PART IV OVERVIEW

National Implications and a Science Strategy for Moving Forward

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Climate change and effects such as sea-level rise have global implications and will increasingly affect the entire nation. While this Product focuses primarily on the mid-Atlantic region of the United States, many of the issues discussed in earlier chapters are relevant at the national scale.

Chapter 13 draws on findings from the mid-Atlantic focus area that have relevance to other parts of the United States, provides an overview of coastal environments and landforms in the United States, and describes the issues faced in understanding how these environments may be impacted and respond to sea-level rise. The diversity of U.S. coastal settings includes bedrock coasts in Maine; glacial bluffs in New York; barrier islands in the Mid-Atlantic and Gulf of Mexico; coral reefs in Florida, the Caribbean, and Hawaii; one of the world's major delta systems in Louisiana; a wide variety of pocket beaches and cliffed coasts along the Pacific coast; Pacific atolls; and a number of arctic coastline types in Alaska. In addition, the large bays and estuaries around the country also exhibit a diverse range of shoreline types, large wetland systems, and extensive coastal habitats. Understanding how the different coastal environments of the United States will respond to future climate and sea-level change is a major challenge. In addition, as highlighted in earlier Parts of this Product, human actions and policy decisions also substantially influence the evolution of the coast. The knowledge gaps and data limitations identified in this Product focusing on the Mid-Atlantic have broad relevance to the rest of the United States.

Chapter 14 identifies opportunities for increasing the scientific understanding of future sea-level rise impacts. This includes basic and applied research in the natural and the social sciences. A significant emphasis is placed on developing linkages between scientists, policy makers, and stakeholders at all levels, so that information can be shared and utilized efficiently and effectively as sea-level rise mitigation and adaptation plans evolve.

13

CHAPTER

Implications of Sea-Level Rise to the Nation

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KEY FINDINGS

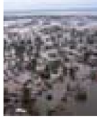
- Nationwide, more than one-third of the U.S. population currently lives in the coastal zone and movement to the coast and development continues, along with the current and growing vulnerability to coastal hazards such as storms and sea-level rise. Fourteen of the 20 largest U.S. urban centers are located along the coast. With the very likely accelerated rise in sea level and increased storm intensity, the conflicts between people and development at the coast and the natural processes will increase, causing economic and societal impacts.

- For much of the United States, shores comprised of barrier islands, dunes, spits, and sandy bluffs, erosion processes will dominate at highly variable rates in response to sea-level rise and storms over the next century and beyond. Some coastal landforms in the United States may undergo large changes in shape and location if the rate of sea-level rise increases as predicted. Increased inundation and more frequent flooding will affect estuaries and low-lying coastal areas. The response to these driving forces will vary depending on the type of coastal landform and local conditions, but will be more extreme, more variable, and less predictable than the changes observed over the last century.

- For higher sea-level rise scenarios, some barrier island coasts and wetlands may cross thresholds and undergo significant and irreversible changes. These changes include rapid landward migration and segmentation of some barrier islands and disintegration and drowning of wetlands.

- Nationally, tidal wetlands already experiencing submergence by sea-level rise and associated land loss, in concert with other factors, will continue to deteriorate in response to changing climate.

- Coastal change is driven by complex and interrelated processes. Over the next century and beyond, with an expected acceleration in sea-level rise, the potential for coastal change is likely to be greater than has been observed in historic past. These changes to coastal regions will have especially large impacts on urban centers and developed areas. Some portions of the U.S. coast will be subject primarily to inundation from sea-level rise over the next century. A substantial challenge remains to quantify the various effects of sea-level rise and to identify the dominant coastal change processes for each region of the U.S. coast.



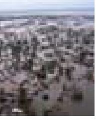
- Many coastal areas in the United States will likely experience an increased frequency and magnitude of storm-surge flooding and coastal erosion due to storms over the next century in response to sea-level rise. The impacts from these storm events are likely to extend farther inland from the coast than those that would be affected by sea-level rise alone.

- Understanding, predicting, and responding to the environmental and societal effects of sea-level rise would benefit from a national program of integrated research that includes the natural and social sciences. Research on adaptation, mitigation, and avoidance-of-risk measures would enable improved understanding of the many and varied potential societal impacts of sea-level rise that would benefit the United States as well as coastal nations around the world.

13.1 INTRODUCTION

As defined in the SAP 4.1 Prospectus and discussed in earlier chapters, this Product focuses on assessing potential impacts to the mid-Atlantic region; however, some discussion of impacts to other regions and the nation as a whole is warranted. The mid-Atlantic region is highly vulnerable to sea-level rise, but regions like the central Gulf Coast (Louisiana, Texas) are just as vulnerable or more so. The challenge in carrying out a national assessment is that nationwide databases and scientific publications of national scale and scope are limited. Modest efforts at monitoring and observations for national-scale assessments of coastal change and hazards are underway by various organizations, but more effort is needed. The discussion in Section 13.3 is largely the expert opinions of the lead authors, informed by results of the two expert science panel reports (Reed *et al.*, 2008, Gutierrez, *et al.*, 2007) and available scientific literature. Because of the relative lack of adequate background literature and high reliance on expert opinion, the likehood statements as used in other chapters are not included in this discussion of potential impacts to the nation.

