maps, Digital Elevation Models, and Accuracy Standards

Topographic maps with elevation contours are perhaps the most recognized form of elevation information. The U.S. Geological Survey (USGS) has been a primary source of topographic maps for well over a century. The base topographic map series for the United States (except Alaska) is published at a scale of 1:24,000, and the elevation information on the maps is available in digital form as digital elevation models. The USGS began production of DEMs matching the 1:24,000-scale quadrangle maps in the mid-1970s using a variety of image-based (photogrammetric) and cartographic techniques (Osborn *et al*., 2001). Coverage of the conterminous United States with 30-meter (m) (98-foot [ft]) horizontal resolution DEMs was completed in 1999, with most of the individual elevation models being derived from the elevation contours and spot heights on the corresponding topographic maps. Most of these maps have a 5-ft, 10-ft, 20-ft, or 40-ft contour interval, with 5 ft being the contour interval used in many low relief areas along the coast. About the time 30-m DEM coverage was completed, the USGS began development of a new seamless raster (gridded) elevation database known as the National Elevation Dataset (NED) (Gesch *et al*., 2002). As the primary elevation data product produced and distributed by the USGS, the NED includes many USGS DEMs as well as other sources of elevation data. The diverse source datasets are processed to a specification with a consistent resolution, coordinate system, elevation units, and horizontal and vertical datums to provide the user with an elevation product that represents the best publicly available data (Gesch, 2007). DEMs are also produced and distributed in various formats by many other organizations, and they are used extensively for mapping, engineering, and earth science applications (Maune, 2007; Maune *et al*., 2007a).

Because sea-level rise impact assessments often rely on elevation data, it is important to understand the inherent accuracy of the underlying data and its effects on the uncertainty of any resulting maps and statistical summaries from the assessments. For proper quantitative use of elevation data, it is important to identify and understand the vertical accuracy of the data. Vertical accuracy is an expression of the overall quality of the elevations contained in the dataset in comparison to the true ground elevations at corresponding locations. Accuracy standards and guidelines exist in general for geospatial data and specifically for elevation data. For topographic maps, the National Map Accuracy Standards (NMAS) issued in 1947 are the most commonly used; they state that "vertical accuracy, as applied to contour maps on all publication scales, shall be such that not more than 10 percent of the elevations tested shall be in error by more than one-half the contour interval" (USGS, 1999). An alternative way to state the NMAS vertical accuracy standard is that an elevation obtained from the topographic map will be accurate to within one-half of the contour interval 90 percent of the time. This has also been referred to as "linear error at 90 percent confidence" (LE90) (Greenwalt and Shultz, 1962). For example, on a topographic map with a 10-ft contour interval that meets NMAS, 90 percent of the elevations will be accurate to within 5 ft, or stated alternatively, any elevation taken from the map will be within 5 ft of the actual elevation with a 90-percent confidence level. Even though the NMAS was developed for printed topographic maps and it predates the existence of DEMs, it is important to understand its application because many DEMs are derived from topographic maps.



As the production and use of digital geospatial data became commonplace in the 1990s, the Federal Geographic Data Committee (FGDC) developed and published geospatial positioning accuracy standards in support of the National Spatial Data Infrastructure (Maune *et al*., 2007b). The FGDC standard for testing and reporting the vertical accuracy of elevation data, termed the National Standard for Spatial Data Accuracy (NSSDA), states that the "reporting standard in the vertical component is a linear uncertainty value, such that the true or theoretical location of the point falls within +/- of that linear uncertainty value 95 percent of the time" (Federal Geographic Data Committee, 1998). In practice, the vertical accuracy of DEMs is often reported as the root mean square error (RMSE). The NSSDA provides the method for translating a reported RMSE to a linear error at the 95-percent confidence level. Maune *et al.* (2007b) provide a useful comparison of NMAS and NSSDA vertical

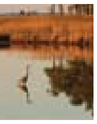


Table 2.1 Comparison of National Map Accuracy Standards (NMAS) and National Standard for Spatial Data Accuracy (NSSDA) Vertical Accuracy Values with the Equivalent Common Contour Intervals (Maune *et al.*, 2007b).

NMAS Equivalent contour interval	NMAS 90-percent confidence level (LE90)	NSSDA RMSE	NSSDA 95-percent confidence level
1 ft	0.5 ft	0.30 ft (9.25 cm)	0.60 ft (18.2 cm)
2 ft	1 ft	0.61 ft (18.5 cm)	1.19 ft (36.3 cm)
5 ft	2.5 ft	1.52 ft (46.3 cm)	2.98 ft (90.8 cm)
10 ft	5 ft	3.04 ft (92.7 cm)	5.96 ft (1.816 m)
20 ft	10 ft	6.08 ft (1.853 m)	11.92 ft (3.632 m)
cm = centimeters; m = meters; ft = feet			

accuracy measures for common contour intervals (Table 2.1) and methods to convert between the reporting standards. The NSSDA, and in some cases even the older NMAS, provides a useful approach for testing and reporting the important vertical accuracy information for elevation data used in sea-level rise assessments.

2.2.2 Lidar Elevation Data

Currently, the highest resolution elevation datasets are those derived from lidar surveys. Collected and post-processed under industry-standard best practices, lidar elevation data routinely achieve vertical accuracies on the order of 15 centimeters (cm) (RMSE). Such accuracies are well suited for analyses of impacts of sea-level rise in sub-meter increments (Leatherman, 2001). Using the conversion methods between accuracy standards documented by Maune *et al.* (2007b), it can be shown that lidar elevation data with an accuracy of equal to or better than 18.5 cm (RMSE) is equivalent to a 2-ft contour interval map meeting NMAS.

Lidar is a relatively recent remote sensing technology that has advanced significantly over the last 10 years to the point where it is now a standard survey tool used by government agencies and the mapping industry to collect very detailed, high-accuracy elevation measurements, both on land and in shallow water coastal areas. The discussion of lidar in this Chapter is limited to topographic lidar used to map land areas. Lidar measurements are acquired using laser technology to precisely measure distances, most often from an aircraft, that are then converted to elevation data and integrated with Global Positioning System (GPS) information (Fowler *et al.*, 2007). Because of their high vertical accuracy and spatial resolution, elevation data derived from lidar surveys are especially useful for applications in low relief coastal environments. The technical advantages of lidar in dynamic coastal settings, including the ability to perform repeat high-precision surveys, have facilitated successful use of the data in studies of coastal changes due to storm impacts (Brock *et al.*, 2002; Sallenger *et al.*, 2003; Stockdon *et al.*, 2007). Numerous organizations, including many state programs, have recognized the advantages of lidar for use in mapping the coastal zone. As an example, the Atlantic states of Maine, Connecticut, New Jersey, Delaware, Maryland, North Carolina, and Florida have invested in lidar surveys for use in their coastal programs (Coastal States Organization, 2007; Rubinoff, *et al.*, 2008).

2.2.3 Tides, Sea Level, and Reference Datums

Sea-level rise assessments typically focus on understanding potential changes in sea level, but elevation datasets are often referenced to a "vertical datum", or reference point, that may differ from sea level at any specific location. In any work dealing with coastal elevations, water depths, or water levels, the reference to which measurements are made must be carefully addressed and thoroughly documented. All elevations, water depths, and sea-level data are referenced to a defined vertical datum, but different datums are used depending on the data types and the original purpose of the measurements. A detailed treatment of the theory behind the development of vertical reference systems is beyond the scope of this Product. However, a basic understanding of vertical datums is necessary for fully appreciating the important issues in using coastal elevation data to assess sea-level rise vulnerability. Zilkoski (2007), Maune *et al.* (2007a), and NOAA (2001) provide detailed explanations of vertical datums and tides, and the brief introduction here is based largely on those sources.

Land elevations are most often referenced to an orthometric (sea-level referenced) datum, which is based on a network of surveyed (or "leveled") vertical control benchmarks. These benchmarks are related to local mean sea level at specific tide stations along the coast. The elevations on many topographic maps, and thus DEMs derived from those maps, are referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29), which uses mean sea level at 26 tide gauge sites (21 in the United States and 5 in Canada). Advances in surveying techniques and the advent of computers for performing complex calculations allowed the development of a new vertical datum, the North American Vertical Datum of 1988 (NAVD 88). Development of NAVD 88 provided an improved datum that allowed for the correction of errors that had been introduced into the national vertical control network because of crustal motion and ground subsidence. In contrast to NGVD 29, NAVD 88 is tied to mean sea level at only one tide station, located at Father Point/Rimouski, Quebec, Canada. Orthometric datums such as NGVD 29 and NAVD 88 are referenced to tide gauges, so they are sometimes informally referred to as "sea level" datums because they are inherently tied to some form of mean sea level. NAVD 88 is the official vertical datum of the United States, as stated in the Federal Register in 1993, and as such, it should serve as the reference for all products using land elevation data.

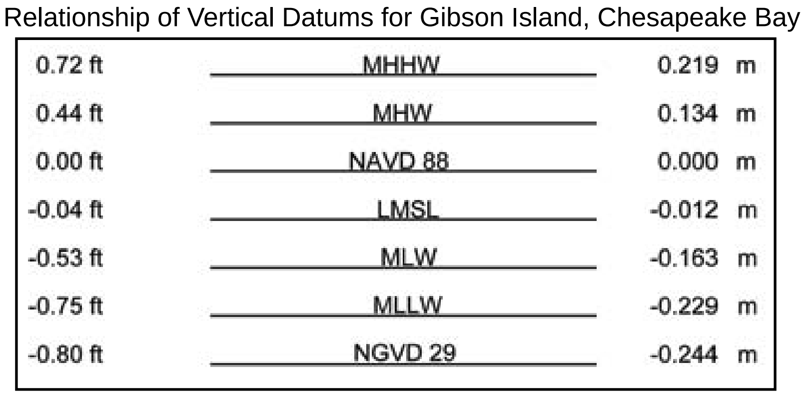
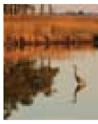


Figure 2.1 Diagram of the VDatum-derived relationship among vertical datums for a point on the shore at Gibson Island, Chesapeake Bay (shown in feet [ft] and meters [m]). The point is located between the tide stations at Baltimore and Annapolis, Maryland, where datum relationships are based on observations. The numbers represent the vertical difference above or below NAVD 88. For instance, at this location in the Chesapeake Bay the estimated MLLW reference is more than 20 centimeters (cm) below the NAVD 88 zero reference, whereas local mean sea level is only about 1 cm below NAVD zero.



Water depths (bathymetry data) are usually referenced vertically to a tidal datum, which is defined by a specific phase of the tides. Unlike orthometric datums such as NGVD 29 and NAVD 88, which have national or international coverage, tidally referenced datums are local datums because they are relative to nearby tide stations. Determination of tidal datums in the United States is based on observations of water levels over a 19-year period, or tidal epoch. The current official tidal epoch in use is the 1983-2001 National Tidal Datum Epoch (NTDE). Averaging over this period is necessary to remove random and periodic variations caused by seasonal differences and the nearly 19-year cycle of the lunar orbit. NTDEs are updated approximately every 25 years to account for relative sea-level change (NOAA, 2001). The following are the most commonly used tidal datums:

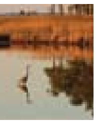
- Mean higher high water (MHHW): the average of the higher high water levels observed over a 19-year tidal epoch (only the higher water level of the pair of high waters in a tidal day is used);
- Mean high water (MHW): the average of the high water levels observed over a 19-year tidal epoch;
- Local mean sea level (LMSL): the average of hourly water levels observed over a 19-year tidal epoch;
- Mean low water (MLW): the average of the low water levels observed over a 19-year tidal epoch; and
- Mean lower low water (MLLW): the average of the lower low water levels observed over a 19-year tidal epoch (only the lower water level of the pair of low waters in a tidal day is used). MLLW is the reference chart datum used for NOAA nautical chart products.

As an illustration, Figure 2.1 depicts the relationship among vertical datums for a point located on the shore at Gibson Island, Chesapeake Bay. These elevations were calculated with use of the "VDatum" vertical datum transformation tool (Parker *et al.*, 2003; Myers, 2005), described in the following section. Sea-level rise trends at specific tide stations are generally calculated based on observed monthly mean sea level values to filter out the high frequency fluctuations in tide levels.

Based on surveys at tide stations, NAVD 88 ranges from 15 cm below to 15 cm above LMSL in the mid-Atlantic region. Due to slopes in the local sea surface from changes in tidal hydrodynamics, LMSL generally increases in elevation relative to NAVD 88 for locations increasingly farther up estuaries and tidal rivers. For smaller scale topographic maps and coarser resolution DEMs, the two datums are often reported as being equivalent, when in reality they are not. The differences should be reported as part of the uncertainty analyses. Differences between NAVD 88 and LMSL on the U.S. West Coast often exceed 100 cm and must be taken into account in any inundation mapping application. Similarly, but more importantly, many coastal projects still inappropriately use NGVD 29 as a proxy for local mean sea level in planning, designing, and reference mapping. In the Mid-Atlantic, due to relative sea level change since 1929, the elevation of NGVD 29 ranges from 15 cm to more than 50 cm below the elevation of LMSL (1983-2001 NTDE). This elevation difference must be taken into account in any type of inundation mapping. Again, because LMSL is a sloped surface relative to orthometric datums due to the complexity of tides in estuaries and inland waterways, the elevation separation between LMSL and NGVD 29 increases for locations farther up estuaries and tidal rivers.

2.2.4 Topographic/Bathymetric/Water Level Data Integration

High-resolution datasets that effectively depict elevations across the land-sea boundary from land into shallow water are useful for many coastal applications (NRC, 2004), although they are not readily available for many areas. Sea-level rise studies can benefit from the use of integrated



topographic/bathymetric models because the dynamic land/water interface area, including the intertidal zone, is properly treated as one seamless entity. In addition, other coastal research topics rely on elevation data that represent near-shore topography and bathymetry (water depths), but because existing topographic, bathymetric, and water level data have been collected independently for different purposes, they are difficult to use together. The USGS and the National Oceanic and Atmospheric Administration (NOAA) have worked collaboratively to address the difficulties in using disparate elevation and depth information, initially in the Tampa Bay region in Florida (Gesch and Wilson, 2002). The key to successful integration of topographic, bathymetric, and water level data is to place them in a consistent vertical reference frame, which is generally not the case with terrestrial and marine data. A vertical datum transformation tool called VDatum developed by NOAA's National Ocean Service provides the capability to convert topographic, bathymetric and water level data to a common vertical datum (Parker *et al*., 2003; Myers, 2005). Work was completed in mid-2008 on providing VDatum coverage for the mid-Atlantic region. VDatum uses tidal datum surfaces, derived from hydrodynamic models corrected to match observations at tide stations, to interpolate the elevation differences between LMSL and NAVD 88. An integrated uncertainty analysis for VDatum is currently underway by NOAA.

The National Research Council (NRC, 2004) has recognized the advantages of seamless data across the land/water interface and has recommended a national implementation of VDatum and establishment of protocols for merged topographic/bathymetric datasets (NOAA, 2008). Work has continued on production of other such merged datasets for coastal locations, including North Carolina and the Florida panhandle (Feyen *et al*., 2005, 2008). Integrated topographic/bathymetric lidar (Nayegandhi *et al*., 2006; Guenther, 2007) has been identified as a valuable technology for filling critical data gaps at the land/water interface, which would facilitate development of more high quality datasets (NRC, 2004).

2.3 VULNERABILITY MAPS AND ASSESSMENTS

Maps that depict coastal areas at risk of potential inundation or other adverse effects of sea-level rise are appealing to planners and land managers that are charged with communicating, adapting to, and reducing the risks (Coastal States Organization, 2007). Likewise, map-based analyses of sea-level rise vulnerability often include statistical summaries of population, infrastructure, and economic activity in the mapped impact zone, as this information is critical for risk management and mitigation efforts. Many studies have relied on elevation data to delineate potential impact zones and quantify effects. During the last 15 years, this approach has also been facilitated by the increasing availability of spatially extensive elevation, demographic, land use/land cover, and economic data and advanced geographic information system (GIS) tools. These tools have improved access to data and have provided the analytical software capability for producing map-based analyses and statistical summaries. The body of peer reviewed scientific literature cited in this Chapter includes numerous studies that have focused on mapping and quantifying potential sea-level rise impacts.

A number of terms are used in the literature to describe the adverse effects of sea-level rise, including *inundation*, *flooding*, *submergence*, and *land loss*. Likewise, multiple terms are used to refer to what this Chapter has called vulnerability, including *at risk*, *subject to*, *impacted by*, and *affected by*. Many reports do not distinguish among the range of responses to sea-level rise, as described in Section 2.1. Instead, simple inundation, as a function of increased water levels projected onto the land surface, is assumed to reflect the vulnerability.

Monmonier (2008) has recognized the dual nature of sea-level rise vulnerability maps as both tools for planning and as cartographic instruments to illustrate the potential catastrophic impacts of climate change. Monmonier cites reports that depict inundation areas due to very large increases in global sea level. Frequently, however, the sea-level rise map depictions have no time scales and no indication of uncertainty or data limitations. Presumably, these broad-scale maps are in the illustration category, and only site-specific, local scale products are true planning tools, but therein is the difficulty. With many studies it is not clear if the maps (and associated statistical summaries) are intended simply to raise awareness of potential broad impacts or if they are intended to be used in decision making for specific locations.

2.3.1 Large-Area Studies (Global and United States)

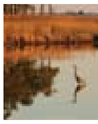
Sea-level rise as a consequence of climate change is a global concern, and this is reflected in the variety of studies conducted for locations around the world as well as within the United States. Table 2.2 summarizes the characteristics of a number of the sea-level rise assessments conducted over broad areas, with some of the studies discussed in more detail below.

Schneider and Chen (1980) presented one of the early reports on potential sea-level rise impacts along U.S. coastlines. They used the 15-ft and 25-ft contours from USGS 1:24,000-scale maps to "derive approximate areas flooded within individual counties" along the coast. As with many of the vulnerability studies, Schneider and Chen also combined their estimates of submerged areas with population and

Table 2.2 Characteristics of Some Sea-Level Rise Assessments Conducted over Broad Areas. GTOPO30 is a global raster DEM with a horizontal grid spacing of 30 arc seconds (approximately 1 kilometer). SRTM is the Shuttle Radar Topography Mission data. NED is the National Elevation Dataset.

Study*	Study Area	Elevation Data*	Sea-Level Rise Scenario*	Elevation Accuracy Reported?	Maps Published?
Schneider and Chen (1980)	Conterminous United States	15- and 25-ft contours from USGS 1:24,000-scale maps	4.6 and 7.6 m	No	Yes
U.S. EPA (1989)	Conterminous United States	Contours from USGS maps	0.5, 1, and 2 m	No	No
Titus *et al.* (1991)	Conterminous United States	Contours from USGS maps, wetland delineations, and tide data	0.5, 1, and 2 m	No	No
FEMA (1991)	United States	Coastal floodplain maps	1 ft and 3 ft	No	No
Small and Nicholls (2003)	Global	GTOPO30	5-m land elevation increments	Estimated a 5-m uncertainty for elevation data (no error metric specified)	No
Ericson *et al.* (2006)	40 deltas distributed worldwide	GTOPO30	0.5-12.5 mm per year for years 2000-2050	No	No
Rowley *et al.* (2007)	Global	GLOBE (GTOPO30)	1, 2, 3, 4, 5, and 6 m	No	Yes
McGranahan *et al.* (2007)	Global	SRTM	Land elevations 0 to 10 m (to define the "low elevation coastal zone")	No, although 10-m elevation increment was used in recognition of data limitations	Yes
Demirkesen *et al.* (2007)	Izmir, Turkey	SRTM	2 and 5 m	Yes, but no error metric specified	Yes
Demirkesen *et al.* (2008)	Turkey	SRTM	1, 2, and 3 m	Yes, but no error metric specified	Yes
Marfai and King (2008)	Semarang, Indonesia	Local survey data	1.2 and 1.8 m	No	Yes
Kafalenos *et al.* (2008)	U.S. Gulf coast	NED	2 and 4 ft	No	Yes

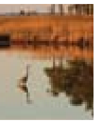
* Abbreviations used: U.S. EPA = United States Environmental Protection Agency; FEMA = United States Federal Emergency Management Agency; USGS = United States Geological Survey; m = meters; mm = millimeters; ft = feet



property value data to estimate socioeconomic impacts, in this case on a state-by-state basis.

Reports to Congress by the U.S. Environmental Protection Agency (U.S. EPA) and the Federal Emergency Management Agency (FEMA) contributed to the collection of broad area assessments for the United States. The U.S. EPA report (U.S. EPA, 1989; Titus *et al.*, 1991) examined several different global sea-level rise scenarios in the range of 0.5 to 2 m (1.6 to 6.6 ft), and also discussed impacts on wetlands under varying shoreline protection scenarios. For elevation information, the study used contours from USGS topographic maps supplemented with wetland delineations from Landsat satellite imagery and tide gauge data. The study found that the available data were inadequate for production of detailed maps. The FEMA (1991) report estimated the increase of land in the 100-year floodplain from sea-level rises of 1 ft (0.3 m) and 3 ft (0.9 m). FEMA also estimated the increase in annual flood damages to insured properties by the year 2100, given the assumption that the trends of development would continue.

Elevation datasets with global or near-global extent have been used for vulnerability studies across broad areas. For their studies of the global population at risk from coastal hazards, Small and Nicholls (2003) and Ericson *et al.* (2006) used GTOPO30, a global 30-arc-second (about 1-kilometer [km]) elevation dataset produced by the USGS (Gesch *et al.*, 1999). Rowley *et al.* (2007) used the GLOBE 30-arc-second DEM (Hastings and Dunbar, 1998), which is derived mostly from GTOPO30. As with many vulnerability studies, these investigations used the delineations of low-lying lands from the elevation model to quantify the population at risk from sea-level rise, in one instance using increments as small as 1 m (Rowley *et al*., 2007).



Elevation data from the Shuttle Radar Topography Mission (SRTM) (Farr *et al*., 2007) are available at a 3-arc-second (about 90-m) resolution with near-global coverage. Because of their broad area coverage and improved resolution over GTOPO30, SRTM data have been used in several studies of the land area and population potentially at risk from sea-level rise (McGranahan *et al*., 2007; Demirkesen *et al*., 2007, 2008). Similar to other studies, McGranahan *et al.* (2007) present estimates of the population at risk, while Demirkesen *et al.* (2007) document the dominant land use/land cover classes in the delineated vulnerable areas.

2.3.2 Mid-Atlantic Region, States, and Localities

A number of sea-level rise vulnerability studies have been published for sites in the mid-Atlantic region, the focus area for this Product. Table 2.3 summarizes the characteristics for these reports, and important information from some of the studies is highlighted.

A study by Titus and Richman (2001) is often referred to in discussions of the land in the United States that is subject to the effects of sea-level rise. The methods used to produce the maps in that report are clearly documented. However, because they used very coarse elevation data (derived from USGS 1:250,000-scale topographic maps), the resulting products are general and limited in their applicability. The authors acknowledge the limitations of their results because of the source data they used, and clearly list the caveats for proper use of the maps. As such, these maps are useful in depicting broad implications of sea-level rise, but are not appropriate for site-specific decision making.

Numerous studies have used the NED, or the underlying USGS DEMs from which much of the NED is derived, as the input elevation information. Najjar *et al.* (2000) show an example of using USGS 30-m DEMs for a simple inundation model of Delaware for a 2-ft (0.6-m) sea-level rise. In another study, Kleinosky *et al.* (2007) used elevation information from USGS 10-m and 30-m DEMs to depict vulnerability of the Hampton Roads, Virginia area to storm surge flooding in addition to sea-level rise. Storm surge heights were first determined by modeling, then 30-, 60-, and 90-cm increments of sea-level rise were added to project the expansion of flood risk zones onto the land surface. In addition, Wu *et al.* (2002) conducted a study for Cape May County, New Jersey using an approach similar to Kleinosky *et al.* (2007), where they added 60 cm to modeled storm surge heights to account for sea-level rise.

More recently, Titus and Wang (2008) conducted a study of the mid-Atlantic states (New York to North Carolina) using a variety of elevation data sources including USGS 1:24,000-scale topographic maps (mostly with 5- or 10-ft

Table 2.3 Characteristics of Some Sea-Level Rise Vulnerability Studies Conducted over Mid-Atlantic Locations. GTOPO30 is a global raster DEM with a horizontal grid spacing of 30 arc seconds (approximately 1 kilometer). SRTM is the Shuttle Radar Topography Mission data. NED is the National Elevation Dataset.

Study	Study Area	Elevation Data	Sea-Level Rise Scenario	Elevation Accuracy Reported?	Maps Published?
Titus and Richman (2001)	U.S. Atlantic and Gulf coasts	USGS DEMs derived from 1:250,000-scale maps	1.5- and 3.5-m land elevation increments	No	Yes
Najjar *et al.* (2000)	Delaware	30-m USGS DEMs	2 ft	No	Yes
Kleinosky *et al.* (2007)	Hampton Roads, Virginia	10-m and 30-m USGS DEMs	30, 60, and 90 cm	No	Yes
Wu *et al.* (2002)	Cape May County, New Jersey	30-m USGS DEMs	60 cm	No	Yes
Gornitz *et al.* (2002)	New York City area	30-m USGS DEMs	5-ft land elevation increments	No, although only qualitative results were reported	Yes
Titus and Wang (2008)	Mid-Atlantic states	Contours from USGS 1:24,000-scale maps, lidar, local data	0.5-m land elevation increments	Yes, RMSE *vs.* lidar for a portion of the study area	Yes
Larsen *et al.* (2004)	Blackwater National Wildlife Refuge, Maryland	lidar	30-cm land elevation increments	No	Yes
Gesch (2009)	North Carolina	GTOPO30, SRTM, NED, lidar	1 m	Yes, with NSSDA error metric (95% confidence)	Yes
cm = centimeters; m = meters; ft = feet					

contour intervals), lidar data, and some local data provided by state agencies, counties, and municipalities. They used an approach similar to that described in Titus and Richman (2001) in which tidal wetland delineations are employed in an effort to estimate additional elevation information below the first topographic map contour.

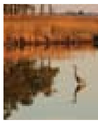
2.3.3 Other Reports

In addition to reports by federal government agencies and studies published in the peer-reviewed scientific literature, there have been numerous assessment reports issued by various non-governmental organizations, universities, state and local agencies, and other private groups (*e.g.*, Anthoff *et al*., 2006; Dasgupta *et al*., 2007; Stanton and Ackerman, 2007; US DOT, 2008; Mazria and Kershner, 2007; Glick *et al*., 2008; Cooper *et al*., 2005; Lathrop and Love, 2007; Johnson *et al*., 2006; Bin *et al*., 2007; Slovinsky and Dickson, 2006). While it may be difficult to judge the technical veracity of the results in these reports, they do share common characteristics with the studies reviewed in Sections 2.3.1 and 2.3.2. Namely, they make use of the same elevation datasets (GTOPO30, SRTM, NED, and lidar) to project inundation from sea-level rise onto the land surface to quantify vulnerable areas, and they present statistical summaries of impacted population and other socioeconomic variables. Many of these reports include detailed maps and graphics of areas at risk. Although some are also available in printed formats, all of the reports listed above are available online (see Chapter 2 References for website information).

This category of reports is highlighted because some of the reports have gained wide public exposure through press releases and subsequent coverage in the popular press and on Internet news sites. For example, the report by Stanton and Ackerman (2007) has been cited at least eight times by the mainstream media (see: <http://ase.tufts.edu/gdae/Pubs/rp/FloridaClimate.html>). The existence of this type of report, and the attention it has received, is likely an indication of the broad public interest in sea-level rise issues. These reports are often written from an economic or public policy context rather than from a geosciences perspective. Nevertheless, it is important for the coastal science community to be cognizant of them because the reports often cite journal papers and they serve as a conduit for communicating recent sea-level rise research results to less technical audiences. It is interesting to note that all of the reports listed here were produced over the last three years; thus, it is likely that that this type of outlet will continue to be used to discuss sea-level rise issues as global climate change continues to garner more public attention. Arguably, sea-level rise is among the most visible and understandable consequences of climate change for the general public, and they will continue to seek information about it from the popular press, Internet sites, and reports such as those described here.

2.3.4 Limitations of Previous Studies

It is clear from the literature reviewed in Sections 2.3.1, 2.3.2, and 2.3.3 that the development of sea-level rise impact assessments has been an active research topic for the past 25 years. However, there is still significant progress to be made in improving the physical science-based information needed for decision making by planners and land and resource managers in the coastal zone. Although previous studies have brought ample attention to the problem of mapping and quantifying sea-level rise impacts, the quality of the available input data and the common tendency to overlook the consequences of coarse data resolution and large uncertainty ranges hinder the usefulness and applicability of many results. Specifically, for this Product, none of the previous studies covering the mid-Atlantic region can be used to fully answer with high confidence the Synthesis and Assessment Product (SAP) 4.1 prospectus question (CCSP, 2006) that relates directly to coastal elevations: "Which lands are currently at an elevation that could lead them to be inundated by the tides without shore protection measures?" The collective limitations of previous studies are described in this Section, while the "lessons learned", or recommendations for required qualities of future vulnerability assessments, are discussed in Section 2.4.

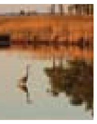


Overall, there has been little recognition in previous studies that inundation is only one response out of a number of possible responses to sea-level rise (see Section 2.1). Some studies do mention the various types of coastal impacts (erosion, saltwater intrusion, more extreme storm surge flooding) (Najjar *et al*., 2000; Gornitz *et al*., 2002), and some studies that focus on wetland impacts do consider more than just inundation (U.S. EPA, 1989; Larsen *et al*., 2004). However, in general, many vulnerability maps (and corresponding statistical summaries) imply that a simple inundation scenario is an adequate representation of the impacts of rising seas (Schneider and Chen, 1980; Rowley *et al*., 2007; Demirkesen *et al*., 2008; Najjar *et al*., 2000).

Based on the review of the studies cited in Sections 2.3.1, 2.3.2, and 2.3.3, these general limitations have been identified:

1. *Use of lower resolution elevation data with poor vertical accuracy.* Some studies have had to rely on elevation datasets that are poorly suited for detailed inundation mapping (*e.g.*, GTOPO30 and SRTM). While these global datasets may be useful for general depictions of low elevation zones, their relatively coarse spatial detail precludes their use for production of detailed vulnerability maps. In addition to the limited spatial detail, these datasets have elevation values quantized only to whole meter intervals, and their overall vertical accuracy is poor when compared to the intervals

of predicted sea-level rise over the next century. The need for better elevation information in sea-level rise assessments has been broadly recognized (Leatherman, 2001; Marbaix and Nicholls, 2007; Jacob *et al*., 2007), especially for large-scale planning maps (Monmonier, 2008) and detailed quantitative assessments (Gornitz *et al*., 2002).



2. *Lack of consideration of uncertainty of input elevation data*. A few studies generally discuss the limitations of the elevation data used in terms of accuracy (Small and Nicholls, 2003; McGranahan *et al*., 2007; Titus and Wang, 2008). However, none of these studies exhibit rigorous accuracy testing and reporting according to accepted national standards (NSSDA and NMAS). Every elevation dataset has some vertical error, which can be tested and measured, and described by accuracy statements. The overall vertical error is a measure of the uncertainty of the elevation information, and that uncertainty is propagated to any derived maps and statistical summaries. Gesch (2009) demonstrates why it is important to account for vertical uncertainty in sea-level rise vulnerability maps and area statistics derived from elevation data (see Box 2.1).

3. *Elevation intervals or sea-level rise increments not supported by vertical accuracy of input elevation data*. Most elevation datasets, with the exception of lidar, have vertical accuracies of several meters or even tens of meters (at the 95 percent confidence level). Figure 2.2 shows a graphical representation of DEM vertical accuracy using error bars around a specified elevation. In this case, a lidar-derived DEM locates the 1-meter elevation to within ±0.3 m at 95-percent confidence. (In other words, the true elevation at that location falls within a range of 0.7 to 1.3 m.) A less accurate topographic map-derived DEM locates the 1-m elevation to within ±2.2 m at 95-percent confidence, which means the true land elevation at that location falls within a range of 0 (assuming sea level was delineated accurately on the original topographic map) to 3.2 m. Many of the studies reviewed in this Chapter use land elevation intervals or sea-level rise increments that are 1 m or less. Mapping of sub-meter increments of sea-level rise is highly questionable if the elevation data used have a vertical accuracy of a meter or more (at the 95-percent confidence level) (Gesch, 2009). For example, by definition a topographic map with a 5-ft contour interval that meets NMAS has an absolute vertical accuracy (which accounts for all effects of systematic and random errors) of 90.8 cm at the 95-percent confidence level (Maune, *et al*., 2007b). Likewise, a 10-ft contour interval map has an absolute vertical accuracy of 181.6 cm (1.816 m) at the 95-percent confidence level. If such maps were used to delineate the inundation zone from a 50-cm sea-level rise, the results would be uncertain because the vertical increment of rise is well within the bounds of statistical uncertainty of the elevation data.

Sea-Level Rise Mapped onto Land Surface

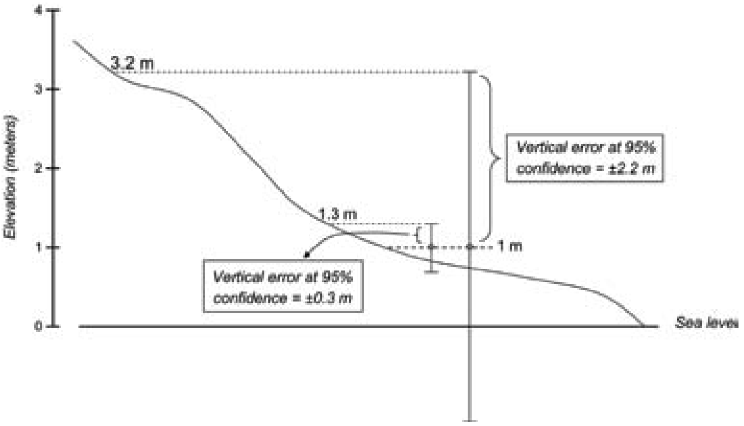


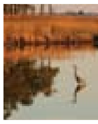
Figure 2.2 Diagram of how a sea-level rise of 1 meter is mapped onto the land surface using two digital elevation models with differing vertical accuracies. The more accurate lidar-derived DEM (±0.3 m at 95-percent confidence) results in a delineation of the inundation zone with much less uncertainty than when the less accurate topographic map-derived DEM (±2.2 m at 95-percent confidence) is used (Gesch, 2009).

4. *Maps without symbology or caveats concerning the inherent vertical uncertainty of input elevation data*. Some studies have addressed limitations of their maps and statistics (Titus and Richman, 2001; Najjar *et al*., 2000), but most reports present maps without any indication of the error associated with the underlying elevation data (see number 3 above). Gesch (2009) presents one method of spatially portraying the inherent uncertainty of a mapped sea-level rise inundation zone (see Box 2.1).

5. *Inundated area and impacted population estimates reported without a range of values that reflect the inherent vertical uncertainty of input elevation data*. Many studies use the mapped inundation zone to calculate the at-risk area, and then overlay that delineation with spatially distributed population data or other socioeconomic variables to estimate impacts. If a spatial expression of the uncertainty of the inundation zone (due to the vertical error in the elevation data) is not included, then only one total can be reported. More complete and credible information would be provided if a second total was calculated by including the variable (area, population, or economic parameter)

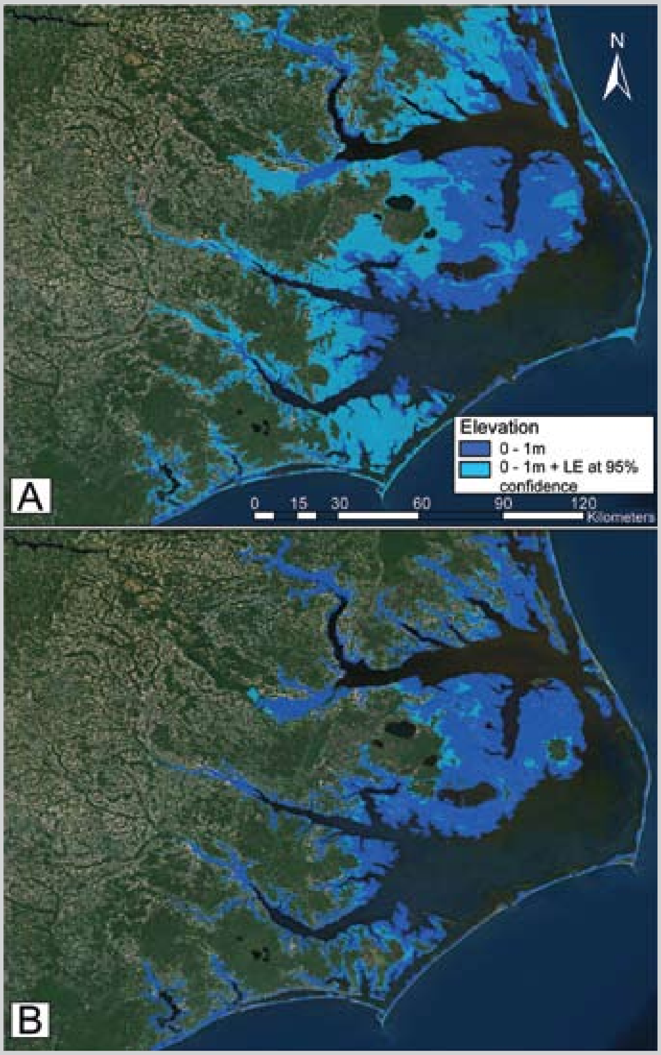
that falls within an additional delineation that accounts for elevation uncertainty. A range of values can then be reported, which reflects the uncertainty of the mapped inundation zone.

6. *Lack of recognition of differences among reference orthometric datums, tidal datums, and spatial variations in sea-level datums.* The vertical reference frame of the data used in a particular study needs to be specified, especially for local studies that produce detailed maps, since there can be significant differences between an orthometric datum zero reference and mean sea level (Figure 2.1; see also Section 2.2.3). As described earlier, there are important distinctions between vertical reference systems that are used for land elevation datasets and those that are used to establish the elevations of sea level. Most of the reviewed studies did not specify which vertical reference frame was used. Often, it was probably an orthometric datum because most elevation datasets are in reference to such datums. Ideally, a tool such as VDatum will be available so that data may be easily transformed into a number vertical reference frames at the discretion of the user.



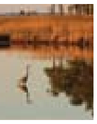
BOX 2.1: A Case Study Using Lidar Elevation Data

To illustrate the application of elevation uncertainty information and the advantages of lidar elevation data for sea-level rise assessment, a case study for North Carolina (Gesch, 2009) is presented and summarized here. North Carolina has a broad expanse of low-lying land (Titus and Richman, 2001), and as such is a good site for a mapping comparison. Lidar data at 1/9-arc-second (about 3 meters [m]) grid spacing were analyzed and compared to 1-arc-second (about 30 m) DEMs derived from 1:24,000-scale topographic maps. The potential inundation zone from a 1-m sea-level rise was mapped from both elevation datasets, and the corresponding areas were compared. The analysis produced maps and statistics in which the elevation uncertainty was considered. Each elevation dataset was "flooded" by identifying the grid cells that have an elevation at or below 1 m and are connected hydrologically to the ocean through a continuous path of adjacent inundated grid cells. For each dataset, additional areas were delineated to show a spatial representation of the uncertainty of the projected inundation area. This was accomplished by adding the linear error at 95-percent confidence to the 1-m sea-level increase and extracting the area at or below that elevation using the same flooding algorithm. The lidar data exhibited ±0.27 m error at 95-percent confidence based on accuracy reports from the data producer, while the topographic map-derived DEMs had ±2.21 m error at 95-percent confidence based on an accuracy assessment with high-quality surveyed control points.



Box Figure 2.1 (A) Lands vulnerable to a 1-meter sea-level rise, developed from topographic map-derived DEMs and (B) lidar elevation data (Gesch, 2009). The background is a recent true color orthoimage.

Box Figure 2.1 and Box Table 2.1 show the results of the North Carolina mapping comparison. In Box Figure 2.1 the darker blue tint represents the area at or below 1 m in elevation, and the lighter blue tint represents the additional area in the vulnerable zone given the vertical uncertainty of the input elevation datasets. The more accurate lidar data for delineation of the vulnerable zone results in a more certain delineation (Box Figure 2.1B), or in other words the zone of uncertainty is small.



BOX 2.1: A Case Study Using Lidar Elevation Data *cont'd*

Box Table 2.1 compares the vulnerable areas as delineated from the two elevation datasets. The delineation of the 1-meter (m) zone from the topographic map-derived DEMs more than doubles when the elevation uncertainty is considered, which calls into question the reliability of any conclusions drawn from the delineation. It is apparent that for this site the map-derived DEMs do not have the vertical accuracy required to reliably delineate a 1-m sea-level rise inundation zone. Lidar is the appropriate elevation dataset for answering the question about how much land in the study site is vulnerable to a 1-m sea-level rise, for which the answer is: "4,195 to 4,783 square kilometers (sq km) at a 95-percent confidence level". This case study emphasizes why a range of values should be given when reporting the size of the inundation area for a given sea-level rise scenario, especially for sites where high-accuracy lidar data are not available. Without such a range being reported, users of an assessment report may not understand the amount of uncertainty associated with area delineations from less accurate data and their implications for any subsequent decisions based on the reported statistics.

Box Table 2.1 The Area of Land (in square kilometers [sq km]) Vulnerable to a 1-Meter (m) Sea-Level Rise (as calculated from two elevation datasets [see Box Figure 2.1], as well as the area of vulnerability, when the uncertainty of the elevation data is considered [Gesch, 2009]).

Elevation Dataset	Area less than or equal to 1 meter in elevation (sq km)	Area less than or equal to 1 meter in elevation at 95-percent confidence (sq km)	Percent increase in vulnerable area when elevation uncertainty is included
1-arc-second (30-m) DEMs derived from 1:24,000-scale topographic maps	4,014	8,578	114%
1/9-arc-second (3-m) lidar elevation grid	4,195	4,783	14%

2.4 FUTURE VULNERABILITY ASSESSMENTS

To fully answer the relevant elevation question from the prospectus for this SAP 4.1 (see Section 2.3.4), there are important technical considerations that need to be incorporated to improve future sea-level rise impact assessments, especially those with a goal of producing vulnerability maps and statistical summaries of impacts. These considerations are important for both the researchers who develop impact assessments, as well as the users of those assessments who must understand the technical issues to properly apply the information. The recommendations for improvements described below are based on the review of the previous studies cited in Sections 2.3.1, 2.3.2, 2.3.3, and other recent research:

1. *Determine where inundation will be the primary response to sea-level rise.* Inundation (submergence of the uplands) is only one of a number of possible responses to sea-level rise (Leatherman, 2001; Valiela, 2006; FitzGerald *et al.*, 2008). If the complex nature of coastal change is not recognized up front in sea-level rise assessment reports, a reader may mistakenly assume that all stretches of the coast that are deemed vulnerable will experience the same "flooding" impact, as numerous reports have called it. For the coastal settings in which inundation is the primary vulnerability, elevation datasets should be analyzed as detailed below to produce comprehensive maps and statistics.

2. *Use lidar elevation data (or other high-resolution, high-accuracy elevation source).* To meet the need for more accurate, detailed, and up-to-date sea-level rise vulnerability assessments, new studies should be based on recently collected high-resolution, high-accuracy, lidar elevation data. Other mapping approaches, including photogrammetry and ground surveys, can produce high-quality elevation data suitable for detailed assessments, but lidar is the preferred approach for cost-effective data collection over broad coastal areas. Lidar has the added advantage that, in addition to high-accuracy measurements of ground elevation, it also can be used to produce information on buildings, infrastructure, and vegetation, which may be important for sea-level rise impact assessments. As Leatherman (2001) points out, inundation is a function of slope. The ability of lidar to measure elevations very precisely facilitates the accurate determination of even small slopes, thus it is quite useful for mapping low-relief coastal landforms. The numerous advantages of lidar elevation mapping in the coastal zone have been widely recognized (Leatherman, 2001; Coastal States Organization, 2007; Monmonier, 2008; Subcommittee on Disaster Reduction, 2008;

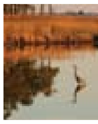
Feyen *et al*., 2008; Gesch, 2009). A recent study by the National Research Council (NRC, 2007) concluded that FEMA's requirements for floodplain mapping would be met in all areas by elevation data with 1-ft to 2-ft equivalent contour accuracy, and that a national lidar program called "Elevation for the Nation" should be carried out to create a new national DEM. Elevation data meeting 1-ft contour interval accuracy (NMAS) would allow effective sea-level rise inundation modeling for increments in the 0.35 m range, while data with 2-ft contour interval accuracy would be suitable for increments of about 0.7 m.

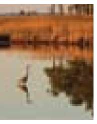
3. *Test and report absolute vertical accuracy as a measure of elevation uncertainty.* Any studies that use elevation data as an input for vulnerability maps and/or statistics need to have a clear statement of the absolute vertical accuracy (in reference to true ground elevations). The NSSDA vertical accuracy testing and reporting methodology (Federal Geographic Data Committee, 1998), which uses a metric of linear error at 95-percent confidence, is the preferred approach. Vertical accuracy may be reported with other metrics including RMSE, standard deviation (one sigma error), LE90, or three sigma error. Maune *et al.* (2007b) and Greenwalt and Shultz (1962) provide methods to translate among the different error metrics. In any case, the error metric must be identified because quoting an accuracy figure without specifying the metric is meaningless. For lidar elevation data, a specific testing and reporting procedure that conforms to the NSSDA has been developed by the National Digital Elevation Program (NDEP) (2004). The NDEP guidelines are useful because they provide methods for accuracy assessment in "open terrain" versus other land cover categories such as forest or urban areas where the lidar sensor may not have detected ground level. NDEP also provides guidance on accuracy testing and reporting when the measured elevation model errors are from a non-Gaussian (non-normal) distribution.

4. *Apply elevation uncertainty information in development of vulnerability maps and area statistics.* Knowledge of the uncertainty of input elevation data should be incorporated into the development of sea-level rise impact assessment products. In this case, the uncertainty is expressed in the vertical error determined through accuracy testing, as described above. Other hydrologic applications of elevation data, including rainfall runoff modeling (Wu *et al*., 2008) and riverine flood inundation modeling (Yilmaz *et al*., 2004, 2005), have benefitted from the incorporation of elevation uncertainty. For sea-level rise inundation modeling, the error associated with the input elevation dataset is used to include a zone of uncertainty in the delineation of vulnerable land at or below a specific elevation. For example, assume a map of lands vulnerable to a 1-m sea-level rise is to be developed using a DEM. That DEM, similar to all elevation datasets, has an overall vertical error. The challenge, then, is how to account for the elevation uncertainty (vertical error) in the mapping of the vulnerable area. Figure 2.2 (Gesch, 2009) shows how the elevation uncertainty associated with the 1-m level, as expressed by the absolute vertical accuracy, is projected onto the land surface. The topographic profile diagram shows two different elevation datasets with differing vertical accuracies depicted as error bars around the 1-m elevation. One dataset has a vertical accuracy of ±0.3 m at the 95-percent confidence level, while the other has an accuracy of ±2.2 m at the 95-percent confidence level. By adding the error to the projected 1-m sea-level rise, more area is added to the inundation zone delineation, and this additional area is a spatial representation of the uncertainty. The additional area is interpreted as the region in which the 1-m elevation may actually fall, given the statistical uncertainty of the DEMs.

   Recognizing that elevation data inherently have vertical uncertainty, vulnerability maps derived from them should include some type of indication of the area of uncertainty. This could be provided as a caveat in the map legend or margin, but a spatial portrayal with map symbology may be more effective. Merwade *et al.* (2008) have demonstrated this approach for floodplain mapping where the modeled inundation area has a surrounding uncertainty zone depicted as a buffer around the flood boundary. Gesch (2009) used a similar approach to show a spatial representation of the uncertainty of the projected inundation area from a 1-m sea-level rise, with one color for the area below 1 m in elevation and another color for the adjacent uncertainty zone (see Box 2.1).

   As with vulnerability maps derived from elevation data, statistical summaries of affected land area, population, land use/land cover types, number of buildings, infrastructure extent, and other socioeconomic variables should include recognition of the vertical uncertainty of the underlying data. In many studies, the delineated inundation zone is intersected with geospatial representations of demographic or economic variables in order to summarize the quantity of those variables within the potential impact zone. Such overlay and summarizing operations should also include the area of uncertainty associated with the inundation zone, and thus ranges of the variables should be reported. The range for a particular variable would increase from the total for just the projected inundation zone up to the combined total





for the inundation zone plus the adjacent uncertainty zone. Additionally, because the combined area of the inundation zone and its adjacent uncertainty zone has a known confidence level, the range can be reported with that same confidence level. Merwade *et al.* (2008) have recommended such an approach for floodplain mapping when they state that the flood inundation extent should be reported as being "in the range from x units to y units with a z-% confidence level".

An important use of elevation data accuracy information in an assessment study is to guide the selection of land elevation intervals or sea-level rise increments that are appropriate for the available data. Inundation modeling is usually a simple process wherein sea level is effectively raised by delineating the area at and below a specified land elevation to create the inundation zone. This procedure is effectively a contouring process, so the vertical accuracy of a DEM must be known to determine the contour interval that is supported. DEMs can be contoured at any interval, but, just by doing so, it does not mean that the contours meet published accuracy standards. Likewise, studies can use small intervals of sea-level rise, but the underlying elevation data must have the vertical accuracy to support those intervals. The intervals must not be so small that they are within the bounds of the statistical uncertainty of the elevation data.

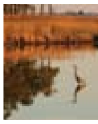
5. *Produce spatially explicit maps and detailed statistics that can be used in local decision making.* The ultimate use of a sea-level rise assessment is as a planning and decision-making tool. Some assessments cover broad areas and are useful for scoping the general extent of the area of concern for sea-level rise impacts. However, the smaller-scale maps and corresponding statistics from these broad area assessments cannot be used for local decision making, which require large-scale map products and site-specific information. Such spatially explicit planning maps require high-resolution, high-accuracy input data as source information. Monmonier (2008) emphasizes that "reliable large-scale planning maps call for markedly better elevation data than found on conventional topographic maps". Even with source data that supports local mapping, it is important to remember, as Frumhoff *et al.* (2007) point out, due to the complex nature of coastal dynamics that "projecting the impacts of rising sea level on specific locations is not as simple as mapping which low-lying areas will eventually be inundated".

Proper treatment of elevation uncertainty is especially important for development of large-scale maps that will be used for planning and resource management decisions. Several states have realized the advantages of using high-accuracy lidar data to reduce uncertainty in sea-level rise studies and development of local map products (Rubinoff *et al*., 2008). Accurate local-scale maps can also be generalized to smaller-scale maps for assessments over larger areas. Such aggregation of detailed information benefits broad area studies by incorporating the best available, most detailed information.

Development of large-scale spatially explicit maps presents a new set of challenges. At scales useful for local decision making, the hydrological connectivity of the ocean to vulnerable lands must be mapped and considered. In some vulnerable areas, the drainage network has been artificially modified with ditches, canals, dikes, levees, and seawalls that affect the hydrologic paths rising water can traverse (Poulter and Halpin, 2007; Poulter *et al*., 2008). Fortunately, lidar data often include these important features, which are important for improving large-scale inundation modeling (Coastal States Organization, 2007). Older, lower resolution elevation data often do not include these fine-scale manmade features, which is another limitation of these data for large-scale maps.

Other site-specific data should be included in impact assessments for local decision making, including knowledge of local sea-level rise trends and the differences among the zero reference for elevation data (often an orthometric datum), local mean sea level, and high water (Marbaix and Nicholls, 2007; Poulter and Halpin, 2007). The high water level is useful for inundation mapping because it distinguishes the area of periodic submergence by tides from those areas that may become inundated as sea-level rises (Leatherman, 2001). The importance of knowing the local relationships of water level and land vertical reference systems emphasizes the need for a national implementation of VDatum (Parker *et al*., 2003; Myers, 2005) so that accurate information on tidal dynamics can be incorporated into local sea-level rise assessments.

Another useful advance for detailed sea-level rise assessments can be realized by better overlay analysis of a delineated vulnerability zone and local population data. Population data are aggregated and reported in census blocks and tracts, and are often represented in area-based statistical thematic maps, also known as choropleth maps. However, such maps usually do not represent actual population density and distribution across the landscape because census units include both inhabited and uninhabited land. Dasymetric mapping (Mennis, 2003) is a technique that is used to disaggregate population density data into a more realistic spatial distribution based on ancillary land use/land cover information or remote sensing images (Sleeter and Gould, 2008; Chen, 2002). This technique holds promise for bet-



ter analysis of population, or other socioeconomic data, to report statistical summaries of sea-level rise impacts within vulnerable zones.

2.5 SUMMARY, CONCLUSIONS, AND FUTURE DIRECTIONS

The topic of coastal elevations is most relevant to the first SAP 4.1 prospectus question (CCSP, 2006): "Which lands are currently at an elevation that could lead them to be inundated by the tides without shore protection measures?" The difficulty in directly answering this question for the mid-Atlantic region with a high degree of confidence was recognized. Collectively, the available previous studies do not provide the full answer for this region with the degree of confidence that is optimal for local decision making. Fortunately, new elevation data, especially lidar, are becoming available and are being integrated into the USGS NED (Gesch, 2007) as well as being used in sea-level rise applications (Coastal States Organization, 2007). Also, research is progressing on how to take advantage of the increased spatial resolution and vertical accuracy of new data (Poulter and Halpin, 2007; Gesch, 2009).

Using national geospatial standards for accuracy assessment and reporting, the currently best available elevation data for the entire mid-Atlantic region do not support an assessment using a sea-level rise increment of 1 m or less, which is slightly above the range of current estimates for the remainder of this century and the high scenario used in this Product. Where lidar data meeting current industry standards for accuracy are available, the land area below the 1-m contour (simulating a 1-m sea-level rise) can be estimated for those sites along the coast at which inundation will be the primary response. The current USGS holdings of the best available elevation data include lidar for North Carolina, parts of Maryland, and parts of New Jersey (Figure 2.3). Lidar data for portions of Delaware and more of New Jersey and Maryland will be integrated into the NED in 2009. However, it may be some time before the full extent of the mid-Atlantic region has sufficient coverage of elevation data that are suitable for detailed assessments of sub-meter increments of sea-level rise and development of spatially explicit local planning maps.

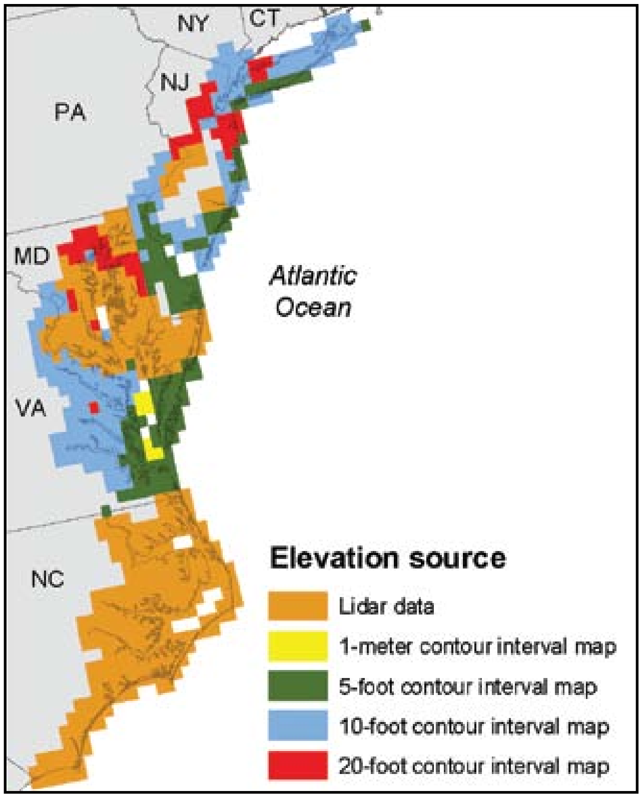
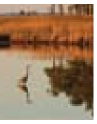


Figure 2.3 The current best available elevation source data (as of August 2008) for the National Elevation Dataset over the mid-Atlantic region.

Given the current status of the NED for the mid-Atlantic region (Figure 2.3), the finest increment of sea-level rise that is supported by the underlying elevation data varies across the area (Table 2.4 and Figure 2.4). At a minimum, a sea-level rise increment used for inundation modeling should not be smaller than the range of statistical uncertainty of the elevation data. For instance, if an elevation dataset has a vertical accuracy of ±1 m at 95-percent confidence, the

Table 2.4 Minimum Sea-Level Rise Scenarios for Vulnerability Assessments Supported by Elevation Datasets of Varying Vertical Accuracy.

Elevation Data Source	Vertical accuracy: RMSE	Vertical accuracy: linear error at 95-percent confidence	Minimum sea-level rise increment for inundation modeling
1-ft contour interval map	9.3 cm	18.2 cm	36.4 cm
lidar	15.0 cm	29.4 cm	58.8 cm
2-ft contour interval map	18.5 cm	36.3 cm	72.6 cm
1-m contour interval map	30.4 cm	59.6 cm	1.19 m
5-ft contour interval map	46.3 cm	90.7 cm	1.82 m
10-ft contour interval map	92.7 cm	1.82 m	3.64 m
20-ft contour interval map	1.85 m	3.63 m	7.26 m
cm = centimeters; m = meters; ft = feet			



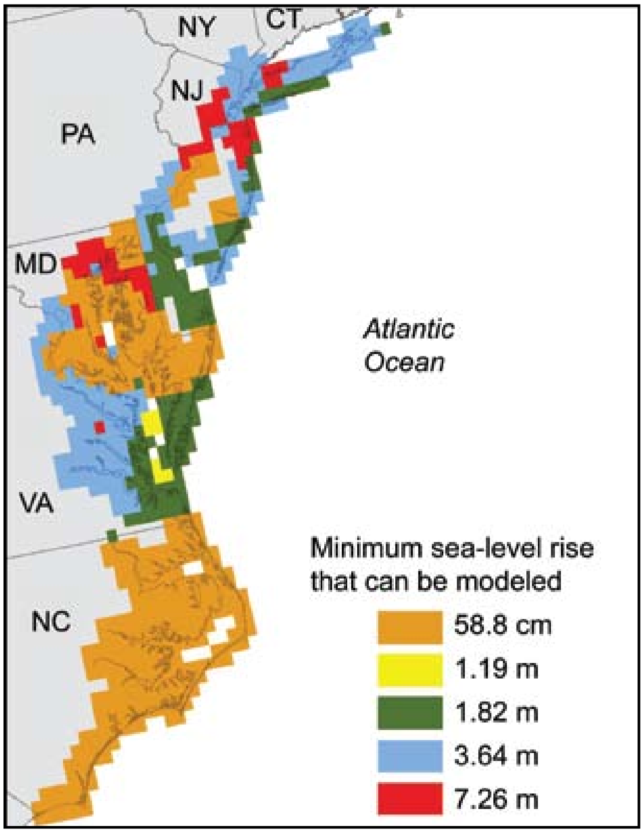


Figure 2.4 Estimated minimum sea-level rise scenarios (in centimeters [cm] and meters [m]) for inundation modeling in the mid-Atlantic region given the current best available elevation data.

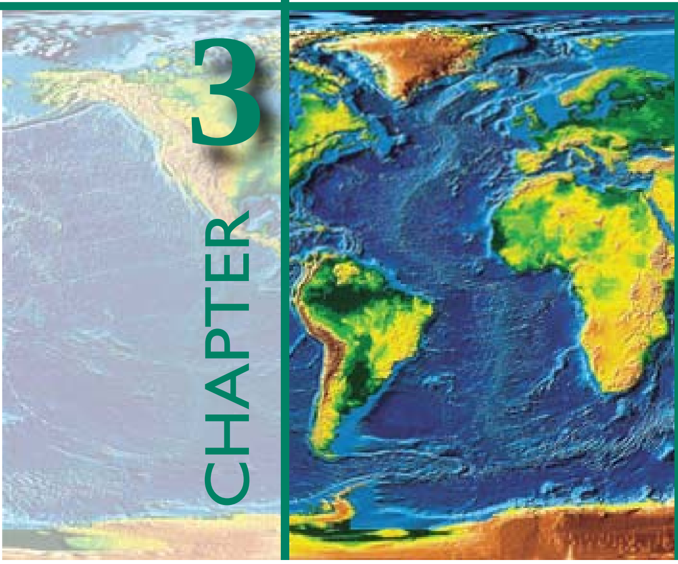
smallest sea-level rise increment that should be considered is 1 m. Even then, the reliability of the vulnerable area delineation would not be high because the modeled sea-level rise increment is the same as the inherent vertical uncertainty of the elevation data. Thus, the reliability of a delineation of a given sea-level rise scenario will be better if the inherent vertical uncertainty of the elevation data is much less than the modeled water level rise For example, a sea-level rise of 0.5 m is reliably modeled with elevation data having a vertical accuracy of ±0.25 m at 95-percent confidence. This guideline, with the elevation data being at least twice as accurate as the modeled sea-level rise, was applied to derive the numbers in Table 2.4.

High-quality lidar elevation data, such as that which could be collected in a national lidar survey, would be necessary for the entire coastal zone to complete a comprehensive assessment of sea-level rise vulnerability in the mid-Atlantic region. Lidar remote sensing has been recognized as a means to provide highly detailed and accurate data for numerous applications, and there is significant interest from the geospatial community in developing an initiative for a national lidar collection for the United States (Stoker *et al.*, 2007, 2008). If such an initiative is successful, then a truly national assessment of potential sea-level rise impacts could be realized. A U.S. national lidar dataset would facilitate consistent assessment of vulnerability across state or jurisdictional boundaries, an approach for which coastal states have voiced strong advocacy (Coastal States Organization, 2007). Even with the current investment in lidar by several states, there is a clear federal role in the development of a national lidar program (NRC, 2007; Monmonier, 2008; Stoker *et al.*, 2008).

Use of recent, high-accuracy lidar elevation data, especially with full consideration of elevation uncertainty as described in Section 2.4, will result in a new class of vulnerability maps and statistical summaries of impacts. These new assessment products will include a specific level of confidence, with ranges of variables reported. The level of statistical confidence could even be user selectable if assessment reports publish results at several confidence levels.

It is clear that improved elevation data and analysis techniques will lead to better sea-level rise impact assessments. However, new assessments must include recognition that inundation, defined as submergence of the uplands, is the primary response to rising seas in only some areas. In other areas, the response may be dominated by more complex responses such as those involving shoreline erosion, wetland accretion, or barrier island migration. These assessments should first consider the geological setting and the dominant local physical processes at work to determine where inundation might be the primary response. Analysis of lidar elevation data, as outlined above, should then be conducted in those areas.

Investigators conducting sea-level rise impact studies should strive to use approaches that generally follow the guidelines above so that results can be consistent across larger areas and subsequent use of the maps and data can reference a common baseline. Assessment results, ideally with spatially explicit vulnerability maps and summary statistics having all the qualities described in Section 2.4, should be published in peer-reviewed journals so that decision makers can be confident of a sound scientific base for their decisions made on the basis of the findings. If necessary, assessment results can be reformatted into products that are more easily used by local planners and decision makers, but the scientific validity of the information remains.



CHAPTER 3

Ocean Coasts

Lead Authors: Benjamin T. Gutierrez, USGS; S. Jeffress Williams, USGS; E. Robert Thieler, USGS

KEY FINDINGS

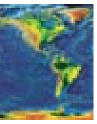
- Along the ocean shores of the Mid-Atlantic, which are comprised of headlands, barrier islands, and spits, it is *virtually certain* that erosion will dominate changes in shoreline position in response to sea-level rise and storms over the next century.

- It is *very likely* that landforms along the mid-Atlantic coast of the United States will undergo large changes if the higher sea-level rise scenarios occur. The response will vary depending on the type of coastal landforms and the local geologic and oceanographic conditions, and could be more variable than the changes observed over the last century.

- For higher sea-level rise scenarios, it is *very likely* that some barrier island coasts will cross a threshold and undergo significant changes. These changes include more rapid landward migration or segmentation of some barrier islands.

3.1 INTRODUCTION

The general characteristics of the coast, such as the presence of beaches *versus* cliffs, reflects a complex and dynamic interaction between physical processes (*e.g.*, waves and tidal currents) that act on the coast, availability of sediment transported by waves and tidal currents, underlying geology, and changes in sea level (see review in Carter and Woodroffe, 1994a). Variations in these factors from one region to the next are responsible for the different coastal landforms, such as beaches, barrier islands, and cliffs that are observed along the coast today. Based on studies of the geologic record, the scope and general nature of the changes that can occur in response to sea-level rise are widely recognized (Curray, 1964; Carter and Woodroffe, 1994a; FitzGerald *et al.*, 2008). On the other hand, determining precisely how these changes occur in response to a specific rise in sea level has been difficult. Part of the complication arises due to the range of physical processes and factors that modify the coast and operate over a range of time periods (*e.g.*, from weeks to centuries to thousands of years) (Cowell and Thom, 1994; Stive *et al.*, 2002; Nicholls *et al.*, 2007). Because of the complex interactions between these factors and the difficulty in determining their exact influence, it has been difficult to resolve a quantitative relationship between sea-level rise and shoreline change (*e.g.*, Zhang *et al.*, 2004; Stive, 2004). Consequently, it has been difficult to reach a consensus among coastal scientists as to whether or not sea-level rise can be quantitatively related to observed shoreline changes and determined using quantitative models (Dubois, 2002; Stive, 2004; Pilkey and Cooper, 2004; Cowell *et al.*, 2006).



Along many U.S. shores, shoreline changes are related to changes in the shape of the landscape at the water's edge (*e.g.*, the shape of the beach). Changes in beach dimensions, and the resulting shoreline changes, do not occur directly as the result of sea-level rise but are in an almost continual state of change in response to waves and currents as well as the availability of sediment to the coastal system (see overviews in Carter and Woodroffe, 1994b; Stive *et al.*, 2002; Nicholls *et al.*, 2007). This is especially true for shoreline changes observed over the past century, when the increase in sea level has been relatively small (about 30 to 40 centimeters, or 12 to 16 inches, along the mid-Atlantic coast). During this time, large storms, variations in sediment supply to the coast, and human activity have had a more obvious influence on shoreline changes. Large storms can cause changes in shoreline position that persist for weeks to a decade or more (Morton *et al.*, 1994; Zhang *et al.*, 2002, 2004; List *et al.*, 2006; Riggs and Ames, 2007). Complex interactions with nearshore sand bodies and/or underlying geology (the geologic framework), the mechanics of which are not yet clearly understood, also influence the behavior of beach morphology over a range of time periods (Riggs *et al.*, 1995; Honeycutt and Krantz, 2003; Schupp *et al.*, 2006; Miselis and McNinch, 2006). In addition, human actions to control changes to the shore and coastal waterways have altered the behavior of some portions of the coast considerably (*e.g.*, Assateague Island, Maryland, Dean and Perlin, 1977; Leatherman, 1984; also see reviews in Nordstrom, 1994, 2000; Nicholls *et al.*, 2007).

It is even more difficult to develop quantitative predictions of how shorelines may change in the future (Stive, 2004; Pilkey and Cooper, 2004; Cowell *et al.*, 2006). The most easily applied models incorporate relatively few processes and rely on assumptions that do not always apply to real-world settings (Thieler *et al.*, 2000; Cooper and Pilkey, 2004). In addition, model assumptions often apply best to present conditions, but not necessarily to future conditions. Models that incorporate more factors are applied at specific locations and require precise knowledge regarding the underlying geology or sediment budget (*e.g.*, GEOMBEST, Stolper *et al.*, 2005), and it is therefore difficult to apply these models over larger coastal regions. Appendix 2 presents brief summaries of a few basic methods that have been used to predict the potential for shoreline changes in response to sea-level rise.

As discussed in Chapter 2, recent and ongoing assessments of sea-level rise impacts commonly examine the vulnerability of coastal lands to inundation by specific sea-level rise scenarios (*e.g.*, Najjar *et al.*, 2000; Titus and Richman, 2001; Rowley *et al.*, 2007). This approach provides an estimate of the land area that may be vulnerable, but it does not incorporate the processes (*e.g.*, barrier island migration) nor the environmental changes (*e.g.*, salt marsh deterioration) that may occur as sea level rises. Because of these complexities, inundation can be used as a basic approach to approximate the extent of land areas that could be affected by changing sea level. Because the majority of the U.S. coasts, including those along the Mid-Atlantic, consist of sandy shores, inundation alone is unlikely to reflect the potential consequences of sea-level rise. Instead, long-term shoreline changes will involve contributions from both inundation and erosion (Leatherman, 1990, 2001) as well as changes to other coastal environments such as wetland losses.

Most portions of the open coast of the United States will be subject to significant physical changes and erosion over the next century because the majority of coastlines consist of sandy beaches which are highly mobile and in a continual state of change. This Chapter presents an overview and assessment of the important factors and processes that influence potential changes to the mid-Atlantic ocean coast due to sea-level rise expected by the end of this century. This overview is based in part on a panel assessment (*i.e.*, expert judgement) that was undertaken to address this topic for this Product (Gutierrez *et al.*, 2007). The panel assessment

BOX 3.1: The Panel Assessment Process Used in SAP 4.1, Chapter 3

As described in this Product, there is currently a lack of scientific consensus regarding local-, regional-, and national-scale coastal changes in response to sea-level rise, due to limited elevation and observational data and lack of adequate scientific understanding of the complex processes that contribute to coastal change. To address the question of potential future changes to the mid-Atlantic coast posed in the SAP 4.1 Prospectus, the authors assembled 13 coastal scientists for a meeting to evaluate the potential outcomes of the sea-level rise scenarios used in this Product. These scientists were chosen on the basis of their technical expertise and experience in the coastal research community, and also their involvement with coastal management issues in the mid-Atlantic region. Prior to the meeting, the scientists were provided with documents describing the Climate Change Science Program, and the Prospectus for this Product. The Prospectus included key questions and topics that the panel was charged to address. The panel was also provided a draft version of the report by Reed *et al.* (2008), which documented a similar panel-assessment approach used in developing Chapter 4 of this Product.

The sea-level rise impact assessment effort was conducted as an open discussion facilitated by the USGS authors over a two-day period. The main topics that the panel discussed were:

1. Approaches that can be used to conduct long-term assessments of coastal change;
2. Key geomorphic environments in the mid-Atlantic region from Long Island, New York to North Carolina;
3. Potential responses of these environments to sea-level rise based on an understanding of important factors and processes contributing to coastal change; and
4. The likelihood of these responses to the sea-level rise scenarios used in this Product (see Section 3.7).

The qualitative, consensus-based assessment of potential changes and their likelihood developed by the panel was based on their review and understanding of peer reviewed published coastal science literature, as well as field observations drawn from other studies conducted in the mid-Atlantic region. The likelihood statements reported in Section 3.7 were determined based on the results of the discussion during the two-day meeting and revised according comments from panelists during the drafting of a summary report. The USGS report (Gutierrez *et al.*, 2007) summarizing the process used, the basis in the published literature, and a synthesis of the resulting assessment was produced based on results of the meeting, reviewed as part of the USGS peer review process, and approved by members of the panel.

process is described in Section 3.2 and Box 3.1. Section 3.3 reviews the geological characteristics of the mid-Atlanic coast. Section 3.4 provides an overview of the basic factors that influence sea-level rise-driven shoreline changes. Sections 3.5 and 3.6 describe the coastal landforms of the mid-Atlantic coast of the United States and what is known regarding how these landforms respond to changes in sea-level based on a literature review included as part of the panel assessment (Gutierrez *et al.*, 2007). The potential responses of mid-Atlantic coastal landforms to sea-level rise, which were defined in the panel assessment, are presented in Section 3.7 and communicated using the likelihood terms specified in the Preface (see Figure P.1).

3.2 ASSESSING THE POTENTIAL IMPACT OF SEA-LEVEL RISE ON THE OCEAN COASTS OF THE MID-ATLANTIC

Lacking a single agreed-upon method or scientific consensus view about shoreline changes in response to sea-level rise at a regional scale, a panel was consulted to address the key question that guided this Chapter (Gutierrez *et al.*, 2007). The panel consisted of coastal scientists whose research experiences have focused on the mid-Atlantic region and have been involved with coastal management in the mid-Atlantic region[1]. The panel discussed the changes that might be expected to occur to the ocean shores of the U.S. mid-Atlantic coast in response to predicted accelerations in sea-level rise over the next century, and considered the important geologic, oceanographic, and anthropogenic factors that contribute to shoreline changes in this region. The assessment presented here is based on the professional

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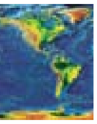
[1] Fred Anders (New York State, Dept. of State, Albany, NY), K. Eric Anderson (USGS, NOAA Coastal Services Center, Charleston, SC), Mark Byrnes (Applied Coastal Research and Engineering, Mashpee, MA), Donald Cahoon (USGS, Beltsville, MD), Stewart Farrell (Richard Stockton College, Pomona, NJ), Duncan FitzGerald (Boston University, Boston, MA), Paul Gayes (Coastal Carolina University, Conway, SC), Benjamin Gutierrez (USGS, Woods Hole, MA), Carl Hobbs (Virginia Institute of Marine Science, Gloucester Pt., VA), Randy McBride (George Mason University, Fairfax, VA), Jesse McNinch (Virginia Institute of Marine Science, Gloucester Pt., VA), Stan Riggs (East Carolina University, Greenville, NC), Antonio Rodriguez (University of North Carolina, Morehead City, NC), Jay Tanski (New York Sea Grant, Stony Brook, NY), E. Robert Thieler (USGS, Woods Hole, MA), Art Trembanis (University of Delaware, Newark, DE), S. Jeffress Williams (USGS, Woods Hole, MA).



judgment of the panel. This qualitative assessment of potential changes that was developed by the panel is based on an understanding of both coastal science literature and their personal field observations.

This assessment focuses on four sea-level rise scenarios. As defined in the Preface, the first three sea-level rise scenarios (Scenarios 1 through 3) assume that: (1) the sea-level rise rate observed during the twentieth century will persist through the twenty-first century; (2) the twentieth century rate will increase by 2 millimeters (mm) per year, and (3) the twentieth century rate will increase by 7 mm per year. Lastly, a fourth scenario is discussed, which considers a 2-meter (m) (6.6-foot [ft]) rise over the next few hundred years. In the following discussions, sea-level change refers to the relative sea-level change, which is the combination of global sea-level change and local change in land elevation. Using these scenarios, this assessment focuses on:

- Identifying important factors and processes contributing to shoreline change over the next century;
- Identifying key geomorphic settings along the coast of the mid-Atlantic region;
- Defining potential responses of shorelines to sea-level rise; and
- Assessing the likelihood of these responses.

3.3 GEOLOGICAL CHARACTER OF THE MID-ATLANTIC COAST

The mid-Atlantic margin of the United States is a gently sloping coastal plain that has accumulated over millions of years in response to the gradual erosion of the Appalachian mountain chain. The resulting sedimentation has constructed a broad coastal plain and a continental shelf that extends almost 300 kilometers (approximately 185 miles) seaward of the present coast (Colquhoun *et al*., 1991). The current morphology of this coastal plain has resulted from the incision of rivers that drain the region and the construction of barrier islands along the mainland occurring between the river systems. Repeated ice ages, which have resulted in sea-level fluctuations up to 140 meters (460 feet) (Muhs *et al*., 2004), caused these rivers to erode large valleys during periods of low sea level that then flooded and filled with sediments when sea levels rose. The northern extent of the mid-Atlantic region considered in this Product, Long Island, New York, was also shaped by the deposition of glacial outwash plains and moraines that accumulated from the retreat of the Laurentide ice sheet, which reached its maximum extent approximately 21,000 years ago. This sloping landscape that characterizes the entire mid-Atlantic margin, in combination with slow rates of sea-level rise over the past 5,000 years and sufficient sand supply, is also thought to have enabled the formation of the barrier islands that comprise the majority of the Atlantic Coast (Walker and Coleman, 1987; Psuty and Ofiara, 2002).

The mid-Atlantic coast is generally described as a sediment-starved coast (Wright, 1995). Presently, sediments from the river systems of the region are trapped in estuaries and only minor amounts of sediment are delivered to the open ocean coast (Meade, 1969, 1972). In addition, these estuaries trap sandy sediment from the continental shelf (Meade, 1969). Consequently, the sediments that form the mainland beach and barrier beach environments are thought to be derived mainly from the wave-driven erosion of the mainland substrate and sediments from the seafloor of the continental shelf (Niedoroda *et al*., 1985; Swift *et al*., 1985; Wright, 1995). Since the largest waves and associated currents occur during storms along the Atlantic Coast, storms are often thought to be significant contributors to coastal changes (Niedoroda *et al*., 1985; Swift *et al*., 1985; Morton and Sallenger, 2003).

The majority of the open coasts along the mid-Atlantic region are sandy shores that include the beach and barrier environments. Although barriers comprise only 15 percent of the world coastline (Glaeser, 1978), they are the dominant shoreline type along the Atlantic Coast. Along the portion of the mid-Atlantic coast examined here, which ranges between Montauk, New York and Cape Lookout, North Carolina, barriers line the majority of the open coast. Consequently, scientific investigations exploring coastal geology of this portion of North America have focused on understanding barrier island systems (Fisher, 1962, 1968; Pierce and Colquhoun, 1970; Kraft, 1971; Leatherman, 1979; Moslow and Heron, 1979, 1994; Swift, 1975; Nummedal, 1983; Oertel, 1985; Belknap and Kraft, 1985; Hine and Snyder, 1985; Davis, 1994).

3.4 IMPORTANT FACTORS FOR MID-ATLANTIC SHORELINE CHANGE

Several important factors influence the evolution of the mid-Atlantic coast in response to sea-level rise including: (1) the geologic framework, (2) physical processes, (3) the sediment supply, and (4) human activity. Each of these factors influences the response of coastal landforms to changes in sea level. In addition, these factors contribute to the local and regional variations of sea-level rise impacts that are difficult to capture using quantitative prediction methods.

3.4.1 Geologic Framework

An important factor influencing coastal morphology and behavior is the underlying geology of a setting, which is also referred to as the geological framework (Belknap and Kraft, 1985; Demarest and Leatherman, 1985; Schwab *et al*., 2000). On a large scale, an example of this is the contrast in the characteristics of the Pacific Coast *versus* the Atlantic Coast of the United States. The collision of tectonic plates along the Pacific margin has contributed to the development of a steep coast where cliffs line much of the shoreline (Inman and Nordstrom, 1971; Muhs *et al*., 1987; Dingler and Clifton, 1994; Griggs and Patsch, 2004; Hapke *et al*., 2006; Hapke and Reid, 2007). While common, sandy barriers and beaches along the Pacific margin are confined to river mouths and low-lying coastal plains that stretch between rock outcrops and coastal headlands. On the other hand, the Gulf of Mexico and Atlantic coasts of the United States are situated on a passive margin where tectonic activity is minor (Walker and Coleman, 1987). As a result, these coasts are composed of wide coastal plains and wide continental shelves extending far offshore. The majority of these coasts are lined with barrier beaches and lagoons, large estuaries, isolated coastal capes, and mainland beaches that abut high grounds in the surrounding landscape.

From a smaller-scale perspective focused on the mid-Atlantic region, the influence of the geological framework involves more subtle details of the regional geology. More specifically, the distribution, structure, and orientation of different rock and sediment units, as well as the presence of features such as river and creek valleys eroded into these units, provides a structural control on a coastal environment (*e.g*., Kraft, 1971; Belknap and Kraft, 1985; Demarest and Leatherman, 1985; Fletcher *et al*., 1990; Riggs *et al*., 1995; Schwab *et al*., 2000; Honeycutt and Krantz, 2003). Moreover, the framework geology can control (1) the location of features, such as inlets, capes, or sand-ridges, (2) the erodibility of sediments, and (3) the type and abundance of sediment available to beach and barrier island settings. In the mid-Atlantic region, the position of tidal inlets, estuaries, and shallow water embayments can be related to the existence of river and creek valleys that were present in the landscape during periods of lower sea level in a number of cases (*e.g*., Kraft, 1971; Belknap and Kraft, 1985; Fletcher *et al*., 1990). Elevated regions of the landscape, which can often be identified by areas where the mainland borders the ocean coast, form coastal headlands. The erosion of these features supplies sand to the nearshore system. Differences in sediment composition (*e.g*., sediment size or density), can sometimes be related to differences in shoreline retreat rates (*e.g*., Honeycutt and Krantz, 2003). In addition, the distribution of underlying geological units (rock outcrops, hardgrounds, or sedimentary strata) in shallow regions offshore of the coast can modify waves and currents and influencing patterns of sediment erosion, transport, and deposition on the adjacent shores (Riggs *et al*., 1995; Schwab *et al*., 2000). These complex interactions with nearshore sand bodies and/or underlying geology can also influence the behavior of beach morphology over a range of time scales (Riggs *et al*., 1995; Honeycutt and Krantz, 2003; Schupp *et al*., 2006; Miselis and McNinch, 2006).

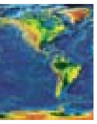
3.4.2 Physical Processes

The physical processes acting on the coast are a principal factor shaping coastal landforms and consequently changes in shoreline position (see reviews in Davis, 1987; Komar, 1998). Winds, waves, and tidal currents continually erode, rework, winnow, redistribute, and shape the sediments that make up these landforms. As a result, these forces also have a controlling influence on the composition and morphology of coastal landforms such as beaches and barrier islands.

Winds have a range of effects on coastal areas. They are the main cause of waves and also generate currents that transport sediments in shallow waters. In addition, winds are a significant mechanism transporting sand along beaches and barrier islands that generate and sustain coastal dunes.

Waves are either generated by local winds or result from far-away disturbances such as large storms out at sea. As waves propagate into shallow water, their energy decreases but they are also increasingly capable of moving the sediment on the seabed. Close to shore each passing wave or breaking wave suspends sediments off the seabed. Once suspended above the bottom, these sediments can be carried by wave- or tide-generated currents.

Wave-generated currents are important agents of change on sandy shores. The main currents that waves generate are longshore currents, rip currents, and onshore and offshore directed currents that accompany the surge and retreat of breaking waves. Longshore currents are typically the most important for sediment transport that influences changes in shoreline position. Where waves approach the coast at an angle, longshore currents are generated. The speed of these currents varies, depending on the wave climate (*e.g*., average wave height and direction) and more specifically, on the power and angle of approach of the waves (*e.g.*, high waves during storms, low waves during fair weather). These currents provide a mechanism for sand transport along the coast, referred to as littoral transport, longshore drift, or longshore transport. During storms, high incoming waves can generate longshore currents exceeding 1 meter (3 feet) per second and storm waves can transport thousands of cubic meters of sand in a relatively short time period, from hours to days. During calm conditions, waves are weaker but can still gradually transport large volumes of sand over longer time periods, ranging from weeks to months. Where there are changes in coastal orientation, the angle at which waves approach the coast changes and can lead to local reversals in longshore sediment transport. These variations can result in the creation of abundances or deficits of longshore sediment transport and contribute to the seaward growth or landward retreat of the shoreline at a particular location (*e.g.*, Cape Lookout, North Carolina: McNinch and Wells, 1999).



The effect of tidal currents on shores is more subtle except for regions near the mouths of inlets, bays, or areas where there is a change in the orientation of the shore. The rise and fall of the water level caused by tides moves the boundary between the land and sea (the shoreline), causing the level that waves act on a shore to move as well. In addition, this controls the depth of water which influences the strength of breaking waves. In regions where there is a large tidal range, there is a greater area over which waves can act on a shore. The rise and fall of the water level also generates tidal currents. Near the shore, tidal currents are small in comparison to wave-driven currents. Near tidal inlets and the mouths of bays or estuaries, tidal currents are strong due to the large volumes of water that are transported through these conduits in response to changing water levels. In these settings, tidal currents transport sediment from ocean shores to back-barrier wetlands, inland waterways on flood tides and vice versa on ebb tides. Aside from these settings, tidal currents are generally small along the mid-Atlantic region except near changes in shoreline orientation or sand banks (*e.g.*, North Carolina Capes, Cape Henlopen, Delaware). In these settings, the strong currents generated can significantly influence sediment transport pathways and the behavior of adjacent shores.

3.4.3 Sediment Supply

The availability of sediments to a coastal region also has important effects on coastal landforms and their behavior (Curray, 1964). In general, assuming a relatively stable sea level, an abundance of sediment along the coast can cause the coast to build seaward over the long term if the rate of supply exceeds the rate at which sediments are eroded and transported by nearshore currents. Conversely, the coast can retreat landward if the rate of erosion exceeds the rate at which sediment is supplied to a coastal region. One way to evaluate the role of sediment supply in a region or specific location is to examine the amount of sediment being gained or lost along the shore. This is often referred to as the sediment budget (Komar, 1996; List, 2005; Rosati, 2005). Whether or not there is an overall sediment gain or loss from a coastal setting is a critical determinant of the potential response to changes in sea level; however, it is difficult if to quantify with high confidence the sediment budget over time periods as long as a century or its precise role in influencing shoreline changes.

The recent Intergovernmental Panel on Climate Change (IPCC) chapter on coastal systems and low-lying regions noted that the availability of sediment to coastal regions will be a key factor in future shoreline changes (Nicholls *et al.*, 2007). In particular, the deposition of sediments in coastal embayments (*e.g.*, estuaries and lagoons) may be a significant sink for sediments as they deepen in response to sea-level rise and are able to accommodate sediments from coastal river systems and adjacent open ocean coasts. For this reason, it is expected that the potential for erosion and shoreline retreat will increase, especially in the vicinity of tidal inlets (see Nicholls *et al.*, 2007). In addition, others have noted an important link between changes in the dimension of coastal embayments, the sediment budget, and the potential for shoreline changes (FitzGerald *et al.*, 2006, 2008). In the mid-Atlantic region, coastal sediments generally come from erosion of both the underlying coastal landscape and the continental shelf (Swift *et al.*, 1985; Niedoroda *et al.*, 1985). Sediments delivered through coastal rivers in the mid-Atlantic region are generally captured in estuaries contributing minor amounts of sediments to the open-ocean coast (Meade, 1969).

3.4.4 Human Impacts

The human impact on the coast is another important factor affecting shoreline changes. A variety of erosion control practices have been undertaken over the last century along much of the mid-Atlantic region, particularly during the latter half of the twentieth century (see reviews in Nordstrom, 1994, 2000). As discussed later in Chapter 6, shoreline engineering structures such as seawalls, revetments, groins, and jetties have significantly altered sediment transport processes, and consequently affect the availability of sediment (*e.g.*, sediment budget) to sustain beaches and barriers and the potential to exacerbate erosion on a local level (see discussion on Assateague Island in Box 3.2). Beach nourishment, a commonly used approach, has been used on many beaches to temporarily mitigate erosion and provide storm protection by adding to the sediment budget.

The management of tidal inlets by dredging has had a large impact to the sediment budget particularly at local levels (see review in Nordstrom, 1994, 2000). In the past, sand removed from inlet shoals has been transferred out to sea, thereby depleting the amount of sand available to sustain portions of the longshore transport system and, consequently, adjacent shores (Marino and Mehta, 1988; Dean, 1988). More recently, inlet management efforts have attempted to retain this material by returning it to adjacent shores or other shores where sand is needed.

A major concern to coastal scientists and managers is whether or not erosion management practices are sustainable for the long term, and whether or how these shoreline protection measures might impede the ability of natural processes to respond to future sea-level rise, especially at accelerated rates. It is also uncertain whether beach nourishment will be continued into the future due to economic constraints and often limited supplies of suitable sand resources. Chapter 6 describes some of these erosion control practices and their management and policy implications further. In addition, Chapter 6 also describes the important concept of "Regional Sediment Management" which is used to guide the management of sediment in inlet dredging, beach nourishment, or other erosion control activities.

3.5 COASTAL LANDFORMS OF THE MID-ATLANTIC

For this assessment, the coastal landforms along the shores of the mid-Atlantic region are classified using the criteria developed by Fisher (1967, 1982), Hayes (1979), and Davis and Hayes (1984). Four distinct geomorphic settings, including spits, headlands, and wave-dominated and mixed-energy barrier islands, occur in the mid-Atlantic region, as shown and described in Figure 3.1.

3.5.1 Spits

The accumulation of sand from longshore transport has formed large spits that extend from adjacent headlands into the mouths of large coastal embayments (Figure 3.1, Sections 4, 9, and 15). Outstanding examples of these occur at the entrances of Raritan Bay (Sandy Hook, New Jersey) and Delaware Bay (Cape Henlopen, Delaware). The evolution and existence of these spits results from the interaction between alongshore transport driven by incoming waves and the tidal flow through the large embayments. Morphologically, these areas can evolve rapidly. For example, since 1842 Cape Henlopen (Figure 3.1, Section 9) has extended

Coastal Landform Types Along U.S. Mid-Atlantic Coast

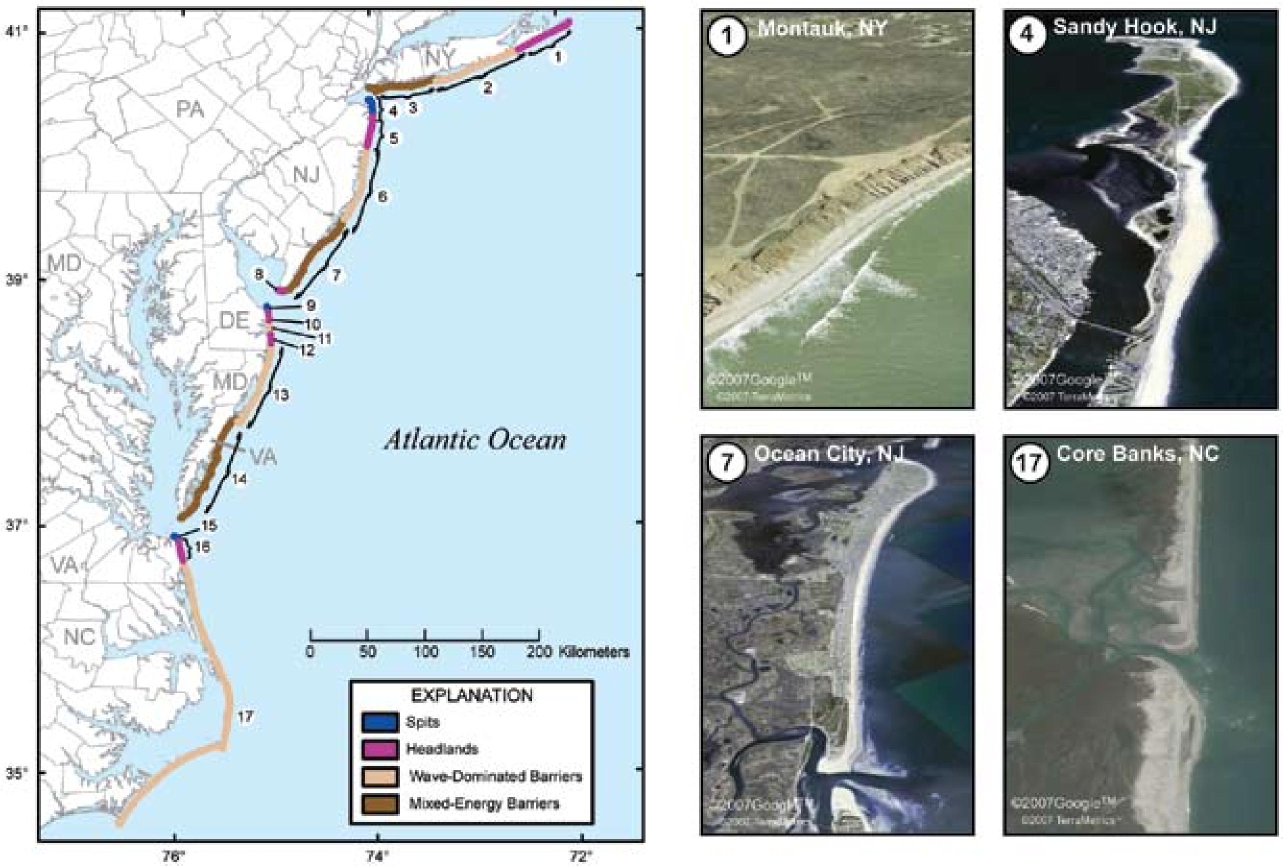
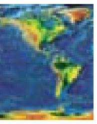


Figure 3.1 Map of the mid-Atlantic coast of the United States showing the occurrence of the four coastal landform types**.** Numbers on the map designate distinct portions of the coast divided by landform type and refer to the discussions in Sections 3.5 and 3.7. Numbers on the photographs refer to specific sections of the coast that are depicted on the map. Images from Google Earth (Gutierrez *et al*., 2007).

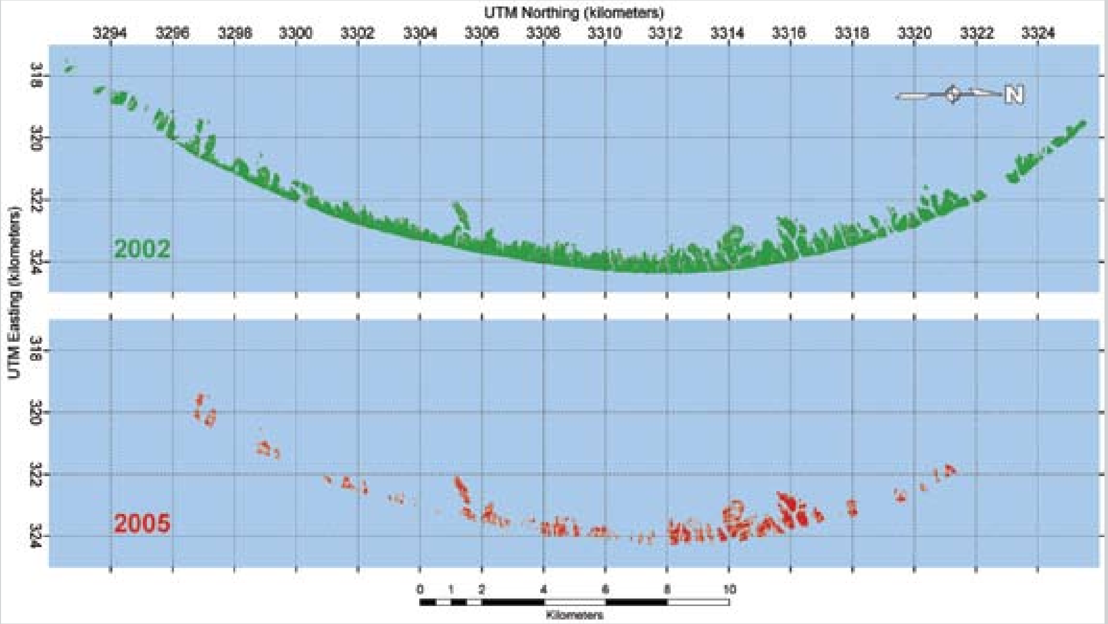
BOX 3.2: Evidence for Threshold Crossing of Coastal Barrier Landforms

Barrier islands change and evolve in subtle and somewhat predictable ways over time in response to storms, changing sediment supply, and changes in sea level. Recent field observations suggest that some barrier islands can reach a "threshold" condition: that is, a point where they become unstable and disintegrate. Two sites where barrier island disintegration is occurring and may continue to occur are along the 72 kilometer- (about 45 mile-) long Chandeleur Islands in Louisiana, east of the Mississippi River Delta, due to impacts of Hurricane Katrina in September 2005; and the northern 10 kilometers (6 miles) of Assateague Island National Seashore, Maryland due to 70 years of sediment starvation caused by the construction of jetties to maintain Ocean City Inlet.



Chandeleur Islands, Louisiana

In the Chandeleur Islands, the high storm surge (about 4 meters, or 13 feet) and waves associated with Hurricane Katrina in 2005 completely submerged the islands and eroded about 85 percent of the sand from the beaches and dunes (Sallenger *et al.*, 2007). Box Figure 3.2a (UTM Northing) shows the configuration of the barriers in 2002, and in 2005 after Katrina's passage. Follow-up aerial surveys by the U.S. Geological Survey indicate that erosion has continued since that time. When the Chandeleur Islands were last mapped in the late 1980s and erosion rates were calculated from the 1850s, it was estimated that the Chandeleurs would last approximately 250 to 300 years (Williams *et al.*, 1992). The results from post-Katrina studies suggest that a threshold has been crossed such that conditions have changed and natural processes may not contribute to the rebuilding of the barrier in the future.



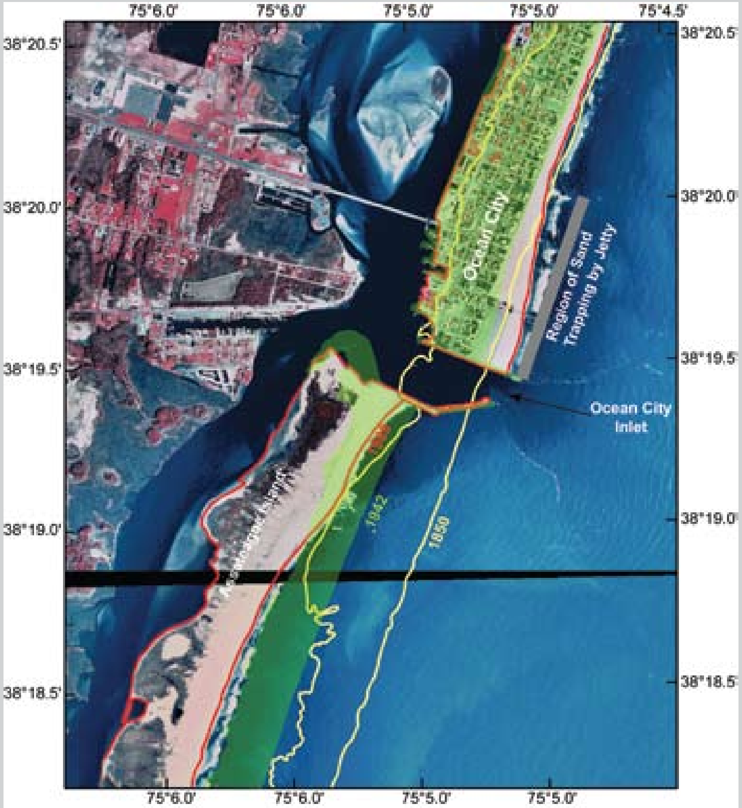
Box Figure 3.2a Maps showing the extent of the Chandeleur Islands in 2002, three years before Hurricane Katrina and in 2005, after Hurricane Katrina. Land area above mean high water. *Source*: A. Sallenger, USGS.

Assateague Island National Seashore, Maryland

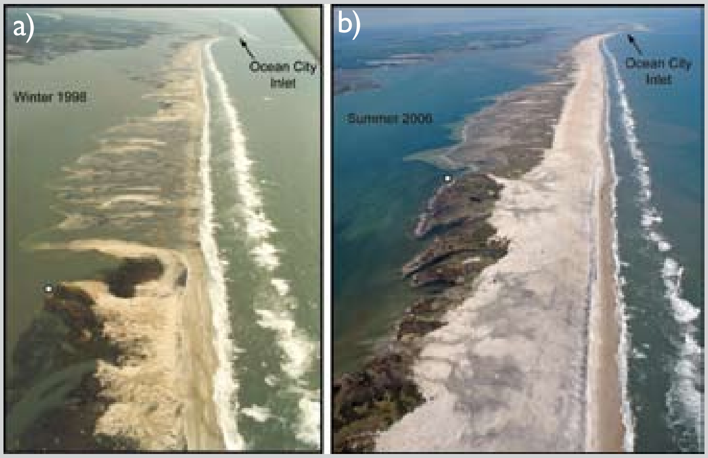
An example of one shoreline setting where human activity has increased the vulnerability of the shore to sea-level rise is Assateague Island, Maryland. Prior to a hurricane in 1933, Assateague Island was a continuous, straight barrier connected to Fenwick Island (Dolan *et al.*, 1980). An inlet that formed during the storm separated the island into two sections at the southern end of Ocean City, Maryland. Subsequent construction of two stone jetties to maintain the inlet for navigation interrupted the longshore transport of sand to the south. Since then, the jetties have trapped sand, building the Ocean City shores seaward by 250 meters (820 feet) by the mid-1970s (Dean and Perlin, 1977). In addition, the development of sand shoals (ebb tidal deltas) around the inlet mouth has sequestered large volumes of sand from the longshore transport system (Dean and Perlin, 1977; FitzGerald, 1988).

BOX 3.2: Evidence for Threshold Crossing of Coastal Barrier Landforms *cont'd*

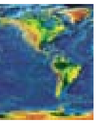
South of the inlet, the opposite has occurred. The sand starvation on the northern portion of Assateague Island has caused the shore to migrate almost 700 meters (2,300 feet) landward and transformed the barrier into a low-relief, overwash-dominated barrier (Leatherman, 1979; 1984). This extreme change in barrier island sediment supply has caused a previously stable segment of the barrier island to migrate. To mitigate the effects of the jetties, and to restore the southward sediment transport that was present prior to the existence of Ocean City inlet, the U.S. Army Corps of Engineers and National Park Service mechanically transfer sand from the inlet and the ebb and flood tidal deltas, where the sand is now trapped, to the shallow nearshore regions along the north end of the island. Annual surveys indicate that waves successfully transport the sediment alongshore and have slowed the high shoreline retreat rates present before the project began (Schupp *et al.*, 2007). Current plans call for continued biannual transfer of sand from the tidal deltas to Assateague Island to mitigate the continued sediment starvation by the Ocean City inlet jetties.



Box Figure 3.2b Aerial photo of northern Assateague Island and Ocean City, Maryland showing former barrier positions. Note that in 1850, a single barrier island, shown in outlined in yellow, occupied this stretch of coast. In 1933, Ocean City inlet was created by a hurricane. The inlet improved accessibility to the ocean and was stabilized by jetties soon after. By 1942, the barrier south of the inlet had migrated landward (shown as a green shaded region). Shorelines acquired from the State of Maryland Geological Survey. Photo source: NPS.



Box Figure 3.2c North oblique photographs of northern Assateague Island in 1998 after a severe winter storm. The left photo of Assateague Island barrier shows clear evidence of overwash. The right 2006 photo shows a more robust barrier that had been augmented by recent beach nourishment. The white circles in the photos specify identical locations on the barrier. The offset between Fenwick Island (north) and Assateague Island due to Ocean City inlet and jetties can be seen at the top of the photo. Photo sources: a) National Park Service, b) Jane Thomas, IAN Photo and Video Library.



almost 1.5 kilometers (0.9 miles) to the north into the mouth of Delaware Bay as the northern Delaware shoreline has retreated and sediment has been transported north by longshore currents (Kraft, 1971; Kraft *et al.*, 1978; Ramsey *et al.*, 2001).

3.5.2 Headlands

Along the shores of the mid-Atlantic region, coastal headlands typically occur where elevated regions of the landscape intersect the coast. These regions are often formed where drainage divides that separate creeks and rivers from one another occur in the landscape, or where glacial deposits create high grounds (Taney, 1961; Kraft, 1971; Nordstrom *et al.*, 1977). The erosion of headlands provides a source of sediment that is incorporated into the longshore transport system that supplies and maintains adjacent beaches and barriers. Coastal headlands are present on Long Island, New York (see Figure 3.1), from Southampton to Montauk (Section 1), in northern New Jersey from Monmouth to Point Pleasant (Section 5; Oertel and Kraft, 1994), in southern New Jersey at Cape May (Section 8), on Delaware north and south of Indian River and Rehoboth Bays (Sections 10 and 12; Kraft, 1971; Oertel and Kraft, 1994; Ramsey *et al.*, 2001), and on the Virginia Coast, from Cape Henry to Sandbridge (Section 16).

3.5.3 Wave-Dominated Barrier Islands

Wave-dominated barrier islands occur as relatively long and thin stretches of sand fronting shallow estuaries, lagoons, or embayments that are bisected by widely-spaced tidal inlets (Figure 3.1, Sections 2, 6, 11, 13, and 17). These barriers are present in regions where wave energy is large relative to tidal energy, such as in the mid-Atlantic region (Hayes, 1979; Davis and Hayes, 1984). Limited tidal ranges result in flow-through tidal inlets that are marginally sufficient to flush the sediments that accumulate from longshore sediment transport. In some cases, this causes the inlet to migrate over time in response to a changing balance between tidal flow through the inlet and wave-driven longshore transport. Inlets on wave-dominated coasts often exhibit large flood-tidal deltas and small ebb-tidal deltas as tidal currents are often stronger during the flooding stage of the tide.

In addition, inlets on wave-dominated barriers are often temporary features. They open intermittently in response to storm-generated overwash and migrate laterally in the overall direction of longshore transport. In many cases, these inlets are prone to filling with sands from alongshore sediment transport (*e.g.*, McBride, 1999).

Overwash produced by storms is common on wave-dominated barriers (*e.g.*, Morton and Sallenger, 2003; Riggs and Ames, 2007). Overwash erodes low-lying dunes into the island interior. Sediment deposition from overwash adds to the island's elevation. Overwash deposits (washover fans) that extend into the back-barrier waterways form substrates for back-barrier marshes and submerged aquatic vegetation.

The process of overwash is an important mechanism by which some types of barriers migrate landward and upward over time. This process of landward migration has been referred to as "roll-over" (Dillon, 1970; Godfrey and Godfrey, 1976; Fisher, 1982; Riggs and Ames, 2007). Over decades to centuries, the intermittent processes of overwash and inlet formation enable the barrier to migrate over and erode into back-barrier environments such as marshes as relative sea-level rise occurs over time. As this occurs, back-barrier environments are eroded and buried by barrier beach and dune sands.

3.5.4 Mixed-Energy Barrier Islands

The other types of barrier islands present along the U.S. Atlantic coast are mixed-energy barrier islands, which are shorter and wider than their wave-dominated counterparts (Hayes, 1979; Figure 3.1, Sections 3, 7, and 14). The term "mixed-energy" refers to the fact that both waves and tidal currents are important factors influencing the morphology of these systems. Due to the larger tidal range and consequently stronger tidal currents, mixed energy barriers are shorter in length and well-developed tidal inlets are more abundant than for wave-dominated barriers. Some authors have referred to the mixed-energy barriers as tide-dominated barriers along the New Jersey and Virginia coasts (*e.g.*, Oertel and Kraft, 1994).

The large sediment transport capacity of the tidal currents within the inlets of these systems maintains large ebb-tidal deltas seaward of the inlet mouth. The shoals that comprise ebb-tidal deltas cause incoming waves to refract around the large sand body that forms the delta such that local reversals of alongshore currents and sediment transport occur downdrift of the inlet. As a result, portions of the barrier downdrift of inlets accumulate sediment which form recurved sand ridges and give the barrier islands a "drumstick"-like shape (Hayes, 1979; Davis, 1994).

3.6 POTENTIAL RESPONSES TO FUTURE SEA-LEVEL RISE

Based on current understanding of the four landforms discussed in the previous section, three potential responses could occur along the mid-Atlantic coast in response to sea-level rise over the next century.

3.6.1 Bluff and Upland Erosion

Shorelines along headland regions of the coast will retreat landward with rising sea level. As sea level rises over time, uplands will be eroded and the sediments incorporated into the beach and dune systems along these shores. Along coastal headlands, bluff and upland erosion will persist under all four of the sea-level rise scenarios considered in this Product. A possible management reaction to bluff erosion is shore armoring (*e.g.*, Nordstrom, 2000; Psuty and Ofiara, 2002; see Chapter 6). This may reduce bluff erosion in the short term but could increase long-term erosion of the adjacent coast by reducing sediment supplies to the littoral system.

3.6.2 Overwash, Inlet Processes, and Barrier Island Morphologic Changes

For barrier islands, three main processes are agents of change as sea level rises. First, with higher sea level, storm overwash may occur more frequently. This is especially critical if the sand available to the barrier, such as from longshore transport, is insufficient to allow the barrier to maintain its width and/or build vertically over time in response to rising water levels. If sediment supplies or the timing of the barrier recovery are insufficient, storm surges coupled with breaking waves will affect increasingly higher elevations of the barrier systems as mean sea level increases, possibly causing more extensive erosion and overwash. In addition, it is possible that future hurricanes may become more intense, possibly increasing the potential for episodic overwash, inlet formation, and shoreline retreat. The topic of recent and future storm trends has been debated in the scientific community, with some researchers suggesting that other climate change impacts such as strengthening wind shear may lead to a decrease in future hurricane frequency (see Chapter 1 and reviews in Meehl *et al*., 2007; Karl *et al*., 2008; Gutowski *et al*., 2008). It is also expected that extratropical storms will be more frequent and intense in the future, but these effects will be more pronounced at high latitudes (60° to 90°N) and possibly decreased at midlatitudes (30° to 60°N) (Meehl *et al*., 2007; Karl *et al*., 2008; Gutowski *et al*., 2008).

Second, tidal inlet formation and migration will contribute to important changes in future shoreline positions. Storm surges coupled with high waves can cause not only barrier island overwash but also breach the barriers and create new inlets. In some cases, breaches can be large enough to form inlets that persist for some time until the inlet channels fill with sediments accumulated from longshore transport. Numerous deposits have been found along the shores of the mid-Atlantic region, indicating former inlet positions (North Carolina: Moslow and Heron, 1979 and Everts *et al*., 1983; Fire Island, New York: Leatherman, 1985). Several inlets along the mid-Atlantic coast were formed by the storm surges and breaches from an unnamed 1933 hurricane, including Shackleford inlet in North Carolina; Ocean City inlet in Maryland; Indian River inlet in Delaware; and Moriches inlet in New York. Recently, tidal inlets were formed in the North Carolina Outer Banks in response to Hurricane Isabel in 2003. While episodic inlet formation and migration are natural processes and can occur independently of long-term sea-level rise, a long-term increase in sea level coupled with limited sediment supply and increases in storm frequency and/or intensity could increase the likelihood for future inlet breaching.

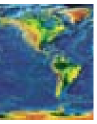
Third, the combined effect of rising sea level and stronger storms could accelerate barrier island shoreline changes. These will involve both changes to the seaward facing and landward facing shores of some barrier islands. Assessments of shoreline change on barrier islands indicate that barriers have thinned in some areas over the last century (Leatherman, 1979; Jarrett, 1983; Everts *et al*., 1983; Penland *et al*., 2005). Evidence of barrier migration is not widespread on the mid-Atlantic coast (Morton *et al*., 2003), but is documented at northern Assateague Island in Maryland (Leatherman, 1979) and Core Banks, North Carolina (Riggs and Ames, 2007).

3.6.3 Threshold Behavior

Barrier islands are dynamic environments that are sensitive to a range of physical and environmental factors. Some evidence suggests that changes in some or all of these factors can lead to conditions where a barrier system becomes less stable and crosses a geomorphic threshold. Once a threshold is crossed, the potential for significant and irreversible changes to the barrier island is high. These changes can involve landward migration or changes to the barrier island dimensions such as reduction in size or an increased presence of tidal inlets. Although it is difficult to precisely define an unstable barrier, indications include:

- Rapid landward migration of the barrier;
- Decreased barrier width and height, due to a loss of sand eroded from beaches and dunes;
- Increased frequency of overwash during storms;
- Increased frequency of barrier breaching and inlet formation; and
- Segmentation of the barrier.

Given the unstable state of some barrier islands under current rates of sea-level rise and climate trends, it is very likely that conditions will worsen under accelerated sea-level rise rates. The unfavorable conditions for barrier maintenance could result in significant changes, for example, to barrier islands as observed in coastal Louisiana (further discussed in Box 3.2; McBride *et al*., 1995; McBride and Byrnes, 1997; Penland *et al*., 2005; Day *et al*., 2007; Sallenger *et al*., 2007; FitzGerald *et al*., 2008). In one case, recent observations indicate that the Chandeleur Islands are undergoing a significant land loss due to several factors which include: (1) limited sediment supply by longshore or cross-shore transport, (2) accelerated rates of sea-level rise, and (3) permanent sand removal from the barrier system by storms such



as Hurricanes Camille, Georges, and Katrina. Likewise, a similar trend has been observed for Isle Dernieres, also on the Louisiana coast (see review in FitzGerald *et al*., 2008). In addition, recent studies from the North Carolina Outer Banks indicate that there have been at least two periods during the past several thousand years where fully open-ocean conditions have occurred in Albemarle and Pamlico Sounds, which are estuaries fronted by barrier islands at the present time (Mallinson *et al*., 2005; Culver *et al*., 2008). This indicates that portions of the North Carolina barrier island system may have segmented or become less continuous than the present time for periods of a few hundred years, and later reformed. Given future increases in sea level and/or storm activity, the potential for a threshold crossing exists, and portions of these barrier islands could once again become segmented.

Changes in sea level coupled with changes in the hydrodynamic climate and sediment supply in the broader coastal environment contribute to the development of unstable barrier island behavior. The threshold behavior of unstable barriers could result in: barrier segmentation, barrier disintegration, or landward migration and rollover. If the barrier were to disintegrate, portions of the ocean shoreline could migrate or back-step toward and/or merge with the mainland.

The mid-Atlantic coastal regions most vulnerable to threshold behavior can be estimated based on their physical dimensions. During storms, large portions of low-elevation, narrow barriers can be inundated under high waves and storm surge. Narrow, low-elevation barrier islands, such as the northern portion of Assateague Island, Maryland are most susceptible to storm overwash, which can lead to landward migration and the formation of new tidal inlets (*e.g.*, Leatherman, 1979; see also Box 3.2).

The future evolution of some low-elevation, narrow barriers could depend in part on the ability of salt marshes in back-barrier lagoons and estuaries to keep pace with sea-level rise (FitzGerald *et al*., 2006, 2008; Reed *et al*., 2008). A reduction of salt marsh in back-barrier regions could increase the volume of water exchanged with the tides (*e.g.*, the tidal prism) of back-barrier systems, altering local sediment budgets and leading to a reduction in sandy materials available to sustain barrier systems (FitzGerald *et al*., 2006, 2008).

3.7 POTENTIAL CHANGES TO THE MID-ATLANTIC OCEAN COAST DUE TO SEA-LEVEL RISE

In this Section, the responses to the four sea-level rise scenarios considered in this Chapter are described according to coastal landform types (Figure 3.2). The first three sea-level rise scenarios (Scenarios 1 through 3) are: (1) a continuation of the twentieth century rate, (2) the twentieth century rate plus 2 mm per year, and (3) the twentieth century rate plus 7 mm per year. Scenario 4 specifies a 2-m rise (6.6-ft) over the next few hundred years. Because humans have a significant impact on portions of the mid-Atlantic coast, this assessment focuses on assessing the vulnerability of the coastal system as it currently exists (see discussion in Section 3.4). However, there are a few caveats to this approach:

- This is a regional-scale assessment and there are local exceptions to these geomorphic classifications and potential outcomes;
- Given that some portions of the mid-Atlantic coast are heavily influenced by development and erosion mitigation practices, it cannot be assumed that current practices will continue into the future given uncertainties regarding the decision-making process that occurs when these practices are pursued; but,
- At the same time, there are locations where some members of the panel believe that erosion mitigation will be implemented regardless of cost.

To express the likelihood of a given outcome for a particular sea-level rise scenario, the terminology advocated by ongoing CCSP assessments was used (see Preface, Figure P.1; CCSP, 2006). This terminology is used to quantify and communicate the degree of likelihood of a given outcome specified by the assessment. These terms should not be construed to represent a quantitative relationship between a specific sea-level rise scenario and a specific dimension of coastal change, or rate at which a specific process operates on a coastal geomorphic compartment. The potential coastal responses to the sea-level rise scenarios are described below according to the coastal landforms defined in Section 3.5.

3.7.1 Spits

For sea-level rise Scenarios 1 through 3, it is *virtually certain* that the spits along the mid-Atlantic coast will be subject to increased storm overwash, erosion, and deposition over the next century (see Figure 3.2, Sections 4, 9, 15). It is *virtually certain* that some of these coastal spits will continue to grow through the accumulation of sediments from longshore transport as the erosion of updrift coastal compartments occurs. For Scenario 4, it is *likely* that threshold behavior could occur for this type of coastal landform (rapid landward and/or alongshore migration).

3.7.2 Headlands

Over the next century, it is *virtually certain* that these headlands along the mid-Atlantic coast will be subject to increased erosion for all four sea-level rise scenarios (see Figure 3.2, Sections 1, 5, 8, 10, 12, and 16). It is *very likely* that shoreline and upland (bluff) erosion will accelerate in response to projected increases in sea level.

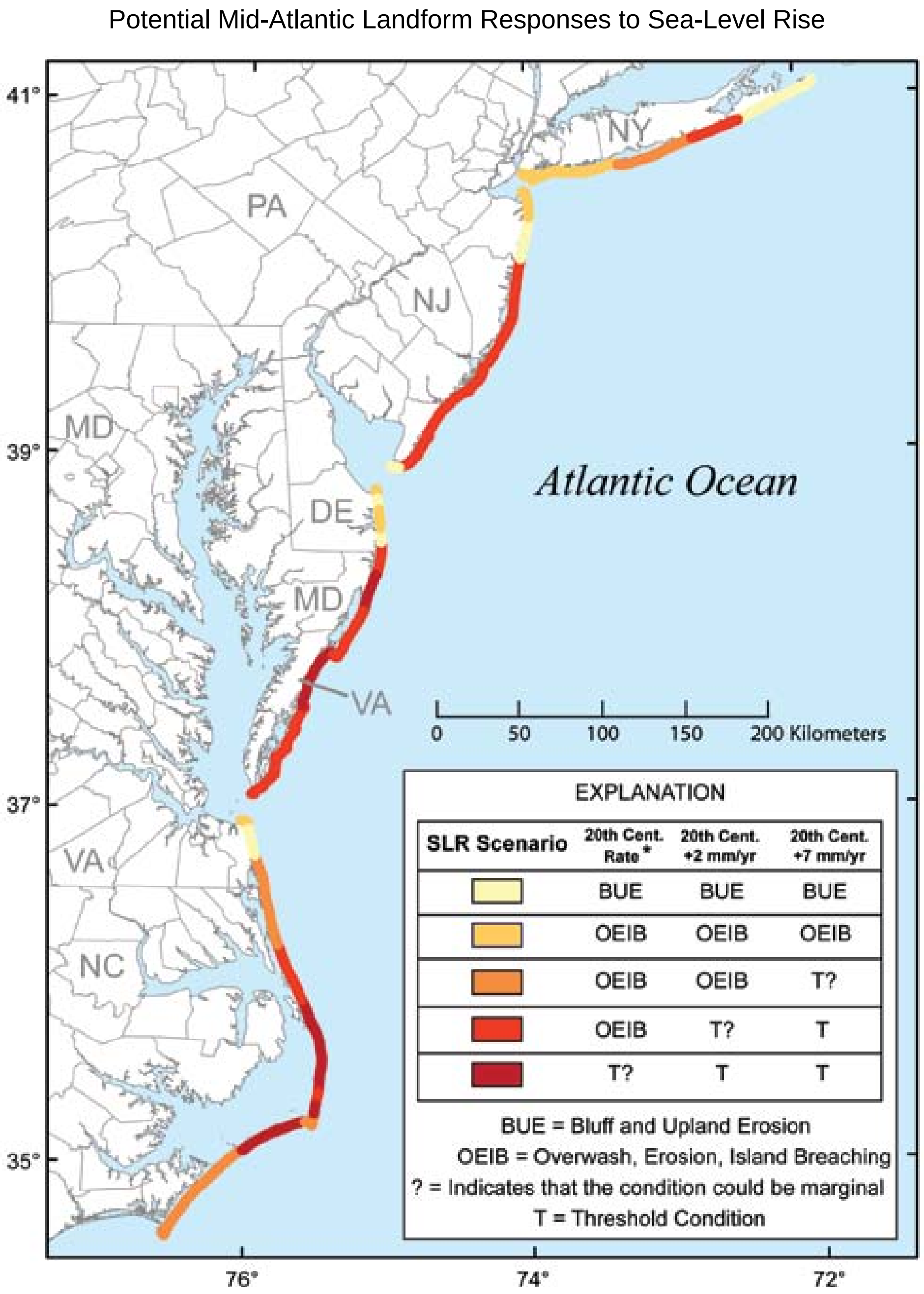
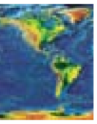


Figure 3.2 Map showing the potential sea-level rise responses (in millimeters [mm] per year [yr]) for each coastal compartment. Colored portions of the coastline indicate the potential response for a given sea-level rise scenario according to the inset table. The color scheme was created using ColorBrewer by Cindy Brewer and Mark Harrower. After Gutierrez *et. al.* (2007).

3.7.3 Wave-Dominated Barrier Islands

Potential sea-level rise impacts on wave-dominated barriers in the Mid-Atlantic vary by location and depend on the sea-level rise scenario (see Figure 3.2, Sections 2, 6, 11, 13, 17). For Scenario 1, it is *virtually certain* that the majority of the wave-dominated barrier islands along the mid-Atlantic coast will continue to experience morphological changes through erosion, overwash, and inlet formation as they have over the last several centuries, except for the northern portion of Assateague Island (Section 13). In this area, the shoreline exhibits high rates of erosion and large portions of this barrier are submerged during moderate storms. In the past, large storms have breached and segmented portions of northern Assateague Island (Morton *et al*., 2003). Therefore, it is possible that these portions of the coast are already at a geomorphic threshold. With any increase in the rate of sea-level rise, it is *virtually certain* that this barrier island will exhibit large changes in morphology, ultimately leading to the degradation of the island. At this site, however, periodic transfer of sand from the shoals of Ocean City inlet appear to be reducing erosion and shoreline retreat in Section 13 (see Box 3.2). Portions of the North Carolina Outer Banks (Figure 3.2) may similarly be nearing a geomorphic threshold.



For Scenario 2, it is *virtually certain* that the majority of the wave-dominated barrier islands in the mid-Atlantic region will continue to experience morphological changes through overwash, erosion, and inlet formation as they have over the last several centuries. It is also *about as likely as not* that a geomorphic threshold will be reached in a few locations, resulting in rapid morphological changes in these barrier systems. Along the shores of northern Assateague Island (Section 13) and a substantial portion of Section 17 it is *very likely* that the barrier islands could exhibit threshold behavior (barrier segmentation). For this scenario, the ability of wetlands to maintain their elevation through accretion at higher rates of sea-level rise may be reduced (Reed *et al.*, 2008). It is *about as likely as not* that the loss of back-barrier marshes will lead to changes in hydrodynamic conditions between tidal inlets and back-barrier lagoons, thus affecting the evolution of barrier islands (*e.g.*, FitzGerald *et al.*, 2006; FitzGerald *et al.*, 2008).

For Scenario 3, it is *very likely* that the potential for threshold behavior will increase along many of the mid-Atlantic barrier islands. It is *virtually certain* that a 2-m (6.6-ft) sea-level rise will lead to threshold behavior (segmentation or disintegration) for this landform type.

3.7.4 Mixed-Energy Barrier Islands

The response of mixed-energy barrier islands will vary (see Figure 3.2, Sections 3, 7, 14). For Scenarios 1 and 2, the mixed-energy barrier islands along the mid-Atlantic will be subject to processes much as have occurred over the last century such as storm overwash and shoreline erosion. Given the degree to which these barriers have been developed, it is difficult to determine the likelihood of future inlet breaches, or whether these would be allowed to persist due to common management decisions to repair breaches when they occur. In addition, changes to the back-barrier shores are uncertain due to the extent of coastal development.

It is *about as likely as not* that four of the barrier islands along the Virginia Coast (Wallops, Assawoman, Metompkin, and Cedar Islands) are presently at a geomorphic threshold. Thus, it, it is *very likely* that further sea-level rise will contribute to significant changes resulting in the segmentation, disintegration and/or more rapid landward migration of these barrier islands.

For the higher sea-level rise scenarios (Scenarios 3 and 4), it is *about as likely as not* that these barriers could reach a geomorphic threshold. This threshold is dependent on the availability of sand from the longshore transport system to supply the barrier. It is *virtually certain* that a 2-m sea-level rise will have severe consequences along the shores of this portion of the coast, including one or more of the extreme responses described above. For Scenario 4, the ability of wetlands to maintain their elevation through accretion at higher rates of sea-level rise may be reduced (Reed *et al.*, 2008). It is *about as likely as not* that the loss of back-barrier marshes could lead to changes in the hydrodynamic conditions between tidal inlets and back-barrier lagoons, affecting the evolution of barrier islands (FitzGerald *et al.*, 2006, 2008).

CHAPTER 4

Coastal Wetland Sustainability

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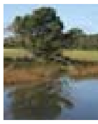


KEY FINDINGS

- It is *virtually certain* that tidal wetlands already experiencing submergence by sea-level rise and associated high rates of loss (*e.g.*, Mississippi River Delta in Louisiana, Blackwater River marshes in Maryland) will continue to lose area in response to future accelerated rates of sea-level rise and changes in other climate and environmental drivers (factors that cause measurable changes).

- It is *very unlikely* that there will be an overall increase in tidal wetland area in the United States over the next 100 years, given current wetland loss rates and the relatively minor accounts of new tidal wetland development (*e.g.*, Atchafalaya Delta in Louisiana).

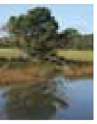
- Current model projections of wetland vulnerability on regional and national scales are uncertain due to the coarse level of resolution of landscape-scale models. In contrast, site-specific model projections are quite good where local information has been acquired on factors that control local accretionary processes in specific wetland settings. However, the authors have low confidence that site-specific model simulations can be successfully generalized so as to apply to larger regional or national scales.

- An assessment of the mid-Atlantic region based on an opinion approach by scientists with expert knowledge of wetland accretionary dynamics projects with a moderate level of confidence that those wetlands keeping pace with twentieth century rates of sea-level rise (Scenario 1) would survive a 2 millimeter per year acceleration of sea-level rise (Scenario 2) only under optimal hydrology and sediment supply conditions, and would not survive a 7 millimeter per year acceleration of sea-level rise (Scenario 3). There may be localized exceptions in regions where sediment supplies are abundant, such as at river mouths and in areas where storm overwash events are frequent.

- The mid-Atlantic regional assessment revealed a wide variability in wetland responses to sea-level rise, both within and among subregions and for a variety of wetland geomorphic settings. This underscores both the influence of local processes on wetland elevation and the difficulty of generalizing from regional/national scale projections of wetland sustainability to the local scale in the absence of local accretionary data. Thus, regional or national scale assessments should not be used to develop local management plans where local accretionary dynamics may override regional controls on wetland vertical development.

- Several key uncertainties need to be addressed in order to improve confidence in projecting wetland vulnerability to sea-level rise, including: a better understanding of maximum rates at which wetland vertical accretion can be sustained; interactions and feedbacks among wetland elevation, flooding, and soil organic matter accretion; broad-scale, spatial variability in accretionary dynamics; land use change effects (*e.g.*, freshwater runoff, sediment supply, barriers to wetland migration) on tidal wetland accretionary processes; and local and regional sediment supplies, particularly fine-grain cohesive sediments needed for wetland formation.

4.1 INTRODUCTION



Given an expected increase in the rate of sea-level rise in the next century, effective management of highly valuable coastal wetland habitats and resources in the United States will be improved by an in-depth assessment of the effects of accelerated sea-level rise on wetland vertical development (*i.e.*, vertical accretion), the horizontal processes of shore erosion and landward migration affecting wetland area, and the expected changes in species composition of plant and animal communities (Nicholls *et al.*, 2007). This Chapter assesses current and projected future rates of vertical buildup of coastal wetland surfaces and wetland sustainability during the next century under the three sea-level rise scenarios, as described briefly above, and in greater detail in Chapter 1.

Many factors must be considered in such an assessment, including: the interactive effects of sea-level rise and other environmental drivers (*e.g.*, changes in sediment supplies related to altered river flows and storms); local processes controlling wetland vertical and horizontal development and the interaction of these processes with the array of environmental drivers; geomorphic setting; and limited opportunities for landward migration (*e.g.*, human development on the coast, or steep slopes) (Figures 4.1 and 4.2). Consequently, there is no simple, direct answer on national or regional scales to the key question facing coastal wetland managers today, namely, "Are wetlands building vertically at a pace equal to current sea-level rise, and will they build vertically at a pace equal to future sea-level rise?" This is a difficult question to answer because of the various combinations of local drivers and processes controlling wetland elevation across the many tidal wetland settings found in North America, and also due to the lack of available data on the critical drivers and local processes across these larger landscape scales.

The capacity of wetlands to keep pace with sea-level rise can be more confidently addressed at the scale of individual sites where data are available on the critical drivers and local processes. However, scaling up from the local to the national perspective is difficult, and rarely done, because of data constraints and because of variations in climate, geology, species composition, and human-induced stressors that become influential at larger scales. Better estimates of coastal wetland sustainability under rising sea levels and the factors influencing future sustainability are needed to inform coastal management decision making. This Chapter provides an overview of the factors influencing wetland sustainability (*e.g.*, environmental drivers, accretionary processes, and geomorphic settings), the state of knowledge of current and future wetland sustainability, including a regional case study analysis of the mid-Atlantic coast of the United States, and information needed to improve projections of future wetland sustainability at continental, regional, and local scales.

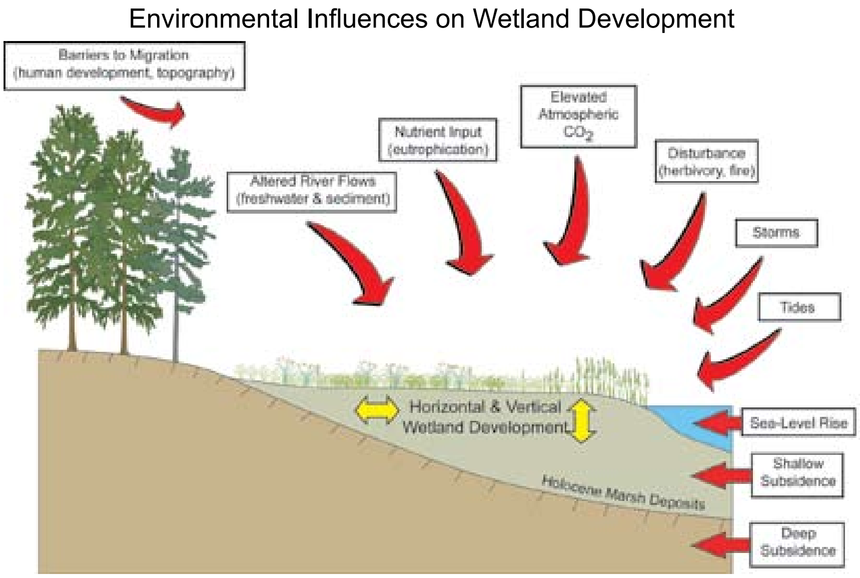


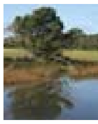
Figure 4.1 Climate and environmental drivers influencing vertical and horizontal wetland development.

4.2 WETLAND SETTINGS OF THE MID-ATLANTIC REGION

Coastal wetlands in the continental United States occur in a variety of physical settings (Table 4.1). The geomorphic classification scheme presented in Table 4.1, developed by Reed *et al.* (2008) (based on Woodroffe, 2002 and Cahoon *et al.*, 2006), provides a useful way of examining and comparing coastal wetlands on a regional scale. Of the geomorphic settings described in Table 4.1, saline fringe marsh, back-barrier lagoon marsh, estuarine brackish marsh, tidal fresh marsh, and tidal fresh forest are found in the mid-Atlantic region of the United States. Back-barrier lagoon salt marshes are either attached to the backside of the barrier island, or are islands either landward of a tidal inlet or behind the barrier island. Saline fringe marshes are located on the landward side of lagoons where they may be able to migrate upslope in response to sea-level rise (see Section 4.3 for a description of the wetland migration process). Estuarine marshes are brackish (a mixture of fresh and salt water) and occur along channels rather than open coasts, either bordering tidal rivers or embayments; or as islands within tidal channels. Tidal fresh marshes and tidal fresh forests occur along river channels, usually above the influence of salinity but not of tides. These wetlands can be distinguished based on vegetative type (species composition; herbaceous *versus* forested) and the salinity of the area. Given the differing hydrodynamics, sediment sources, and vegetative community characteristics of these geomorphic settings, the relationship between sea-level rise and wetland response will also differ.

4.3 VERTICAL DEVELOPMENT AND ELEVATION CHANGE

A coastal marsh will survive if it builds vertically at a rate equal to the rise in sea level; that is, if it maintains its elevation relative to sea level. It is well established that marsh surface elevation changes in response to sea-level rise. Tidal wetland surfaces are frequently considered to be closely coupled with local mean sea level (*e.g.*, Pethick, 1981; Allen, 1990). If a marsh builds vertically at a slower rate than the sea rises, however, then a marsh area cannot maintain its elevation relative to sea level. In such a case, a marsh will gradually become submerged and convert to an intertidal mudflat or to open water over a period of many decades (Morris *et al.*, 2002).



The processes contributing to the capacity of a coastal wetland to maintain a stable relationship with changing sea levels are complex and often nonlinear (Cahoon *et al.*, 2006). For example, the response of tidal wetlands to future sea-level rise will be influenced not only by local site characteristics, such as slope and soil erodibility influences on sediment flux, but also by changes in drivers of vertical accretion, some of which are themselves influenced by climate change (Figure 4.1). In addition to the rate of sea-level rise, vertical accretion dynamics are sensitive to changes in a suite of human and climate-related drivers, including alterations in river and sediment discharge from changes in precipitation patterns and in discharge and runoff related to dams and increases in impervious surfaces, increased frequency and intensity of hurricanes, and increased atmospheric temperatures and carbon dioxide concentrations. Vertical accretion is also affected by local environmental drivers such as shallow (local) and deep (regional) subsidence and direct alterations by human activities (*e.g.*, dredging, diking). The relative roles of these drivers of wetland vertical development vary with geomorphic setting.

4.3.1 Wetland Vertical Development

Projecting future wetland sustainability is made more difficult by the complex interaction of processes by which wetlands build vertically (Figure 4.2) and vary across geomorphic settings (Table 4.1). Figure 4.2 shows how environmental drivers, mineral and organic soil development

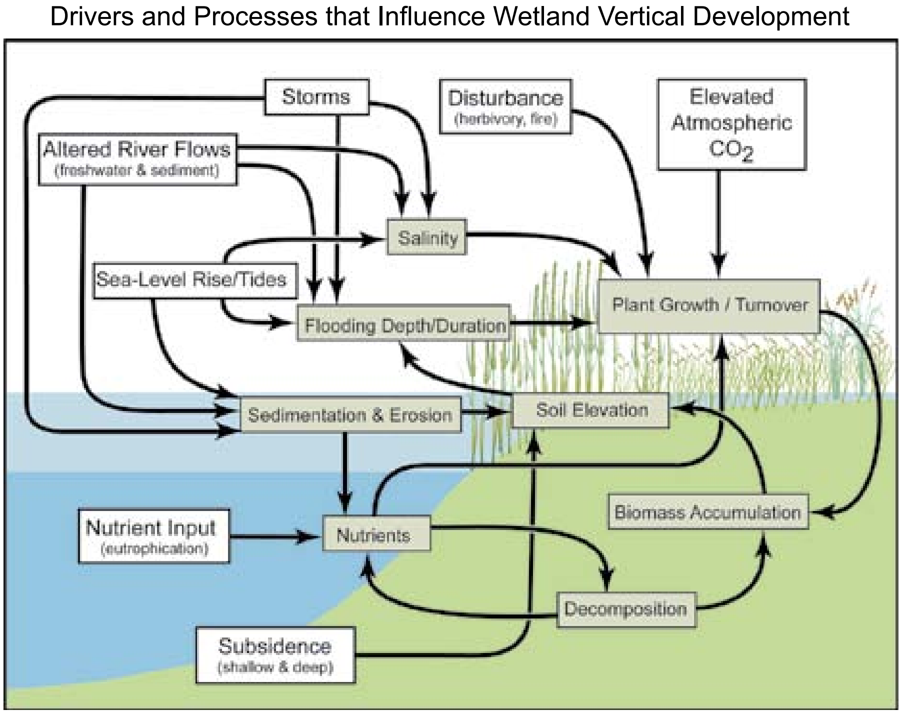
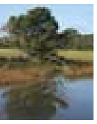


Figure 4.2 A conceptual diagram illustrating how environmental drivers (white boxes) and accretionary processes (grey boxes) influence vertical wetland development.

Table 4.1 Wetland Types and Their Characteristics as They Are Distributed Within Geomorphic Settings in the Continental United States.

Geomorphic setting	Description	Sub-settings	Dominant accretion processes	Example site	Dominant vegetation
Open Coast	Areas sheltered from waves and currents due to coastal topography or bathymetry		Storm sedimentation Peat accumulation	Appalachee Bay, Florida	smooth cordgrass *(Spartina alterniflora)* black needlerush *(Juncus roemerianus)* spike grass *(Distichlis spicata)* salt hay (*Spartina patens*) glasswort (*Salicornia spp.*) saltwort (*Batis maritima*)
Back-Barrier Lagoon Marsh (BB)	Occupies fill within transgressive back-barrier lagoons	Back-barrier Active flood tide delta Lagoonal fill	Storm sedimentation (including barrier overwash) Peat accumulation Oceanic inputs via inlets	Great South Bay, New York; Chincoteague Bay, Maryland, Virginia	smooth cordgrass (*Spartina alterniflora*) black needlerush (*Juncus roemerianus*) spike grass (*Distichlis spicata*) salt hay (*Spartina patens*) glasswort (*Salicornia spp.*) saltwort (*Batis maritima*)
Estuarine Embayment	Shallow coastal embayments with some river discharge, frequently drowned river valleys			Chesapeake Bay, Maryland, Virginia; Delaware Bay, New Jersey, Pennsylvania, Delaware	
Estuarine Embayment **a. Saline Fringe Marsh (SF)**	Transgressive marshes bordering uplands at the lower end of estuaries (can also be found in back-barrier lagoons)		Storm sedimentation Peat accumulation	Peconic Bay, New York; Western Pamlico Sound, North Carolina	smooth cordgrass (*Spartina alterniflora*) black needlerush (*Juncus roemerianus*) spike grass (*Distichlis spicata*) salt hay (*Spartina patens*) glasswort (*Salicornia spp.*) saltwort (*Batis maritima*)
Estuarine Embayment **b. Stream Channel Wetlands**	Occupy estuarine/ alluvial channels rather than open coast			Dennis Creek, New Jersey; Lower Nanticoke River, Maryland	
Estuarine Brackish Marshes (ES)	Located in vicinity of turbidity maxima zone	Meander Fringing Island	Alluvial and tidal inputs Peat accumulation	Lower James River, Virginia; Lower Nanticoke River, Maryland; Neuse River Estuary, North Carolina	smooth cordgrass (*Spartina alterniflora*) salt hay (*Spartina patens*) spike grass (*Distichlis spicata*) black grass (*Juncus gerardi*) black needlerush (*Juncus roemerianus*) sedges (*Scirpus olneyi*) cattails (*Typha spp.*) big cordgrass (*Spartina cynosuroides*) pickerelweed (*Pontederis cordata*)



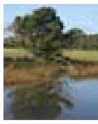
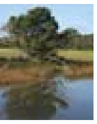


Table 4.1 ***Continued***

Geomorphic setting	Description	Sub-settings	Dominant accretion processes	Example site	Dominant vegetation
Tidal Fresh Marsh (FM)	Located above turbidity maxima zone; develop in drowned river valleys as filled with sediment		Alluvial and tidal inputs Peat accumulation	Upper Nanticoke River, Maryland; Anacostia River, Washington, D.C.	arrow arum (*Peltandra virginica*) pickerelweed (*Pontederis cordata*) arrowhead (*Sagitarria spp.*) bur-marigold (*Bidens laevis*) halberdleaf tearthumb (*Polygonum arifolium*) scarlet rose-mallow (*Hibiscus coccineus*) wild-rice (Zizannia aquatica) cattails (*Typha spp.*) giant cut grass (*Zizaniopsis miliacea*) big cordgrass (*Spartina cynosuroides*)
Tidal Fresh Forests (FF)	Develop in riparian zone along rivers and backwater areas beyond direct influence of seawater	Deepwater Swamps (permanently flooded) Bottomland Hardwood Forests (seasonally flooded) Alluvial input Peat accumulation	Alluvial input Peat accumulation	Upper Raritan Bay, New Jersey; Upper Hudson River, New York	bald cypress (*Taxodium distichum*) blackgum (*Nyssa sylvatica*) oak (*Quercus spp.*) green ash (*Fraxinus pennsylvanica*) (*var. lanceolata*)
Nontidal Brackish Marsh	Transgressive marshes bordering uplands in estuaries with restricted tidal signal		Alluvial input Peat accumulation	Pamlico Sound, North Carolina	black needlerush (*Juncus roemerianus*) smooth cordgrass (*Spartina alterniflora*) spike grass (*Distichlis spicata*) salt hay (*Spartina patens*) big cordgrass (*Spartina cynosuroides*)
Nontidal Forests	Develop in riparian zone along rivers and backwater areas beyond direct influence of seawater in estuaries with restricted tidal signal	Bottomland Hardwood Forests (seasonally flooded)	Alluvial input Peat accumulation	Roanoke River, North Carolina; Albemarle Sound, North Carolina	bald cypress (*Taxodium distichum*) blackgum (*Nyssa sylvatica*) oak (*Quercus spp.*) Green ash (*Fraxinus pennsylvanica*)
Delta	Develop on riverine sediments in shallow open water during active deposition; reworked by marine processes after abandonment		Alluvial input Peat accumulation Compaction/ Subsidence Storm sedimentation Marine Processes	Mississippi Delta, Louisiana	smooth cordgrass (*Spartina alterniflora*) black needlerush (*Juncus roemerianus*) spike grass (*Distichlis spicata*) salt hay (*Spartina patens*) glasswort (*Salicornia spp.*) saltwort (*Batis maritima*) maidencane (*Panicum haemitomon*) arrowhead (*Sagitarria spp.*)

processes, and wetland elevation interact. Tidal wetlands build vertically through the accumulation of mineral sediments and plant organic matter (primarily plant roots). The suite of processes shown in Figure 4.2 controls the rates of mineral sediment deposition and accumulation of plant organic matter in the soil, and ultimately elevation change. Overall mineral sedimentation represents the balance between sediment import and export, which is influenced by sediment supply and the relative abundance of various particle sizes, and varies among geomorphic settings and different tidal and wave energy regimes. Sediment deposition occurs when the surface of a tidal wetland is flooded. Thus, flooding depth and duration are important controls on deposition. The source of sediment may be supplied from within the local estuary (Reed, 1989), and by transport from riverine and oceanic sources. Sediments are remobilized by storms, tides, and, in higher latitudes, ice rafting.



The formation of organic-rich wetland soils is an important contributor to elevation in both mineral sediment rich and mineral sediment poor wetlands (see review by Nyman *et al.*, 2006). Organic matter accumulation represents the balance between plant production (especially by roots and rhizomes) and decomposition and export of plant organic matter (Figure 4.2). Accumulation comes from root and rhizome growth, which contributes mass, volume, and structure to the sediments. The relative importance of mineral and organic matter accumulation can vary depending on local factors such as rates of subsidence and salinity regimes.

4.3.2 Influence of Climate Change on Wetland Vertical Development

Projections of wetland sustainability are further complicated by the fact that sea-level rise is not the only factor influencing accretionary dynamics and sustainability (Figure 4.1). The influence of sea-level rise and other human- and climate-related environmental drivers on mineral sediment delivery systems is complex. For example, the timing and amount of river flows are altered by changes in discharge related to both the effects of dams and impervious surfaces built by humans and to changes in precipitation patterns from changing climate. This results in a change in the balance of forces between river discharge and the tides that control the physical processes of water circulation and mixing, which in turn determines the fate of sediment within an estuary. Where river discharge dominates, highly stratified estuaries prevail, and where tidal motion dominates, well-mixed estuaries tend to develop (Dyer, 1995). Many mid-Atlantic estuaries are partially mixed systems because the influence of river discharge and tides are more balanced.

River discharge is affected by interannual and interseasonal variations and intensities of precipitation and evapotranspiration patterns, and by alterations in land use (*e.g.*, impervious surfaces and land cover types) and control over river flows (*e.g.*, impoundments and withdrawals). Sea-level rise can further change the balance between river discharge and tides by its effect on tidal range (Dyer, 1995). An increase in tidal range would increase tidal velocities and, consequently, tidal mixing and sediment transport, as well as extend the reach of the tide landward. In addition, sea-level rise can affect the degree of tidal asymmetry in an estuary (*i.e.*, ebb *versus* flood dominance). In flood dominant estuaries, marine sediments are more likely to be imported to the estuary. However, an increase in sea level without a change in tidal range may cause a shift toward ebb dominance, thereby reducing the input of marine sediments that might otherwise be deposited on intertidal flats and marshes (Dyer, 1995). Estuaries with relatively small intertidal areas and small tidal amplitudes would be particularly susceptible to such changes. The current hydrodynamic status of estuaries today is the result of thousands of years of interaction between rising sea level and coastal landforms.

The degree of influence of sea-level rise on wetland flooding, sedimentation, erosion, and salinity is directly linked with the influence of altered river flows and storm impacts (Figure 4.2). Changes in freshwater inputs to the coast can affect coastal wetland community structure and function (Sklar and Browder, 1998) through fluctuations in the salt balance up and down the estuary. Low-salinity and freshwater wetlands are particularly affected by increases in salinity. In addition, the location of the turbidity maximum zone (the region in many estuaries where suspended sediment concentrations are higher than in either the river or sea) can shift seaward with increases in river discharge, and the size of this zone will increase with increasing tidal ranges (Dyer, 1995). Heavy rains (freshwater) and tidal surges (salty water) from storms occur over shorter time periods than interannual and interseasonal variation. This can exacerbate or alleviate (at least temporarily) salinity and inundation effects of altered freshwater input and sea-level rise in all wetland types. The direction of elevation change depends on the storm characteristics, wetland type, and local conditions at the area of storm landfall (Cahoon, 2006). Predicted increases in the magnitude of coastal storms from higher sea surface temperatures (Webster *et al.*, 2005) will likely increase storm-induced wetland sedimentation in the mid-Atlantic regional wetlands. Increased storm intensity could increase the resuspension of nearshore sediments and the storm-related import of oceanic sediments into tidal marshes.

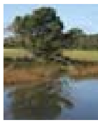
In addition to sediment supplies, accumulation of plant organic matter is a primary process controlling wetland vertical development of soil. The production of organic matter is influenced by factors associated with climate change, including increases in atmospheric carbon dioxide concentrations, rising temperatures, more frequent and extensive droughts, higher nutrient loading from floodwaters and ground waters, and increases in salinity of flood waters. Therefore, a critical question that scientists must address is: "How will these potential changes in plant growth affect wetland elevations and the capacity of the marsh to keep pace with sea-level rise?" Some sites depend primarily on plant matter accumulation to build vertically. For example, in many brackish marshes dominated by salt hay (*Spartina patens*) (McCaffrey and Thomson, 1980) and mangroves on oceanic islands with low mineral sediment inputs (McKee *et al*., 2007), changes in root production (Cahoon *et al*., 2003, 2006) and nutrient additions (McKee *et al*., 2007) can significantly change root growth and wetland elevation trajectories. These changes and their interactions warrant further study.

4.4 HORIZONTAL MIGRATION

Wetland vertical development can lead to horizontal expansion of wetland area (both landward and seaward; Redfield, 1972), depending on factors such as slope, sediment supply, shoreline erosion rate, and rate of sea-level rise. As marshes build vertically, they can migrate inland onto dry uplands, given that the slope is not too steep and there is no human-made barrier to migration (Figure 4.1). Some of the best examples of submerged upland types of wetlands in the mid-Atlantic region are found on the Eastern Shore of Chesapeake Bay, a drowned river valley estuary (Darmody and Foss, 1979). Given a setting with a low gradient slope, low wave energy, and high sediment supply (*e.g*., Barnstable Marsh on Cape Cod, Massachusetts), a marsh can migrate both inland onto uplands and seaward onto sand flats as the shallow lagoon fills with sediment (Redfield, 1972). Most coasts, however, have enough wave energy to prevent seaward expansion of the wetlands. The more common alternative is erosion of the seaward boundary of the marsh and retreat. In these settings, as long as wetland vertical development keeps pace with sea-level rise, wetland area will expand where inland migration is greater than erosion of the seaward boundary, remain unchanged where inland migration and erosion of the seaward boundary are equal, or decline where erosion of the seaward boundary is greater than inland migration (*e.g*., Brinson *et al*., 1995). If wetland vertical development lags behind sea-level rise (*i.e*., wetlands do not keep pace), the wetlands will eventually become submerged and deteriorate even as they migrate, resulting in an overall loss of wetland area, as is occurring at Blackwater National Wildlife Refuge in Dorchester County, Maryland (Stevenson *et al*., 1985). Thus, wetland migration is dependent on vertical accretion, which is the key process for both wetland survival and expansion. If there is a physical obstruction preventing inland wetland migration, such as a road or a bulkhead, and the marsh is keeping pace with sea-level rise, then the marsh will not expand but will survive in place as long as there is no lateral erosion at its seaward edge. Otherwise, the wetland will become narrower as waves erode the shoreline. Thus, having space available with a low gradient slope for inland expansion is critical for maintaining wetland area in a setting where seaward erosion of the marsh occurs.

4.5 VULNERABILITY OF WETLANDS TO TWENTIETH CENTURY SEA-LEVEL RISE

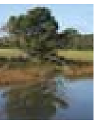
A recent evaluation of accretion and elevation trends from 49 salt marshes located around the world, including sites from the Atlantic, Gulf of Mexico, and Pacific coasts of the United States, provides insights into the mechanisms and variability of wetland responses to twentieth century trends of local sea-level rise (Cahoon *et al*., 2006). Globally, average wetland surface accretion rates were greater than and positively related to local relative sea-level rise, suggesting that the marsh surface level was being maintained by surface accretion within the tidal range as sea level rose. In contrast, average rates of elevation rise were not significantly related to sea-level rise and were significantly lower than average surface accretion rates, indicating that shallow soil subsidence occurs at many sites. Regardless, elevation changes at many sites were greater than local sea-level rise (Cahoon *et al*., 2006). Hence, understanding elevation change, in addition to surface accretion, is important when determining wetland sustainability. Secondly, accretionary dynamics differed strongly among geomorphic settings, with deltas and embayments exhibiting high accretion and high shallow subsidence compared to back-barrier and estuarine settings (see Cahoon *et al*., 2006). Thirdly, strong regional differences in accretion dynamics were observed for the North American salt marshes evaluated, with northeastern U.S. marshes exhibiting high rates of both accretion and elevation change, southeastern Atlantic and Gulf of Mexico salt marshes exhibiting high rates of accretion and low rates of elevation change, and Pacific salt marshes exhibiting low rates of both accretion and elevation change (see Cahoon *et al*., 2006). The marshes with low elevation change rates are likely vulnerable to current and future sea-level rise, with the exception of those in areas where the land surface is rising, such as on the Pacific Northwest coast of the United States.



4.5.1 Sudden Marsh Dieback

An increasing number of reports available online (see *e.g*., <http://wetlands.neers.org/>, <www.inlandbays.org>, <www.brownmarsh.com>, <www.lacoast.gov/watermarks/2004-04/3crms/index.htm>) of widespread "sudden marsh dieback" and "brown marsh dieback" from Maine to Louisiana, along with published studies documenting losses of marshes dominated by saltmarsh cordgrass

(*Spartina alterniflora*) and other halophytes (plants that naturally grow in salty soils), suggest that a wide variety of marshes may be approaching or have actually gone beyond their tipping point where they can continue to accrete enough inorganic material to survive (Delaune *et al*., 1983; Stevenson *et al*., 1985; Kearney *et al*., 1988, 1994; Mendelssohn and McKee, 1988; Hartig *et al*., 2002; McKee *et al*., 2004; Turner *et al*., 2004). Sudden dieback was documented over 40 years ago by marsh ecologists (Goodman and Williams, 1961). However, it is not known whether all recently identified events are the same phenomenon and caused by the same factors. There are biotic factors, in addition to insufficient accretion, that have been suggested to contribute to sudden marsh dieback, including fungal diseases and overgrazing by animals such as waterfowl, nutria, and snails. Interacting factors may cause marshes to decline even more rapidly than scientists would predict from one driver, such as sea-level rise. There are few details about the onset of sudden dieback because most studies are done after it has already occurred (Ogburn and Alber, 2006). Thus, more research is needed to understand sudden marsh dieback. The apparent increased frequency of this phenomenon over the last several years suggests an additional risk factor for marsh survival over the next century (Stevenson and Kearney, in press).



4.6 PREDICTING FUTURE WETLAND SUSTAINABILITY

Projections of future wetland sustainability on regional-to national-scales are constrained by the limitations of the two modeling approaches used to evaluate the relationship between future sea-level rise and coastal wetland elevation: landscape-scale models and site-specific models. Large-scale landscape models, such as the Sea Level Affecting Marshes Model (SLAMM) (Park *et al*., 1989), simulate general trends over large areas, but typically at a very coarse resolution. These landscape models do not mechanistically simulate the processes that contribute to wetland elevation; the processes are input as forcing functions and are not simulated within the model. Thus, this modeling approach does not account for infrequent events that influence wetland vertical development, such as storms and floods, or for frequent elevation feedback mechanisms affecting processes (for example, elevation change alters flooding patterns that in turn affect sediment deposition, decomposition, and plant production). In addition, these models are not suitable for site-specific research and management problems because scaling down of results to the local level is not feasible. Therefore, although landscape models can simulate wetland sustainability on broad spatial scales, their coarse resolution limits their accuracy and usefulness to the local manager.

On the other hand, process oriented site-specific models (*e.g.*, Morris *et al*., 2002; Rybczyk and Cahoon, 2002) are more mechanistic than landscape models and are used to simulate responses for a specific site with a narrow range of conditions and settings. These site-specific models can account for accretion events that occur infrequently, such as hurricanes and major river floods, and the feedback effects of elevation on inundation and sedimentation that influence accretionary processes over timeframes of a century. The use of site-specific conditions in a model makes it possible to predict long-term sustainability of an individual wetland in a particular geomorphic setting. However, like the landscape models, site-specific models also have a scaling problem. Using results from an individual site to make long-term projections at larger spatial scales is problematic because accretionary and process data are not available for the variety of geomorphic settings across these larger-scale landscapes for calibrating and verifying models. Thus, although site-specific models provide high resolution simulations for a local site, at the present time future coastal wetland response to sea-level rise over large areas can be predicted with only low confidence.

Recently, two different modeling approaches have been used to provide regional scale assessments of wetland response to climate change. In a hierarchical approach, detailed site-specific models were parameterized with long-term data to generalize landscape-level trends with moderate confidence for inland wetland sites in the Prairie Pothole Region of the Upper Midwest of the United States (Carroll *et al*., 2005; Voldseth *et al*., 2007; Johnson *et al*., 2005). The utility of this approach for coastal wetlands has not yet been evaluated. Alternatively, an approach was used to assess coastal wetland vulnerability at regional-to-global scales from three broad environmental drivers: (1) ratio of relative sea-level rise to tidal range, (2) sediment supply, and (3) lateral accommodation space (*i.e.*, barriers to wetland migration) (McFadden *et al*., 2007). This model suggests that, from 2000 to 2080, there will be global wetland area losses of 33 percent for a 36 centimeter (cm) rise in sea level and 44 percent for a 72 cm rise; and that regionally, losses on the Atlantic and Gulf of Mexico coasts of the United States will be among the most severe (Nicholls *et al*., 2007). However, this model, called the Wetland Change Model, remains to be validated and faces similar challenges when downscaling, as does the previously described model when scaling up.

Taking into account the limitations of current predictive modeling approaches, the following assessments can be made about future wetland sustainability at the national scale:

- It is *virtually certain* that tidal wetlands already experiencing submergence by sea-level rise and associated high rates of loss (*e.g.*, Mississippi River Delta in Louisiana, Blackwater National Wildlife Refuge marshes in Maryland) will continue to lose area under the influence of future accelerated rates of sea-level rise and changes in other climate and environmental drivers.

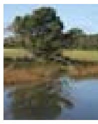
- It is *very unlikely* that there will be an overall increase in tidal wetland area on a national scale over the next 100 years, given current wetland loss rates and the relatively minor accounts of new tidal wetland development (*e.g.*, Atchafalaya Delta in Louisiana).
- Current model projections of wetland vulnerability on regional and national scales are uncertain because of the coarse level of resolution of landscape-scale models. In contrast, site-specific model projections are quite good where local information has been acquired on factors that control local accretionary processes in specific wetland settings. However, the authors have low confidence that site-specific model simulations, as currently portrayed, can be successfully scaled up to provide realistic projections at regional or national scales.

The following information is needed to improve the confidence in projections of future coastal wetland sustainability on regional and continental scales:

- *Models and validation data*. To scale up site-specific model outputs to regional and continental scales with high confidence, detailed data are needed on the various local drivers and processes controlling wetland elevation across all tidal geomorphic settings of the United States. Obtaining and evaluating the necessary data will be an enormous and expensive task, but not an impractical one. It will require substantial coordination with various private and government organizations in order to develop a large, searchable database. Until this type of database becomes a reality, current modeling approaches need to improve or adapt such that they can be applied across a broad spatial scale with better confidence. For example, evaluating the utility of applying the multi-tiered modeling approach used in the Prairie Pothole Region to coastal wetland systems and validating the broad scale Wetland Change Model for North American coastal wetlands will be important first steps. Scientists' ability to predict coastal wetland sustainability will improve as specific ecological and geological processes controlling accretion and their interactions on local and regional scales are better understood.
- *Expert opinion*. Although models driven by empirical data are preferable, given the modeling limitations described, an expert opinion (*i.e.*, subjective) approach can be used to develop spatially explicit landscape-scale predictions of coastal wetland responses to future sea-level rise with a low-to-moderate level of confidence. This approach requires convening a group of scientists with expert knowledge of coastal wetland geomorphic processes, with conclusions based on an understanding of the processes driving marsh survival during sea-level rise and of how the magnitude and nature of these processes might change due to the effects of climate change and other factors. Because of the enormous complexity of these issues at the continental scale, the expert opinion approach would be applied with greater confidence at the regional scale. Two case studies are presented in Sections 4.6.1 and 4.6.2; the first, using the expert opinion approach applied to the mid-Atlantic region from New York to Virginia, the second, using a description of North Carolina wetlands from the Albemarle–Pamlico Region and an evaluation of their potential response to sea-level rise, based on a review of the literature.

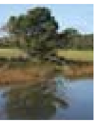
4.6.1 Case Study: Mid-Atlantic Regional Assessment, New York to Virginia

A panel of scientists with diverse and expert knowledge of wetland accretionary processes was convened to develop spatially explicit landscape-scale predictions of coastal wetland response to the three scenarios of sea-level rise assessed in this Product (see Chapter 1) for the mid-Atlantic region from New York to Virginia (see Box 4.1). The results of the panel's effort (Reed *et al*., 2008) inform this Product assessment of coastal elevations and sea-level rise.



BOX 4.1: The Wetland Assessment Process Used by a Panel of Scientists

As described in this Product, scientific consensus regarding regional-scale coastal changes in response to sea-level rise is currently lacking. To address the issue of future changes to mid-Atlantic coastal wetlands, Denise Reed, a wetlands specialist at the University of New Orleans, was contracted by the U.S. EPA to assemble a panel of coastal wetland scientists to evaluate the potential outcomes of the sea-level rise scenarios used in this Product. Denise Reed chose the eight members of this panel on the basis of their technical expertise and experience in the coastal wetland research community, particularly with coastal wetland geomorphic processes, and also their involvement with coastal management issues in the mid-Atlantic region. The panel was charged to address the question, "To what extent can wetlands vertically accrete and thus keep pace with rising sea level, that is, will sea-level rise cause the area of wetlands to increase or decrease?"



The sea-level rise impact assessment effort was conducted as an open discussion facilitated by Denise Reed over a two-day period. Deliberations were designed to ensure that conclusions were based on an understanding of the processes driving marsh survival as sea level rises and how the magnitude and nature of these processes might change in the future in response to climate change and other factors. To ensure a systematic approach across regions within the mid-Atlantic region, the panel:

1. Identified a range of geomorphic settings to assist in distinguishing among the different process regimes controlling coastal wetland accretion (see Figure 4.3 and Table 4.1);
2. Identified a suite of processes that contribute to marsh accretion (see Table 4.1) and outlined potential future changes in current process regimes caused by climate change;
3. Divided the mid-Atlantic into a series of regions based on similarity of process regime and current sea-level rise rates; and
4. Delineated geomorphic settings within each region on 1:250,000 scale maps, and agreed upon the fate of the wetlands within these settings under the three sea-level rise scenarios, with three potential outcomes: keeping pace, marginal, and loss (see Figure 4.4).

The qualitative, consensus-based assessment of potential changes and their likelihood developed by the panel is based on their review and understanding of published coastal science literature (*e.g.*, 88 published rates of wetland accretion from the mid-Atlantic region, and sea-level rise rates based on NOAA tide gauge data), as well as field observations drawn from other studies conducted in the mid-Atlantic region. A report by Reed *et al.* (2008) summarizing the process used, basis in the published literature, and a synthesis of the resulting assessment was produced and approved by all members of the panel.

The report was peer reviewed by external subject-matter experts in accordance with U.S. EPA peer review policies. Reviewers were asked to examine locality-specific maps for localities with which they were familiar, and the documentation for how the maps were created. They were then asked to evaluate the assumptions and accuracy of the maps, and errors or omissions in the text. The comments of all reviewers were carefully considered and incorporated, wherever possible, throughout the report. The final report was published and made available online in February 2008 as a U.S. Environmental Protection Agency report:

<http://epa.gov/climatechange/effects/downloads/section2_1.pdf>

4.6.1.1 Panel Assessment Methods

The general approach used by the panel is summarized in Box 4.1. The panel recognized that accretionary processes differ among settings and that these processes will change in magnitude and direction with future climate change. For example, it is expected that the magnitude of coastal storms will increase as sea surface temperatures increase (Webster *et al*., 2005), likely resulting in an increase in storm sedimentation and oceanic sediment inputs. Also, the importance of peat accumulation to vertical accretion in freshwater systems (Neubauer 2008) is expected to increase in response to sea-level rise up to a threshold capacity, beyond which peat accumulation can no longer increase. However, if salinities also increase in freshwater systems, elevation gains from increased peat accumulation could be offset by increased decomposition from sulfate reduction. Enhanced microbial breakdown of organic-rich soils is likely to be most important in formerly fresh and brackish environments where the availability of sulfate, and not organic matter, generally limits sulfate-reduction rates (Goldhaber and Kaplan, 1974). Increases in air and soil temperatures are expected to diminish the importance of ice effects. Changes in precipitation and human land-use patterns will alter fluvial sediment inputs.

The fate of mid-Atlantic wetlands for the three sea-level rise scenarios evaluated in this Product was determined by the panel through a consensus opinion after all information was considered (see Figure 4.4). The wetlands were classified as keeping pace, marginal, or loss (Reed *et al.*, 2008):

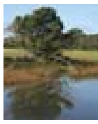
1. *Keeping pace*: Wetlands will not be submerged by rising sea levels and will be able to maintain their relative elevation.

2. *Marginal*: Wetlands will be able to maintain their elevation only under optimal conditions. Depending on the dominant accretionary processes, this could include inputs of sediments from storms or floods, or the maintenance of hydrologic conditions conducive for optimal plant growth. Given the complexity and inherent variability of climatic and other factors influencing wetland accretion, the panel cannot predict the fate of these wetlands. Under optimal conditions they are expected to survive.

3. *Loss*: Wetlands will be subject to increased flooding beyond that normally tolerated by vegetative communities, leading to deterioration and conversion to open water habitat.

The panel recognized that wetlands identified as marginal or loss will become so at an uneven rate and that the rate and spatial distribution of change will vary within and among similarly designated areas. The panel further recognized that wetland response to sea-level rise over the next century will depend upon the rate of sea-level rise, existing wetland condition (*e.g.*, elevation relative to sea level), and local controls of accretion processes. In addition, changes in flooding and salinity patterns may result in a change of dominant species (*i.e.*, less flood-tolerant high marsh species replaced by more flood-tolerant low marsh species), which could affect wetland sediment trapping and organic matter accumulation rates. A wetland is considered marginal when it becomes severely degraded (greater than 50 percent of vegetated area is converted to open water) but still supports ecosystem functions associated with that wetland type. A wetland is considered lost when its function shifts primarily to that of shallow open water habitat.

There are several caveats to the expert panel approach, interpretations, and application of findings. First, regional-scale assessments are intended to provide a landscape-scale projection of wetland vulnerability to sea-level rise (*e.g.*, likely trends, areas of major vulnerability) and not to replace assessments based on local process data. The authors recognize that local exceptions to the panel's regional scale assessment likely exist for some specific sites where detailed accretionary data are available. Second, the panel's projections of back-barrier wetland sustainability assume



Mid-Atlantic Wetland Geomorphic Settings

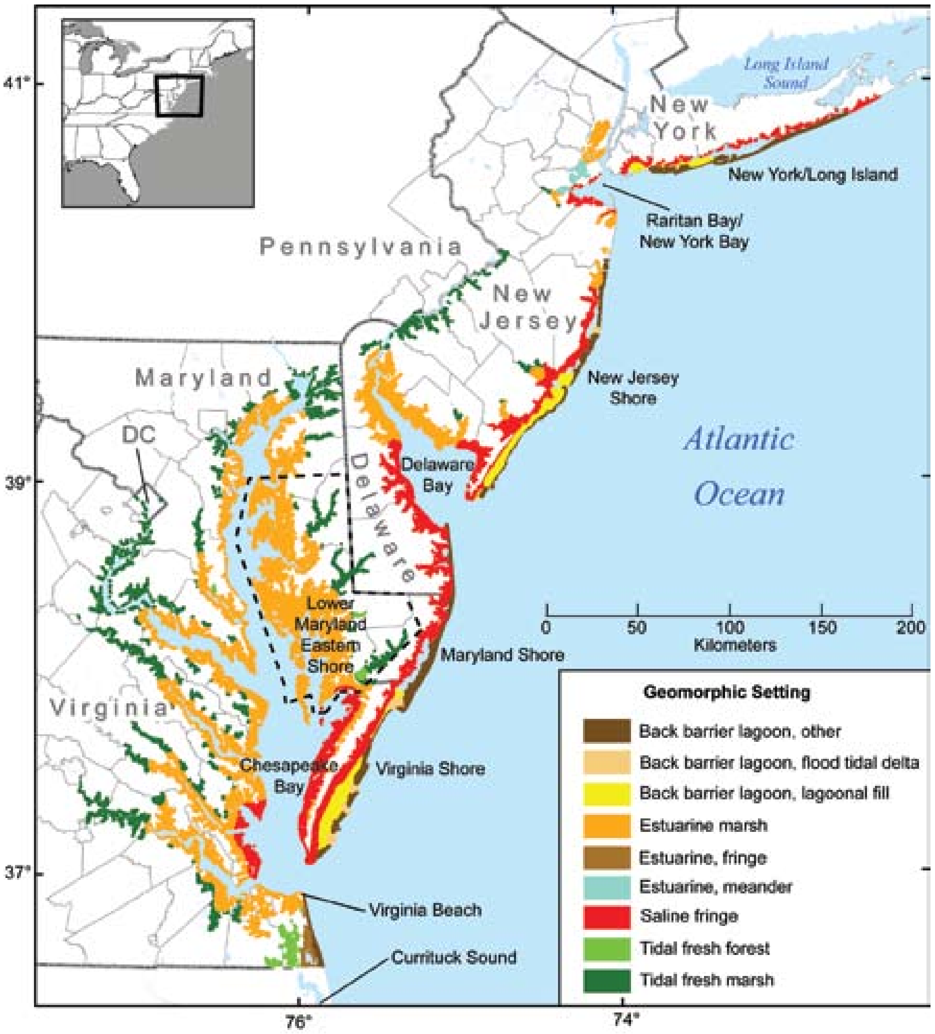
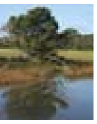


Figure 4.3 Geomorphic settings of mid-Atlantic tidal wetlands (data source: Reed *et al.*, 2008; map source: Titus *et al.*, 2008).

Table 4.2 The Range of Wetland Responses to Three Sea-Level Rise Scenarios (twentieth century rate, twentieth century rate plus 2 mm per year, and twentieth century plus 7 mm per year) Within and Among Geomorphic Settings and Subregions of the Mid-Atlantic Region from New York to Virginia.

	Region																							
Geo-morphic setting	**Long Island, New York**			**Raritan Bay, New York**			**New Jersey**			**Delaware Bay**			**Maryland - Virginia**			**Chesapeake Bay**			**Lower Maryland Eastern Shore**			**Virginia Beach - Currituck Sound**		
	slr	+2	+7	**slr**	+2	+7	**slr**	+2	+7	**slr**	+2	+7	**slr**	+2	+7	**slr**	+2	+7	slr	+2	+7	slr	+2	+7
Back-barrier lagoon, other	K	K,M	K,L				K	M	L				K	M	L							M	M-L	L
Back-barrier lagoon, flood tide delta	K	K	M				K	M	L				K	M	L									
Back-barrier lagoon, lagoonal fill	K,L	K,M, L	K,L				K	M	L				K	M	L									
Estuarine marsh				K	M	L	K	M	L	K,M	M,L	L				K,M, L	M-L	L	L,M	L	L	K	M	L
Estuarine fringe				K	M	L	K	M	L													M	M-L	L
Estuarine meander				K	M	L	K	M	L															
Saline fringe	K	K,L	M	K	M	L	K,L	M,L	L	K	M	L	K,L	M,L	L									
Tidal fresh forest																			K	K	K	M	M-L	
Tidal fresh marsh				K	K	K	K	M	L	K	K	K				K	K	K	K	K	K	K	K	K

K = keeping pace; M = marginal; L = loss; multiple letters under a single sea-level rise scenario (e.g., K,M or K,M,L) indicate more than one response for that geomorphic setting; M-L indicates that the wetland would be either marginal or lost.



that protective barrier islands retain their integrity. Should barrier islands collapse (see Section 3.7.3), the lagoonal marshes would be exposed to an increased wave energy environment and erosive processes, with massive marsh loss likely over a relatively short period of time. (In such a case, vulnerability to marsh loss would be only one of a host of environmental problems.) Third, the regional projections of wetland sustainability assume that the health of marsh vegetation is not adversely affected by local outbreaks of disease or other biotic factors (*e.g.*, sudden marsh dieback). Fourth, the panel considered the effects of a rate acceleration above current of 2 mm per year (Scenario 2) and 7 mm per year (Scenario 3), but not rates in between. Determining wetland sustainability at sea-level rise rates between Scenarios 2 and 3 requires greater understanding of the variations in the maximum accretion rate regionally and among vegetative communities (Reed *et al.*, 2008). Currently, there are few estimates of the maximum rate at which marsh vertical accretion can occur (Bricker-Urso *et al.*, 1989; Morris *et al.*, 2002) and no studies addressing the thresholds for organic matter accumulation in the marshes considered by the panel. Lastly, the panel recognized the serious limitations of scaling down their projections from the regional to local level and would place a low level of confidence on such projections in the absence of local accretionary and process data. *Thus, findings from this regional scale approach should not be used for local planning activities where local effects on accretionary dynamics may override regional controls on accretionary dynamics.*

4.6.1.2 PANEL FINDINGS

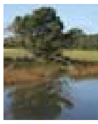
The panel developed an approach for predicting wetland response to sea-level rise that was more constrained by available studies of accretion and accretionary processes in some areas of the mid-Atlantic region (*e.g.*, Lower Maryland Eastern Shore) than in other areas (*e.g.*, Virginia Beach/ Currituck Sound). Given these inherent data and knowledge constraints, the authors classified the confidence level for all findings in Reed *et al.* (2008) as *likely* (*i.e.*, greater than 66 percent likelihood but less than 90 percent).

Figure 4.4 and Table 4.2 present the panel's consensus findings on wetland vulnerability of the mid-Atlantic region. The panel determined that a majority of tidal wetlands settings in the mid-Atlantic region (with some local exceptions) are likely keeping pace with Scenario 1, that is, continued sea-level rise at the twentieth century rate, 3 to 4 mm per year (Table 4.2, and areas depicted in brown, beige, yellow, and green in Figure 4.4) through either mineral sediment deposition, organic matter accumulation, or both. However, under this scenario, extensive areas of estuarine marsh in Delaware Bay and Chesapeake Bay are marginal (areas depicted in red in Figure 4.4), with some areas currently being converted to subtidal habitat (areas depicted in blue in Figure 4.4). It is *virtually certain* that estuarine marshes currently so converted will not be rebuilt or replaced by natural processes. Human manipulation of hydrologic and sedimentary processes and the elimination of barriers to onshore wetland migration would be required to restore and sustain these degrading marsh systems. The removal of barriers to onshore migration invariably would result in land use changes that have other societal consequences such as property loss.

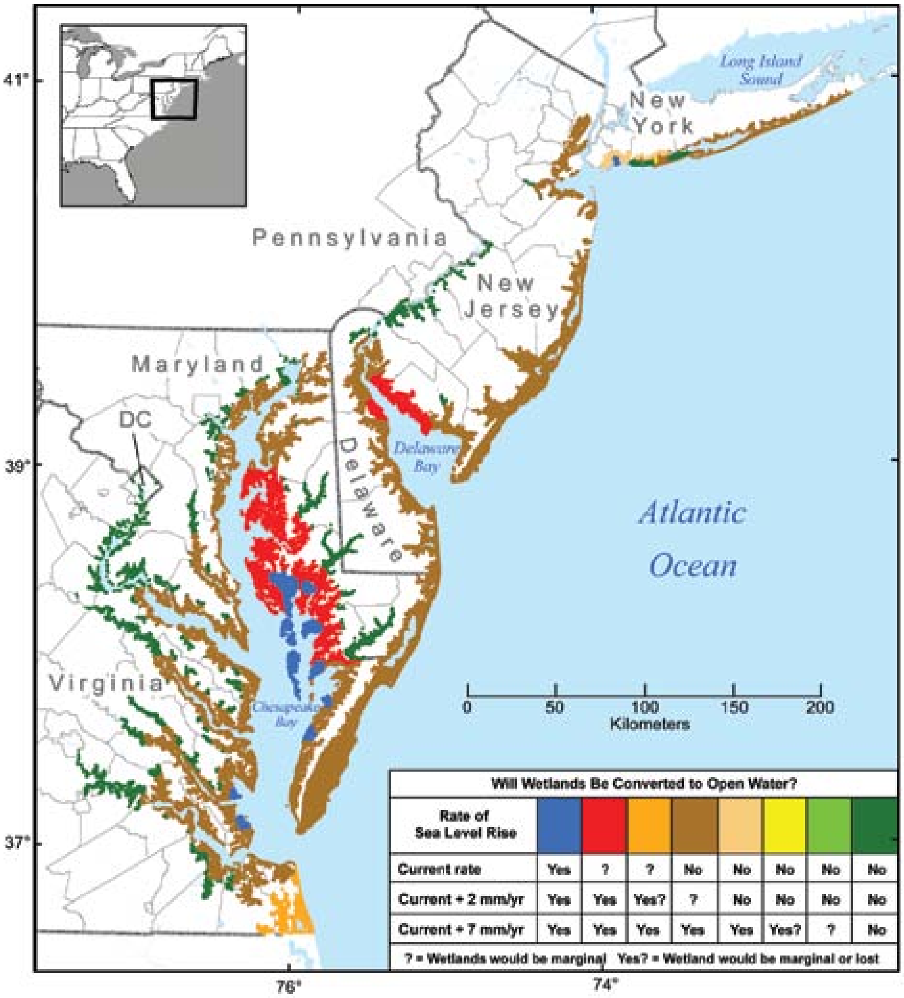
Under accelerated rates of sea-level rise (Scenarios 2 and 3), the panel agreed that wetland survival would very likely depend on optimal hydrology and sediment supply conditions. Wetlands primarily dependent on mineral sediment accumulation for maintaining elevation would be very unlikely to survive Scenario 3, (*i.e.*, at least 10 mm per year rate of sea-level rise when added to the twentieth century rate). Exceptions may occur locally where sediment inputs from inlets, overwash events, or rivers are substantial (*e.g.*, back-barrier lagoon and lagoonal fill marshes depicted in green on western Long Island, Figure 4.4).

Wetland responses to sea-level rise are typically complex. A close comparison of Figure 4.3 and Figure 4.4 reveals that marshes from all geomorphic settings, except estuarine meander (which occurs in only one subregion), responded differently to sea-level rise within and/or among subregions, underscoring why local processes and drivers must be taken into account. Given the variety of marsh responses to sea-level rise among and within subregions (Table 4.2), assessing the likelihood of survival for each wetland setting is best done by subregion, and within subregion, by geomorphic setting.

The scientific panel determined that tidal fresh marshes and forests in the upper reaches of rivers are likely to be sustainable (*i.e.*, less vulnerable to future sea-level rise than most other wetland types) (Table 4.2), because they have higher accretion rates and accumulate more organic carbon than saline marshes (Craft, 2007). Tidal fresh marshes have access to reliable and often abundant sources of mineral sediments, and their sediments typically have 20 to 50 percent organic matter content, indicating that large quantities of plant organic matter are also available. Assuming that salinities do



Potential Mid-Atlantic Wetland Survival



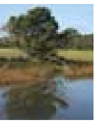
Will Wetlands Be Converted to Open Water?

Rate of Sea Level Rise	🟦	🟥	🟧	🟫	▨	🟨	🟩	🟩
Current rate	Yes	?	?	No	No	No	No	No
Current + 2 mm/yr	Yes	Yes	Yes?	?	No	No	No	No
Current + 7 mm/yr	Yes	Yes	Yes	Yes	Yes	Yes?	?	No

? = Wetlands would be marginal Yes? = Wetland would be marginal or lost

Figure 4.4 Wetland survival in response to three sea-level rise scenarios (in millimeters [mm] per year [yr]) (data source: Reed *et al.*, 2008; map source: Titus *et al.*, 2008).

not increase, a condition that may reduce soil organic matter accumulation rates, and current mineral sediment supplies are maintained, the panel considered it likely that tidal fresh marshes and forests would survive under Scenario 3. Vertical development, response to accelerated sea-level rise, and movement into newly submerged areas are rapid for tidal fresh marshes (Orson, 1996). For several tidal fresh marshes in the high sediment-load Delaware River Estuary, vertical accretion through the accumulation of both mineral and plant matter ranged from 7 mm per year to 17.4 mm per year from the 1930s to the 1980s as tidal influences became more dominant (Orson *et al.*, 1992). Exceptions to the finding that fresh marshes and forests would survive under Scenario 3 are the New Jersey shore, where tidal fresh marsh is considered marginal under Scenario 2 and lost under Scenario 3, and Virginia Beach–Currituck Sound where fresh forest is marginal under Scenario 1, marginal or lost under Scenario 2, and lost under Scenario 3.



Different marshes from the geomorphic settings back-barrier other, back-barrier lagoonal fill, estuarine marsh, and saline fringe settings responded differently to sea-level rise within at least one subregion as well as among subregions (Table 4.2). For example, back-barrier lagoonal fill marshes on Long Island, New York were classified as either keeping pace or lost at the current rate of sea-level rise. Those marshes surviving under Scenario 1 were classified as either marginal (brown) or keeping up (beige and green) under Scenario 2 (Figure 4.4). Under Scenario 3, only the lagoonal fill marshes depicted in green in Figure 4.4 are expected to survive.

The management implications of these findings are important on several levels. The expert panel approach provides a regional assessment of future wetland resource conditions, defines likely trends in wetland change, and identifies areas of major vulnerability. However, the wide variability of wetland responses to sea-level rise within and among subregions for a variety of geomorphic settings underscores not only the influence of local processes on wetland elevation but also the difficulty of scaling down predictions of wetland sustainability from the regional to the local scale in the absence of local accretion data. Most importantly for managers, regional scale assessments such as this should not be used to develop local management plans because local accretionary effects may override regional controls on wetland vertical development (McFadden *et al.*, 2007). Instead, local managers are encouraged to acquire data on the factors influencing the sustainability of their local wetland site, including environmental stressors, accretionary processes, and geomorphic settings, as a basis for developing local management plans.

4.6.2 Case Study: Albemarle–Pamlico Sound Wetlands and Sea-Level Rise

The Albemarle–Pamlico (A–P) region of North Carolina is distinct in the manner and the extent to which rising sea level is expected to affect coastal wetlands. Regional wetlands influenced by sea level are among the most extensive on the U.S. East Coast because of large regions that are less than 3 meters (m) above sea level, as well as the flatness of the underlying surface. Further, the wetlands lack astronomic tides as a source of estuarine water to wetland surfaces in most of the A–P region. Instead, wind-generated water level fluctuations in the sounds and precipitation are the principal sources of water. This “irregular flooding” is the hallmark of the hydrology of these wetlands. Both forested wetlands and marshes can be found; variations in salinity of floodwater determine ecosystem type. This is in striking contrast to most other fringe wetlands on the East Coast.

4.6.2.1 DISTRIBUTION OF WETLAND TYPES

Principal flows to Albemarle Sound are from the Chowan and Roanoke Rivers, and to Pamlico Sound from the Tar and Neuse Rivers. Hardwood forests occupy the floodplains of these major rivers. Only the lower reaches of these rivers are affected by rising sea level. Deposition of riverine sediments in the estuaries approximates the current rate of rising sea level (2 to 3 mm per year) (Benninger and Wells, 1993). These sediments generally do not reach coastal marshes, in part because they are deposited in subtidal areas and in part because astronomical tides are lacking to carry them to wetland surfaces. Storms, which generate high water levels (especially nor’easters and tropical cyclones), deposit sediments on shoreline storm levees and to a lesser extent onto the surfaces of marshes and wetland forests. Blackwater streams that drain pocosins (peaty, evergreen shrub and forested wetlands), as well as other tributaries that drain the coastal plain, are a minor supply of suspended sediment to the estuaries.

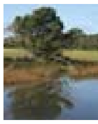
Most wetlands in the A–P region were formed upon Pleistocene sediments deposited during multiple high stands of sea level. Inter-stream divides, typified by the Albemarle–Pamlico Peninsula, are flat and poorly drained, resulting in extensive developments of pocosin swamp forest habitats. The original accumulation of peat was not due to rising sea level but to poor drainage and climatic controls. Basal peat ages of even the deepest deposits correspond to the last glacial period when sea level was over 100 m below its current position. Rising sea level has now intercepted some of these peatlands, particularly those at lower elevations on the extreme eastern end of the A–P Peninsula. As a result, eroding peat shorelines are extensive, with large volumes of peat occurring below sea level (Riggs and Ames, 2003).

Large areas of nontidal marshes and forested wetlands in this area are exposed to the influence of sea level. They can be classified as fringe wetlands because they occur along the periphery of estuaries that flood them irregularly. Salinity, however, is the major control that determines the dominant vegetation type. In the fresh-to-oligohaline (slightly brackish) Albemarle Sound region, forested and shrub-scrub wetlands dominate. As the shoreline erodes into the forested wetlands, bald cypress trees become stranded in the permanently flooded zone and eventually die and fall down. This creates a zone of complex habitat structure of fallen trees and relic cypress knees in shallow water. Landward, a storm levee of coarse sand borders the swamp forest in areas exposed to waves (Riggs and Ames, 2003).

Trees are killed by exposure to extended periods of salinity above approximately one-quarter to one-third sea water, and most trees and shrubs have restricted growth and reproduction at much lower salinities (Conner *et al.*, 1997). In brackish water areas, marshes consisting of halophytes replace forested wetlands. Marshes are largely absent from the shore of Albemarle Sound and mouths of the Tar and Neuse Rivers where salinities are too low to affect vegetation. In Pamlico Sound, however, large areas consist of brackish marshes with few tidal creeks. Small tributaries of the Neuse and Pamlico River estuaries grade from brackish marsh at estuary mouths to forested wetlands in oligohaline regions further upstream (Brinson *et al.*, 1985).

4.6.2.2 Future Sea-Level Rise Scenarios

Three scenarios were used to frame projections of the effects of rising sea level over the next few decades in the North Carolina non-tidal coastal wetlands. The first is a non-drowning scenario that assumes rising sea level will maintain its twentieth century, constant rate of 2 to 4 mm per year (Scenario 1). Predictions in this case can be inferred from wetland response to sea-level changes in the recent past (Spaur and Snyder, 1999; Horton *et al.*, 2006). Accelerated rates of sea-level rise (Scenarios 2 and 3), however, may lead to a drowning scenario. This is more realistic if IPCC predictions and other climate change models prove to be correct (Church and White, 2006), and the Scenario 1 rates double or triple. An additional scenario possible in North Carolina involves the collapse of barrier islands, as hypothesized by Riggs and Ames (2003). This scenario is more daunting because it anticipates a shift from the current non-tidal regime to one in which tides would be present to initiate currents capable of transporting sediments without the need of storms and frequently possibly flooding wetland surfaces now only flooded irregularly. The underlying effects of these three scenarios and effects on coastal wetlands are summarized in Table 4.3.



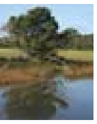
Under the non-drowning scenario, vertical accretion would keep pace with rising sea level as it has for millennia. Current rates (Cahoon, 2003) and those based on basal peats suggest that vertical accretion roughly matches the rate of rising sea level (Riggs *et al.*, 2000; Erlich, 1980; Whitehead and Oakes, 1979). Sources of inorganic sediment to supplement vertical marsh accretion are negligible due to both the large distance between the mouths of piedmont-draining Neuse, Tar, Roanoke, and Chowan Rivers and the absence of tidal currents and tidal creeks to transport sediments to marsh surfaces.

Under the drowning scenario, the uncertainty of the effects of accelerated rates lies in the untested capacity of marshes and swamp forests to biogenically accrete organic matter at sea-level rise rates more rapid than experienced currently. It has been suggested that brackish marshes of the Mississippi Delta cannot survive when subjected to relative rates of sea-level rise of 10 mm per year (Day *et al.*, 2005), well over twice the rate currently experienced in Albemarle and Pamlico Sounds. As is the case for the Mississippi Delta

Table 4.3 Comparison of Three Scenarios of Rising Sea Level and Their Effects on Coastal Processes.

Scenario	Vertical accretion of wetland surface	Shoreline erosion rate	Sediment supply
Non-drowning: historical exposure of wetlands (past hundreds to several thousand years) is predictive of future behavior. Vertical accretion will keep pace with rising sea level (about 2 to 4 millimeters per year)	Keeps pace with rising sea level	Recent historical patterns are maintained	Low due to a lack of sources; vertical accretion mostly biogenic
Drowning: vertical accretion rates cannot accelerate to match rates of rising sea level; barrier islands remain intact	Wetlands undergo collapse and marshes break up from within	Rapid acceleration when erosion reaches collapsed regions	Local increases of organic and inorganic suspended sediments as wetlands erode
Barrier islands breached: change to tidal regime throughout Pamlico Sound	Biogenic accretion replaced by inorganic sediment supply	Rapid erosion where high tides overtop wetland shorelines	Major increase in sediments and their redistribution; tidal creeks develop along antecedent drainages mostly in former upland regions

(Reed *et al*., 2006), external sources of mineral sediments would be required to supplement or replace the process of organic accumulation that now dominates wetlands of the A–P region. Where abundant supplies of sediment are available and tidal currents strong enough to transport them, as in North Inlet, South Carolina, Morris *et al*. (2002) reported that the high salt marsh (dwarf *Spartina*) could withstand a 12 mm per year rate. In contrast to fringe wetlands, swamp forests along the piedmont-draining rivers above the freshwater–seawater interface are likely to sustain themselves under drowning scenario conditions because there is a general abundance of mineral sediments during flood stage. This applies to regions within the floodplain but not at river mouths where shoreline recession occurs in response to more localized drowning.



Pocosin peatlands and swamp forest at higher elevations of the coastal plain will continue to grow vertically since they are both independent of sea-level rise. Under the drowning scenario, however, sea-level influenced wetlands of the lower coastal plain would convert to aquatic ecosystems, and the large, low, and flat pocosin areas identified by Poulter (2005) would transform to aquatic habitat. In areas of pocosin peatland, shrub and forest vegetation first would be killed by brackish water. It is unlikely that pocosins would undergo a transition to marsh for two reasons: (1) the pocosin root mat would collapse due to plant mortality and decomposition, causing a rapid subsidence of several centimeters, and resulting in a transition to ponds rather than marshes and (2) brackish water may accelerate decomposition of peat due to availability of sulfate to drive anaerobic decomposition. With the simultaneous death of woody vegetation and elimination of potential marsh plant establishment, organic-rich soils would be exposed directly to the effects of decomposition, erosion, suspension, and transport without the stabilizing properties of vegetation.

Under the collapsed barrier island scenario (see Section 3.7.3), the A–P regions would undergo a change from a non-tidal estuary to one dominated by astronomic tides due to the collapse of some portions of the barrier islands. A transition of this magnitude is difficult to predict in detail. However, Poulter (2005), using the ADCIRC-2DDI model of Luettich *et al*. (1992), estimated that conversion from a non-tidal to tidal estuary might flood hundreds of square kilometers. The effect is largely due to an increase in tidal amplitude that produces the flooding rather than a mean rise in sea level itself. While the mechanisms of change are speculative, it is doubtful that an intermediate stage of marsh colonization would occur on former pocosin and swamp forest areas because of the abruptness of change. Collapse of the barrier islands in this scenario would be so severe due to the sediment-poor condition of many barrier segments that attempts to maintain and/or repair them would be extremely difficult, or even futile.

The conversion of Pamlico Sound to a tidal system would likely re-establish tidal channels where ancestral streams are located, as projected by Riggs and Ames (2003). The remobilization of sediments could then supply existing marshes with inorganic sediments. It is more likely, however, that marshes would become established landward on newly inundated mineral soils of low-lying uplands. Such a state change has not been observed elsewhere, and computer models are seldom robust enough to encompass such extreme hydrodynamic transitions.

4.7 DATA NEEDS

A few key uncertainties must be addressed in order to increase confidence in the authors' predictions of wetland vulnerability to sea-level rise. First, determining the fate of coastal wetlands over a range of accelerated sea-level rise rates requires more information on variations in the maximum accretion rate regionally, within geomorphic settings, and among vegetative communities. To date, few studies have specifically addressed the maximum rates at which marsh vertical accretion can occur, particularly the thresholds for organic accumulation. Second, although the interactions among changes in wetland elevation, sea level, and wetland flooding patterns are becoming better understood, the interaction of these feedback controls between flooding and changes in other accretion drivers, such as nutrient supply, sulfate respiration, and soil organic matter accumulation is less well understood. Third, scaling up from numerical model predictions of local wetland responses to sea-level rise to long-term projections at regional or continental scales is severely constrained by a lack of available accretionary and process data at these larger landscape scales. Newly emerging numerical models used to predict wetland response to sea-level rise need to be applied across the range of wetland settings. Fourth, scientists need to better understand the role of changing land use on tidal wetland processes, including space available for wetlands to migrate landward and alteration in the amount and timing of freshwater runoff and sediment supply. Finally, sediment supply is a critical factor influencing wetland vulnerability, but the amount and source of sediments available for wetland formation and development is often poorly understood. Coastal sediment budgets typically evaluate coarse-grain sediments needed for beach and barrier development. In contrast, fine-grain cohesive sediments needed for wetland formation and development are typically not evaluated. Improving our understanding of each of these factors is critical for predicting the fate of tidal marshes.

CHAPTER 5

Vulnerable Species: the Effects of Sea-Level Rise on Coastal Habitats

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KEY FINDINGS

- The quality, quantity, and spatial distribution of coastal habitats change continuously as a result of shore erosion, salinity changes, and wetland dynamics; however, accelerated rates of sea-level rise will change some of the major controls of coastal wetland maintenance. Shore protection and development now prevent migration of coastal habitats in many areas. Vulnerable species that rely on these habitats include an array of biota ranging from endangered beetles to commercially important fish and shellfish; and from migratory birds to marsh plants and aquatic vegetation.

- Three key determinants of future tidal marsh acreage are: (1) the capacity of the marsh to raise its surface to match the rate of rising sea level, (2) the rate of erosion of the seaward boundary of the marsh, and (3) the availability of space for the marsh to migrate inland. Depending on local conditions, a tidal marsh may be lost or migrate landward in response to sea-level rise.

- Where tidal marshes become submerged or are eroded, the expected overall loss of wetlands would cause wetland-dependent species of fish and birds to have reduced population sizes. Tidal marshes and associated submerged aquatic plant beds are important spawning, nursery, and shelter areas for fish and shellfish, including commercially important species like the blue crab.

- Many estuarine beaches may also be lost in areas with vertical shore protection and insufficient sediment supply. Endangered beetles, horseshoe crabs, the red knot shorebird, and diamondback terrapins are among many species that rely on sandy beach areas.

- Loss of isolated marsh islands already undergoing submersion will reduce available nesting for bird species, especially those that rely on island habitat for protection from predators. Additional temporary islands may be formed as tidal marshes are inundated, although research on this possibility is limited.

- Many freshwater tidal forest systems such as those found in the Mid-Atlantic are considered globally imperiled, and are at risk from sea-level rise among other threats.

- Tidal flats, a rich source of invertebrate food for shorebirds, may be inundated, though new areas may be created as other shoreline habitats are submerged.

5.1 INTRODUCTION

Coastal ecosystems consist of a variety of environments, including tidal marshes, tidal forests, aquatic vegetation beds, tidal flats, beaches, and cliffs. For tidal marshes, Table 4.1 in Chapter 4 outlines the major marsh types, relevant accretionary processes, and the primary vegetation. These environments provide important ecological and human use services, including habitat for endangered and threatened species. The ecosystem services, described in detail within this Chapter, include not only those processes that support the ecosystem itself, such as nutrient cycling, but also the human benefits derived from those processes, including fish production, water purification, water storage and delivery, and the provision of recreational opportunities that help promote human well-being. The high value that humans place on these services has been demonstrated in a number of studies, particularly of coastal wetlands (NRC, 2005).

The services provided by coastal ecosystems could be affected in a number of ways by sea-level rise and coastal engineering projects designed to protect coastal properties from erosion and inundation. As seas rise, coastal habitats are subject to inundation, storm surges, saltwater intrusion, and erosion. In many cases, the placement of hard structures along the shore will reduce sediment inputs from upland sources and increase erosion rates in front of the structures (USGS, 2003). If less sediment is available, marshes that are seaward of such structures may have difficulty maintaining appropriate elevations in the face of rising seas. Wetlands that are unable to accrete sufficient substrate as sea level rises will gradually convert to open water, even if there is space available for them to migrate inland, thereby eliminating critical habitat for many coastal species. In addition, landward migration of wetlands may replace current upland habitats that are blocked from migration (NRC, 2007; MEA, 2005). Shallow water and shore habitats are also affected by shore responses. Table 6.1 in Chapter 6 provides a preliminary overview of the expected environmental effects of human responses to sea-level rise.

Habitat changes in response to sea-level rise and related processes may include structural changes (such as shifts in vegetation zones or loss of vegetated area) and functional changes (such as altered nutrient cycling). In turn, degraded ecosystem processes and habitat fragmentation and loss may not only alter species distributions and relative abundances, but may ultimately reduce local populations of the species that depend on coastal habitats for feeding, nesting, spawning, nursery areas, protection from predators, and other activities that affect growth, survival, and reproductive success.

BOX 5.1: Finfish, Tidal Salt Marshes, and Habitat Interconnectedness

Tidal salt marshes are among the most productive habitats in the world (Teal, 1986). While this productivity is used within the marshes, marsh-associated organic matter is also exported to food webs supporting marine transient fish production in open waters. Marine transients are adapted to life on a “coastal conveyor belt”, often spawning far out on the continental shelf and producing estuarine-dependent young that are recruited into coastal embayments year-round (Deegan *et al.*, 2000). These fish comprise more than 80 percent of species of commercial and recreational value that occupy inshore waters.

Tidal salt marshes serve two critical functions for young finfish (Boesch and Turner, 1984). First, abundant food and the warm shallow waters of the marsh are conducive to rapid growth of both resident and temporary inhabitants. Second, large predators are generally less abundant in subtidal marsh creeks; consequently marshes and their drainage systems may serve as a shelter from predators for the young fish. Protection, rapid growth, and the ability to deposit energy reserves from the rich marsh diet prepare young fish for the rigors of migration and/or overwintering (Weinstein *et al.*, 2005; Litvin and Weinstein, in press).

Effects of Sea-Level Rise

Intertidal and shallow subtidal waters of estuarine wetlands are “epicenters” of material exchange, primary (plant) and secondary (animal) production, and are primary nurseries for the young of many fish and shellfish species (Childers *et al.*, 2000; Weinstein, 1979; Deegan *et al.*, 2000). The prospect of sea-level rise, sometimes concomitant with land subsidence, human habitation of the shore zone, and shore stabilization, place these critical resources at risk. Such ecological hotspots could be lost as a result of sea-level rise because human presence in the landscape leaves tidal wetlands little or no room to migrate inland. Because of the lack of a well-defined drainage system, small bands of intertidal marsh located seaward of armored shorelines have little ecological value in the production of these finfish (Weinstein *et al.*, 2005; Weinstein, 1983). Due to their interconnectedness with adjacent habitats, loss of tidal salt marshes would significantly affect fish populations, both estuarine and marine, throughout the mid-Atlantic region.

Habitat interactions are extremely complex. Each habitat supports adjacent systems—for example, the denitrifying effects of wetlands aid adjacent submerged vegetation beds by reducing algal growth; the presence of nearshore oyster or mussel beds reduces wave energy which decreases erosion of marsh edges; and primary productivity is exported from marsh to open waters (see Box 5.1). This Chapter presents simplifications of these interactions in order to identify primary potential effects of both increased rates of sea-level rise and likely shore protections on vulnerable species. In particular, sea-level rise is just one factor among many affecting coastal areas: sediment input, nutrient runoff, fish and shellfish management, and other factors all contribute to the ecological condition of the various habitats discussed in this Section. Sea-level rise may also exacerbate pollution through inundation of upland sources of contamination such as landfills, industrial storage areas, or agricultural waste retention ponds. Under natural conditions, habitats are also continually shifting; the focus of this Chapter is the effect that shoreline management will have on the ability for those shifts to occur (*e.g.*, for marshes or barrier islands to migrate, for marsh to convert to tidal flat or *vice versa*) and any interruption to the natural shift.

While habitat migration, loss, and gain have all occurred throughout geological history, the presence of developed shorelines introduces a new barrier. Although the potential ecological effects are understood in general terms, few studies have sought to demonstrate or quantify how the interactions of sea-level rise and different types of shore protections may affect the ecosystem services provided by coastal habitats, and in particular the abundance and distribution of animal species (see Chapter 6 for discussion of shore protections). While some studies have examined impacts of either sea-level rise (*e.g.*, Erwin *et al*., 2006; Galbraith *et al*., 2002) or shore protections (*e.g.*, Seitz *et al*., 2006) on coastal fauna, minimal literature is available on the combined effects of rising seas and shore protections. Nonetheless, it is possible in some cases to identify species most likely to be affected based on knowledge of species-habitat associations. Therefore, this Chapter draws upon the ecological literature to describe the primary coastal habitats and species that are vulnerable to the interactive effects of sea-level rise and shore protection activities, and highlights those species that are of particular concern. While this Chapter provides a detailed discussion on a region-wide scale, Appendix 1 of this Product provides much more detailed discussions of specific local habitats and animal populations that may be at risk on a local scale along the mid-Atlantic coast.

5.2 TIDAL MARSHES

In addition to their dependence on tidal influence, tidal marshes are defined primarily in terms of their salinity: salt, brackish, and freshwater. Chapter 4 describes the structure and flora of these marshes as well as their likely responses to sea-level rise. Table 5.1 presents a general overview of the habitat types, fauna, and vulnerability discussed in this Chapter. Localized information on endangered or threatened species is available through the state Natural Heritage Programs (see Box 5.2).

Salt marshes (back-barrier lagoon marsh or saline fringe marsh, described in Table 4.1) are among the most productive systems in the world because of the extraordinarily high amount of above- and below-ground plant matter that many of them produce, up to 25 metric tons per hectare (ha) aboveground alone (Mitsch and Gosselink, 1993). In turn, this large reservoir of primary production supports a wide variety of invertebrates, fish, birds, and other animals that make up the estuarine food web (Teal, 1986). Insects and other small invertebrates feed on this organic material of the marsh as well as detritus and algae on the marsh surface. These in turn provide food for larger organisms, including crabs, shrimp, and small fishes, which then provide food for larger consumers such as birds and estuarine fishes that move into the marsh to forage (Mitsch and Gosselink, 1993).

Although much of the primary production in a marsh is used within the marsh itself, some is exported to adjacent estuaries and marine waters. In addition, some of the secondary production of marsh resident fishes, particularly mummichog, and of juveniles, such as blue crab, is exported out of the marsh to support both nearshore estuarine food webs as well as fisheries in coastal areas (Boesch and Turner, 1984; Kneib, 1997, 2000; Deegan *et al*., 2000; Beck *et al*., 2003; Dittel *et al*., 2006; Stevens *et al*., 2006)[1]. As studies of flood pulses have shown, the extent of the benefits provided by wetlands may be greater in regularly flooded tidal wetlands than in irregularly flooded areas (Bayley, 1991; Zedler and Calloway, 1999).

Tidal creeks and channels (Figure 5.1) frequently cut through low marsh areas, draining the marsh surface and serving as routes for nutrient-rich plant detritus (dead, decaying organic material) to be flushed out into deeper water as tides recede and for small fish, shrimp, and crabs to move into the marsh during high tides (Mitsch and Gosselink, 1993; Lippson and Lippson, 2006). In addition to mummichog, fish species found in tidal creeks at low tide include Atlantic silverside,

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[1] See Scientific Names section for a list of correspondence between common and scientific names.

Table 5.1 Key Fauna/Habitat Associations and Degree of Dependence

	Habitat Type						
Fauna	**Tidal Marsh**	**Forested Wetland**	**Sea-Level Fens**	**SAV**	**Tidal Flats**	**Estuarine Beaches**	**Unvegetated Cliffs**
Fish (Juvenile)	◆	–	–	◆	⬩	⬩	–
Fish (Adult)	♦	–	–	◆	⬩	⬩	–
Crustaceans/Mollusks	◆	–	–	◆	◆	♦	–
Other invertebrates	◆	♦	♦	♦	◆	◆	◆
Turtles/Terrapins	♦	♦	⬩	♦	–	◆	–
Other reptiles/Amphibians	⬩	♦	⬩	⬩	–	–	–
Wading Birds	♦	–	–	–	◆	⬩	–
Shorebirds	♦	–	–	–	◆	◆	–
Waterbirds	◆	–	–	◆	◆	⬩	–
Songbirds	⬩	◆	–	–	–	–	⬩
Mammals	♦	◆	–	–	–	⬩	⬩

***Notes**:*

Symbols represent the degree of dependence that particular fauna have on habitat types, as described in the sections below.

◆ indicates that multiple species, or certain rare or endangered species, depend heavily on that habitat.

♦ indicates that the habitat provides substantial benefits to the fauna.

⬩ indicates that some species of that fauna type may rely on the habitat, or that portions of their life cycle may be carried out there.

– indicates that negligible activity by a type of fauna occurs in the habitat.

Further details on these interactions, including relevant references, are in the sections by habitat below.

SAV is submerged aquatic vegetation, discussed later in this Chapter (Section 5.5).

striped killifish, and sheepshead minnow (Rountree and Able, 1992). Waterbirds such as great blue herons and egrets are attracted to marshes to feed on the abundant small fish, snails, shrimp, clams, and crabs found in tidal creeks and marsh ponds.

Brackish marshes support many of the same wildlife species as salt marshes, with some notable exceptions. Bald eagles forage in brackish marshes and nest in nearby wooded areas. Because there are few resident mammalian predators (such as red fox and raccoons), small herbivores such as meadow voles thrive in these marshes. Fish species common in the brackish waters of the Mid-Atlantic include striped bass and white perch, which move in and out of brackish waters year-round. Anadromous fish found in the Mid-Atlantic (those that live primarily in salt water but return to freshwater to spawn) include herring and shad, while marine transients such as Atlantic menhaden and drum species are present in summer and fall (White, 1989).

Tidal fresh marshes are characteristic of the upper reaches of estuarine tributaries. In general, the plant species composition of freshwater marshes depends on the degree of flooding, with some species germinating well when completely submerged, while others are relatively intolerant of flooding (Mitsch and Gosselink, 2000). Some tidal fresh marshes possess higher plant diversity than other tidal marsh types (Perry and Atkinson, 1997).

Tidal fresh marshes provide shelter, forage, and spawning habitat for numerous fish species, primarily cyprinids (minnows, shiners, carp), centrarchids (sunfish, crappie, bass),

Figure 5.1 Marsh and tidal creek, Bethels Beach (Mathews County) Virginia (June 2002) [Photo source: ©James G. Titus, used with permission].

BOX 5.2 Identifying Local Ecological Communities and Species at Risk

Every state and Washington, D.C. has Natural Heritage Programs (NHPs) that inventory and track the natural diversity of the state, including rare or endangered species. These programs provide an excellent resource for identifying local ecological communities and species at risk.

Box Table 5.2 State Natural Heritage Program Contact Information

Office	Website	Phone
New York State Department of Environmental Conservation, Division of Fish, Wildlife and Marine Resources	<http://www.nynhp.org/>	(518) 402-8935
New Jersey Department of Environmental Protection, Division of Parks and Forestry, Office of Natural Lands Management	<http://www.state.nj.us/dep/parksandforests/natural/heritage/index.html>	(609) 984-1339
Pennsylvania Department of Conservation and Natural Resources, Office of Conservation Science	<http://www.naturalheritage.state.pa.us/>	(717) 783-1639
Delaware Department of Natural Resources and Environmental Control, Division of Fish and Wildlife	<http://www.dnrec.state.de.us/nhp/>	(302) 653-2880
Maryland Department of Natural Resources, Wildlife and Heritage Service	<http://www.dnr.state.md.us/wildlife/>	(410) 260-8DNR
The District of Columbia's Department of Health, Fisheries and Wildlife Division	<http://dchealth.dc.gov/doh/cwp/view,a,1374,Q,584468,dohNav_GID,1810,.asp>	(202) 671-5000
Virginia Department of Conservation and Recreation	<http://www.dcr.virginia.gov/natural_heritage/index.shtml>	(804) 786-7951
North Carolina Department of Environment and Natural Resources, Office of Conservation and Community Affairs	<http://www.ncnhp.org/index.html>	(919) 715-4195

A useful resource for species data outside of each state's own NHP is NatureServe Explorer. NatureServe (<http://www.natureserve.org/>) is a non-profit conservation organization which represents the state Natural Heritage Programs and other conservation data centers. NatureServe Explorer allows users to search for data on the geographic incidence of plant and animal species in the United States and Canada. The program provides an extensive array of search criteria, including species' taxonomies, classification status, ecological communities, or their national and sub-national distribution. For example, one could search for all vertebrate species federally listed as threatened that live in Delaware's section of the Chesapeake Bay. For identifying threatened and endangered species extant in vulnerable areas, the smallest geographic unit of analysis is county level.

and ictalurids (catfish). In addition, some estuarine fish and shellfish species complete their life cycles in freshwater marshes. Tidal fresh marshes are also important for a wide range of bird species. Some ecologists suggest that freshwater tidal marshes support the greatest diversity of bird species of any marsh type (Mitsch and Gosselink, 2000). The avifauna of these marshes includes waterfowl; wading birds; rails and shorebirds; birds of prey; gulls, terns, kingfishers, and crows; arboreal birds; and ground and shrub species. Perching birds such as red-winged blackbirds are common in stands of cattail. Tidal freshwater marshes support additional species that are rare in saline and brackish environments, such as frogs, turtles, and snakes (White, 1989).

Marsh islands are a critical subdivision of the tidal marshes. These islands are found throughout the mid-Atlantic study region, and are particularly vulnerable to sea-level rise (Kearney and Stevenson, 1991). Islands are common features of salt marshes, and some estuaries and back-barrier bays have islands formed by deposits of dredge spoil. Many islands are a mixture of habitat types, with vegetated and

Figure 5.2 Fringing marsh and bulkhead, Monmouth County, New Jersey (August 2003) [Photo source: ©James G. Titus, used with permission].

unvegetated wetlands in combination with upland areas[2]. These isolated areas provide nesting sites for various bird species, particularly colonial nesting waterbirds, where they are protected from terrestrial predators such as red fox. Gull-billed terns, common terns, black skimmers, and American oystercatchers all nest on marsh islands (Rounds *et al*., 2004; Eyler *et al*., 1999; McGowan *et al*., 2005).

As discussed in Chapter 4, tidal marshes can keep pace with sea-level rise through vertical accretion (*i.e*., soil build up through sediment deposition and organic matter accumulation) as long as a sufficient sediment supply exists. Where inland movement is not impeded by artificial shore structures (Figure 5.2) or by geology (*e.g*., steeply sloping areas between geologic terraces, as found around Chesapeake Bay) (Ward *et al*., 1998; Phillips, 1986), tidal marshes can expand inland, which would increase wetland area if the rate of migration exceeds that of erosion of the marsh's seaward boundary. However, wetland area would decrease even when a marsh migrates inland if the rate of erosion of the seaward boundary exceeds the rate of migration. Further, in areas where sufficient accretion does not occur, increased tidal flooding will stress marsh plants through waterlogging and changes in soil chemistry, leading to a change in plant species composition and vegetation zones. If marsh plants become too stressed and die, the marsh will eventually convert to open water or tidal flat (Callaway *et al*., 1996; Morris *et al*., 2002)[3].

Sea-level rise is also increasing salinity upstream in some rivers, leading to shifts in vegetation composition and the conversion of some tidal fresh marshes into brackish marshes (MD DNR, 2005). At the same time, brackish marshes can deteriorate as a result of ponding and smothering of marsh plants by beach wrack (seaweed and other marine detritus left on the shore by the tide) as salinity increases and storms accentuate marsh fragmentation[4] (Strange *et al*., 2008). While this process may allow colonization by lower-elevation marsh species, that outcome is not certain (Stevenson and Kearney, 1996). Low brackish marshes can change dynamically in area and composition as sea level rises. If they are lost, forage fish and invertebrates of the low marsh, such as fiddler crabs, grass shrimp, and ribbed mussels, may also be lost, which would affect fauna further up the food chain (Strange *et al*., 2008). Though more ponding may provide some additional foraging areas as marshes deteriorate, the associated increase in salinity due to evaporative loss can also inhibit the growth of marsh plants (MD DNR, 2005). Many current marsh islands will be inundated; however, in areas with sufficient sediment, new islands may form, although research on this possibility is limited (Cleary and Hosler, 1979). New or expanded marsh islands are also formed through dredge spoil projects[5].

Effects of marsh inundation on fish and shellfish species are likely to be complex. In the short term, inundation may make the marsh surface more accessible, increasing production. However, benefits will decrease as submergence decreases total marsh habitat (Rozas and Reed, 1993). For example, increased deterioration and mobilization of marsh peat sediments increases the immediate biological oxygen demand and may deplete oxygen in marsh creeks and channels below levels needed to sustain fish. In these oxygen-deficient conditions, mummichogs and other killifish may be among the few species able to persist (Stevenson *et al*., 2002).

Figure 5.3 Marsh drowning and hummock in Blackwater Wildlife Refuge, Maryland (November 2002) [Photo source: ©James G. Titus, used with permission].

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[2] Thompson's Island in Rehoboth Bay, Delaware, is a good example of a mature forested upland with substantial marsh and beach area. The island hosts a large population of migratory birds. See *Maryland and Delaware Coastal Bays* in Strange *et al.* (2008).

[3] The Plum Tree Island National Wildlife Refuge is an example of a marsh deteriorating through lack of sediment input. Extensive mudflats front the marsh (see Appendix 1.F for additional details).

[4] Along the Patuxent River, Maryland, refuge managers have noted marsh deterioration and ponding with sea-level rise. See Appendix 1.F for additional details.

[5] For example, see discussions of Hart-Miller and Poplar Islands in Chesapeake Bay in Appendix 1.F.

In areas where marshes are reduced, remnant marshes may provide lower quality habitat, fewer nesting sites, and greater predation risk for a number of bird species that are marsh specialists and are also important components of marsh food webs, including the clapper rail, black rail, least bittern, Forster's tern, willet, and laughing gull (Figure 5.3) (Erwin *et al.*, 2006). The majority of the Atlantic Coast breeding populations of Forster's tern and laughing gull are considered to be at risk because of loss of lagoonal marsh habitat due to sea-level rise (Erwin *et al.*, 2006). In a Virginia study, scientists found that the minimum marsh size to support significant marsh bird communities was 4.1 to 6.7 hectares (ha) (10.1 to 16.6 acres [ac]) (Watts, 1993). Some species may require even larger marsh sizes; minimum marsh size for successful communities of the saltmarsh sharp-tailed sparrow and the seaside sparrow, both on the Partners in Flight Watch List, are estimated at 10 and 67 ha (25 and 166 ac), respectively (Benoit and Askins, 2002).

Figure 5.5 Inundation and tree mortality in forested wetlands at Swan's Point, Lower Potomac River. These wetlands are irregularly flooded by wind-generated tides, unaffected by astronomic tides; their frequency of inundation is controlled directly by sea level (October 2006) [Photo source: ©Elizabeth M. Strange and Stratus Consulting, used with permission].

5.3 FRESHWATER FORESTED WETLANDS

Forested wetlands influenced by sea level line the mid-Atlantic coast. Limited primarily by their requirements for low-salinity water in a tidal regime, tidal fresh forests occur primarily in upper regions of tidal tributaries in Virginia, Maryland, Delaware, New Jersey, and New York (NatureServe, 2006). The low-lying shorelines of North Carolina also contain large stands of forested wetlands, including cypress swamps and pocosins (Figure 5.4). Also in the mid-Atlantic coastal plains (*e.g.*, around Barnegat Bay, New Jersey) are Atlantic white cedar swamps, found in areas where a saturated layer of peat overlays a sandy substrate (NatureServe, 2006). Forested wetlands support a variety of wildlife, including the prothonotary warbler, the two-toed amphiuma salamander, and the bald eagle. Forested wetlands with thick understories provide shelter and food for an abundance of breeding songbirds (Lippson and Lippson, 2006). Various rare and greatest conservation need (GCN) species reside in mid-Atlantic tidal swamps, including the Delmarva fox squirrel (federally listed as endangered), the eastern red bat, bobcats, bog turtles, and the redbellied watersnake (MD DNR, 2005).

Tidal fresh forests, such as those found in the Mid-Atlantic, face a variety of threats, including sea-level rise, and are currently considered globally imperiled[6]. The responses of these forests to sea-level rise may include retreat at the open-water boundary, drowning in place, or expansion inland. Fleming *et al.* (2006) noted that, "Crown dieback and tree mortality are visible and nearly ubiquitous phenomena in these communities and are generally attributed to sea-level rise and an upstream shift in the salinity gradient in estuarine rivers". Figure 5.5 presents an example of inundation and tree mortality. In Virginia, tidal forest research has indicated that where tree death is present, the topography is limiting inland migration of the hardwood swamp and the understory is converting to tidal marsh (Rheinhardt, 2007).

Figure 5.4 Pocosin in Green Swamp, North Carolina (May 2004) [Photo source: ©Sam Pearsall, used with permission].

5.4 SEA-LEVEL FENS

Sea-level fens are a rare type of coastal wetland with a mix of freshwater tidal and northern bog vegetation, resulting in a unique assemblage that includes carnivorous plants such as sundew and bladderworts (Fleming *et al.*, 2006; VNHP, 2006). Their geographic distribution includes isolated locations on Long Island's South Shore; coastal New Jersey; Sussex County, Delaware; and Accomack County, Virginia. The eastern mud turtle and the rare elfin skimmer dragonfly are among the animal species found in sea-level fens. Fens may occur in areas where soils are acidic and a natural seep from a nearby slope provides nutrient-poor groundwater

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[6] As presented in NatureServe (<http://www.natureserve.org/>), the prevalent tidal forest associations such as freshwater tidal woodlands and tidal freshwater cypress swamps are considered globally imperiled.

(VNHP, 2006). Little research has been conducted on the effects of sea-level rise on groundwater fens; however, the Virginia Natural Heritage Program has concluded that sea-level rise is a primary threat to the fens (VNHP, 2006).

5.5 SUBMERGED AQUATIC VEGETATION

Submerged aquatic vegetation (SAV) is distributed throughout the mid-Atlantic region, dominated by eelgrass in the higher-salinity areas and a large number of brackish and freshwater species elsewhere (*e.g.*, widgeon grass, wild celery) (Hurley, 1990). SAV plays a key role in estuarine ecology, helping to regulate the oxygen content of nearshore waters, trapping sediments and nutrients, stabilizing bottom sediments, and reducing wave energy (Short and Neckles, 1999). SAV also provides food and shelter for a variety of fish and shellfish and the species that prey on them. Organisms that forage in SAV beds feed on the plants themselves, the detritus and the epiphytes on plant leaves, and the small organisms found within the SAV bed (*e.g.*, Stockhausen and Lipcius [2003] for blue crabs; Wyda *et al.* [2002] for fish). The commercially valuable blue crab hides in eelgrass during its molting periods, when it is otherwise vulnerable to predation. In Chesapeake Bay, summering sea turtles frequent eelgrass beds. The Kemp's ridley sea turtle, federally listed as endangered, forages in eelgrass beds and flats, feeding on blue crabs in particular (Chesapeake Bay Program, 2007). Various waterbirds feed on SAV, including brant, canvasback, and American black duck (Perry and Deller, 1996).

Forage for piscivorous birds and fish is also provided by residents of nearby marshes that move in and out of SAV beds with the tides, including mummichog, Atlantic silverside, naked goby, northern pipefish, fourspine stickleback, and threespine stickleback (Strange *et al.*, 2008). Juveniles of many commercially and recreationally important estuarine and marine fishes (such as menhaden, herring, shad, spot, croaker, weakfish, red drum, striped bass, and white perch) and smaller adult fish (such as bay and striped anchovies) use SAV beds as nurseries (NOAA Chesapeake Bay Office, 2007; Wyda *et al.*, 2002). Adults of estuarine and marine species such as sea trout, bluefish, perch, and drum search for prey in SAV beds (Strange *et al.*, 2008).

Effects of sea-level rise on SAV beds are uncertain because fluctuations in SAV occur on a year-to-year basis, a significantly shorter timescale than can be attributed to sea-level rise[7]. However, Short and Neckles (1999) estimate that a 50 centimeter (cm) increase in water depth as a result of sea-level rise could reduce light penetration to current seagrass beds in coastal areas by 50 percent. This would result in a 30 to 40 percent reduction in seagrass growth in those areas due to decreased photosynthesis (Short and Neckles, 1999). Increased erosion, with concomitant increased transport and delivery of sediment, would also reduce available light (MD DNR, 2000).

Although plants in some portion of an SAV bed may decline as a result of such factors, landward edges may migrate inland depending on shore slope and substrate suitability. SAV growth is significantly better in areas where erosion provides sandy substrate, rather than fine-grained or high organic matter substrates (Stevenson *et al.*, 2002).

Sea-level rise effects on the tidal range could also impact SAV, and the effect could be either detrimental or beneficial. In areas where the tidal range increases, plants at the lower edge of the bed will receive less light at high tide, increasing plant stress (Koch and Beer, 1996). In areas where the tidal range decreases, the decrease in intertidal exposure at low tide on the upper edge of the bed will reduce plant stress (Short and Neckles, 1999).

Shore construction and armoring will impede shoreward movement of SAV beds (Short and Neckles, 1999) (see Chapter 6 for additional information on shore protections). First, hard structures tend to affect the immediate geomorphology as well as any adjacent seagrass habitats (Strange *et al.*, 2008). Particularly during storm events, wave reflection off of bulkheads or seawalls can increase water depth and magnify the inland reach of waves on downcoast beaches (Plant and Griggs, 1992; USGS, 2003; Small and Carman, 2005). Second, as sea level rises in armored areas, the nearshore area deepens and light attenuation increases, restricting and finally eliminating seagrass growth (Strange *et al.*, 2008). Finally, high nutrient levels in the water limit vegetation growth. Sediment trapping behind breakwaters, which increases the organic content, may limit eelgrass success (Strange *et al.*, 2008). Low-profile armoring, including stone sills and other "living shorelines" projects, may be beneficial to SAV growth (NRC, 2007). Projects to protect wetlands and restore adjacent SAV beds are taking place and represent a potential protection against SAV loss (*e.g.*, U.S. Army Corps of Engineers restoration for Smith Island in Chesapeake Bay) (USACE, 2004).

Loss of SAV affects numerous animals that depend on the vegetation beds for protection and food. By one estimate, a 50-percent reduction in SAV results in a roughly 25-percent reduction in Maryland striped bass production (Kahn and Kemp, 1985). For diving and dabbling ducks, a decrease in SAV in their diets since the 1960s has been noted (Perry and Deller, 1996). The decreased SAV in Chesapeake Bay is cited as a major factor in the substantial reduction in wintering waterfowl (Perry and Deller, 1996).

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[7] For example, nutrient enrichment and resultant eutrophication are a common problem for SAV beds (USFWS, undated).

5.6 TIDAL FLATS

Tidal flats are composed of mud or sand and provide habitat for a rich abundance of invertebrates. Tidal flats are critical foraging areas for numerous birds, including wading birds, migrating shorebirds, and dabbling ducks (Strange *et al.*, 2008).

In marsh areas where accretion rates lag behind sea-level rise, marsh will eventually revert to unvegetated flats and eventually open water as seas rise (Brinson *et al.*, 1995). For example, in New York's Jamaica Bay, several hundred acres of low salt marsh have converted to open shoals (see Appendix 1.B for additional details). In a modeling study, Galbraith *et al.* (2002) predicted that under a 2°C global warming scenario, sea-level rise could inundate significant areas of intertidal flats in some regions. In some cases where tidal range increases with increased rates of sea-level rise, however, there may be an overall increase in the acreage of tidal flats (Field *et al.*, 1991).

In low energy shores with high sediment supplies, where sediments accumulate in shallow waters, flats may become vegetated as low marsh encroaches waterward, which will increase low marsh at the expense of tidal flats (Redfield, 1972). If sediment inputs are not sufficient, tidal flats will convert to subtidal habitats, which may or may not be vegetated depending on substrate composition and water transparency (Strange *et al.*, 2008).

Loss of tidal flats would eliminate a rich invertebrate food source for migrating birds, including insects, small crabs, and other shellfish (Strange *et al.*, 2008). As tidal flat area declines, increased crowding in remaining areas could lead to exclusion and reductions in local shorebird populations (Galbraith *et al.*, 2002). At the same time, ponds within marshes may become more important foraging sites for the birds if flats are inundated by sea-level rise (Erwin *et al.*, 2004).

5.7 ESTUARINE BEACHES

Throughout most of the mid-Atlantic region and its tributaries, estuarine beaches front the base of low bluffs and high cliffs as well as bulkheads and revetments (see Figure 5.6) (Jackson *et al.*, 2002). Estuarine beaches can also occur in front of marshes and on the mainland side of barrier islands (Jackson *et al.*, 2002).

The most abundant beach organisms are microscopic invertebrates that live between sand grains, feeding on bacteria and single-celled protozoa. It is estimated that there are over two billion of these organisms in a single square meter of sand (Bertness, 1999). They play a critical role in beach food webs as a link between bacteria and larger consumers such as sand diggers, fleas, crabs, and other macroinvertebrates that burrow in sediments or hide under rocks (Strange *et al.*, 2008). In turn, shorebirds such as the piping plover, American oystercatcher, and sandpipers feed on these resources (USFWS, 1988). Various rare and endangered beetles also live on sandy shores. Diamondback terrapins and horseshoe crabs bury their eggs in beach sands. The insects and crustaceans found in deposits of wrack on estuarine beaches are also an important source of forage for birds (Figure 5.7) (Dugan *et al.*, 2003).

Figure 5.6 Estuarine beach and bulkhead along Arthur Kills, Woodbridge Township, New Jersey (August 2003) [Photo source: ©James G. Titus, used with permission].

As sea level rises, the fate of estuarine beaches depends on their ability to migrate and the availability of sediment to replenish eroded sands (Figure 5.8) (Jackson *et al.*, 2002). Estuarine beaches continually erode, but under natural conditions the landward and waterward boundaries usually retreat by about the same distance. Shoreline protection structures may prevent migration, effectively squeezing beaches between development and the water. Armoring that traps sand in one area can limit or eliminate longshore transport, and, as a result, diminish the constant replenishment of sand

Figure 5.7 Peconic Estuary Beach, Riverhead, New York (September 2006) [Photo source: ©James G. Titus, used with permission].

Figure 5.8 Beach with beach wrack and marsh in Bethel Beach (Mathews County), Virginia (June 2002) [Photo source: ©James G. Titus, used with permission].

necessary for beach retention in nearby locations (Jackson *et al*., 2002). Waterward of bulkheads, the foreshore habitat will likely be lost through erosion, frequently even without sea-level rise. Only in areas with sufficient sediment input relative to sea-level rise (*e.g.*, upper tributaries and upper Chesapeake Bay) are beaches likely to remain in place in front of bulkheads.

In many developed areas, estuarine beaches may be maintained with beach nourishment if there are sufficient sources and the public pressure and economic ability to do so. However, the ecological effects of beach nourishment remain uncertain. Beach nourishment will allow retention in areas with a sediment deficit, but may reduce habitat value through effects on sediment characteristics and beach slope (Peterson and Bishop, 2005).

Beach loss will cause declines in local populations of rare beetles found in Calvert County, Maryland. While the Northeastern beach tiger beetle is able to migrate in response to changing conditions, suitable beach habitat must be available nearby (USFWS, 1994).

At present, the degree to which horseshoe crab populations will decline as beaches are lost remains unclear. Early research results indicate that horseshoe crabs may lay eggs in intertidal habitats other than estuarine beaches, such as sandbars and the sandy banks of tidal creeks (Loveland and Botton, 2007). Nonetheless, these habitats may only provide a temporary refuge for horseshoe crabs if they are inundated as well (Strange *et al*., 2008).

Where horseshoe crabs decline because of loss of suitable habitat for egg deposition, there can be significant implications for migrating shorebirds, particularly the red knot, a candidate for protection under the federal Endangered Species Act, which feeds almost exclusively on horseshoe crab eggs during stopovers in the Delaware Estuary (Karpanty *et al*., 2006).

In addition, using high-precision elevation data from nest sites, researchers are beginning to examine the effects that sea-level rise will have on oystercatchers and other shore birds (Rounds and Erwin, 2002). To the extent that estuarine and riverine beaches, particularly on islands, survive better than barrier islands, shorebirds like oystercatchers might be able to migrate to these shores (McGowan *et al*., 2005).

5.8 CLIFFS

Unvegetated cliffs and the sandy beaches sometimes present at their bases are constantly reworked by wave action, providing a dynamic habitat for cliff beetles and birds. Little vegetation exists on the cliff face due to constant erosion, and the eroding sediment augments nearby beaches. Cliffs are present on Chesapeake Bay's western shore and tributaries and its northern tributaries (see Figure 5.9), as well as in Hempstead Harbor on Long Island's North Shore and other areas where high energy shorelines intersect steep slopes (Strange *et al*., 2008).

If the cliff base is armored to protect against rising seas, erosion rates may decrease, eliminating the unvegetated cliff faces that are sustained by continuous erosion and provide habitat for species such as the Puritan tiger beetle and bank swallow. Cliff erosion also provides a sediment source to sustain the adjacent beach and littoral zone (the shore zone between high and low water marks) (Strange *et al*., 2008). Naturally eroding cliffs are "severely threatened by shoreline erosion control practices" according to the Maryland Department of Natural Resource's Wildlife Diversity Conservation Plan (MD DNR, 2005). Shoreline protections may also subject adjacent cliff areas to wave undercutting and higher recession rates as well as reduction in beach sediment (Wilcock *et al*., 1998). Development and shoreline stabilization

Figure 5.9 Crystal Beach, along the Elk River, Maryland (May 2005) [Photo source: ©James G. Titus, used with permission].

structures that interfere with natural erosional processes are cited as threats to bank-nesting birds as well as two species of tiger beetles (federally listed as threatened) at Maryland's Calvert Cliffs (USFWS, 1993, 1994; CCB, 1996).

5.9 SUMMARY OF IMPACTS TO WETLAND-DEPENDENT SPECIES

Based on currently available information, it is possible to identify particular taxa and even some individual species that appear to be at greatest risk if coastal habitats are degraded or diminished in response to sea-level rise and shoreline hardening:

- Degradation and loss of tidal marshes will affect fish and shellfish production in both the marshes themselves and adjacent estuaries.
- Bird species that are marsh specialists, including the clapper rail, black rail, least bittern, Forster's tern, willet, and laughing gull, are particularly at risk. At present, the majority of the Atlantic Coast breeding populations of Forster's tern and laughing gull are considered to be at risk from loss of lagoonal marshes.
- Increased turbidity and eutrophication in nearshore areas and increased water depths may reduce light penetration to SAV beds, reducing photosynthesis, and therefore the growth and survival of the vegetation. Degradation and loss of SAV beds will affect the numerous organisms that feed, carry on reproductive activities, and seek shelter in seagrass beds.
- Diamondback terrapin are at risk of losing both marsh habitat that supports growth and adjoining beaches where eggs are buried.
- Many marsh islands along the Mid-Atlantic, and particularly in Chesapeake Bay, have already been lost or severely reduced as a result of lateral erosion and flooding related to sea-level rise. Loss of such islands poses a serious, near-term threat for island-nesting bird species such as gull-billed terns, common terns, black skimmers, and American oystercatchers.
- Many mid-Atlantic tidal forest associations may be at risk from sea-level rise and a variety of other threats, and are now considered globally imperiled.
- Shoreline stabilization structures interfere with natural erosional processes that maintain unvegetated cliff faces that provide habitat for bank-nesting birds and tiger beetles.
- Loss of tidal flats could lead to increased crowding of foraging birds in remaining areas, resulting in exclusion of many individuals; if alternate foraging areas are unavailable, starvation of excluded individuals may result, ultimately leading to reductions in local bird populations.
- Where horseshoe crabs decline because of loss of suitable beach substrate for egg deposition, there could be significant implications for migrating shorebirds, particularly the red knot, a candidate for protection under the federal Endangered Species Act. Red knot feed almost exclusively on horseshoe crab eggs during stopovers in the Delaware Estuary.