A large and expanding proportion of the U.S. population and related urban development is located along the Atlantic, Gulf of Mexico, and Pacific coasts and increasingly conflicts with the natural processes associated with coastal change from storms and sea-level rise (see review in Williams *et al.*, 1991). Development in low-lying regions (*e.g.*, New Orleans) and islands (*e.g.*, in the Chesapeake Bay, Caribbean, Pacific Ocean) are particularly at risk (see Gibbons and Nicholls, 2006). In the future, as the effects of climate change intensify, these interactions will become more frequent and more challenging to society. Currently, more than one-third of the U.S. population lives in the coastal zone and movement to the coast and development continues, along with the growing vulnerability to coastal hazards. Fourteen of the 20 largest U.S. urban centers are located along the coast (Crossett *et al.*, 2004; Crowell *et al.*, 2007). With the likely accelerated rise in sea level and increased storm intensity, the conflicts between people and development at the coast and the natural processes will increase, affecting all parts of society (Leatherman, 2001; FitzGerald *et al.*, 2008).



Global sea-level rise associated with climate change is likely to be in the range of 19 centimeters (cm) (7.5 inches [in]) to as much as 1 meter (m) (about 3 feet [ft]) over the next century and possibly as much as 4 to 6 m (about 13 to 20 ft) over the next several centuries (IPCC, 2007; Rahmstorf, 2007; Rahmstorf, et *al.*, 2007; Overpeck *et al.*, 2006). The expected rise will increase erosion and the frequency of flooding, and coastal areas will be at increasing risk. For some regions, adaptation using engineering means may be effective; for other coastal areas, however, adaption by relocation landward to higher elevated ground may be appropriate for longer-term sustainability (NRC, 1987).

Coastal landforms reflect the complex interaction between the natural physical processes that act on the coast, the geologic characteristics of the coast, and human activities. Spatial and temporal variations in these physical processes and the geology along the coast are responsible for the wide variety of landforms around the United States (Williams, 2003). With future sea-level rise, portions of the U.S. ocean coast are likely to undergo long-term net erosion, at rates higher than those that have been observed over the past century (see Chapter 3). The exact manner and rates at which these changes are likely to occur depends on the character of coastal landforms (*e.g.*, barrier islands, cliffs) and the physical processes (*e.g.*, waves and winds) that shape these landforms (see Chapters 3 and 4). Low-relief coastal regions, areas undergoing land subsidence, and land subject to frequent storm landfalls, such as the northern Gulf of Mexico, Florida, Hawaii, Puerto Rico, the San Francisco-Sacramento Delta region, and the Mid-Atlantic region, are particularly vulnerable.

13.2 TYPES OF COASTS

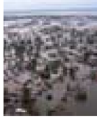
Coasts are dynamic junctions of the oceans, atmosphere, and land and differ greatly in physical character and vulnerability to erosion, storms, and sea-level rise (NRC, 1990). The principal coastal types are described in Chapters 3 and 4, and summarized below. With future sea-level rise, all of these landforms will become more dynamic (Nicholls *et al.*, 2007), but predicting and quantifying changes that are likely to occur with high confidence is currently scientifically challenging.

13.2.1 Cliff and Bluff Shorelines

Substantial portions of the U.S. coast are comprised of coastal cliffs and bluffs that vary greatly in height, morphology, and composition. These occur predominantly along the New England and Pacific coasts, Hawaii, and Alaska. Coastal cliff is a general term that refers to steep slopes along the shoreline that commonly form in response to long-term rise in sea-level. The term "bluff" also can refer to escarpments eroded into unlithified material, such as glacial till, along the shore (Hampton and Griggs, 2004). The terms "cliff" and "bluff" are often used interchangeably. Coastal cliffs erode in response to a variety of both marine and terrestrial processes. Cliff retreat can be fairly constant, but can also be episodic. In contrast to sandy coasts, which may erode landward or accrete seaward, cliffs retreat only in a landward direction. Because rocky cliff coasts are composed of resistant materials, erosion can can occur more slowly than for those comprised of unconsolidated sediments and response times to sea-level rise can be much longer than for sandy coasts (NRC, 1987), but land slumping due to wave action or land surface water runoff can result in rapid retreat. Hampton and Griggs (2004) provide a review of the origin, U.S. distribution, evolution, and regional issues associated with coastal cliffs. Predicting the response of coastal cliffs to future sea-level rise is a topic of active research (Trenhaile, 2001; Walkden and Hall, 2005; Dickson *et al.*, 2007; Walkden and Dickson, 2008).

13.2.2 Sandy Shores, Pocket Beaches, Barrier Beaches, Spits, and Dunes

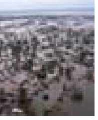
Sandy beaches are often categorized into a few basic types which commonly include mainland, pocket, and barrier beaches (Wells, 1995; Davis and FitzGerald, 2004). The sediments that comprise beaches are derived mainly from the erosion of the adjacent mainland and continental shelf, and sometimes from sediments supplied from coastal rivers. Mainland beaches occur where the land intersects the shore. Some mainland beaches occur in low-relief settings and are backed by coastal dunes, while others occur along steep portions of the coast and are backed by bluffs. Examples of mainland beaches include the shores of eastern Long Island, northern New Jersey (Oertel and Kraft, 1994), and parts of Delaware, (Kraft, 1971). Pocket beaches form in small bays, often occurring between rocky headlands and are common along parts of the southern New England coast, portions of California and Oregon (Hapke *et al.*, 2006), and in parts of the Hawaiian Islands. Barrier beaches and spits are the most abundant coastal landforms along the Atlantic and Gulf of Mexico coasts. In general, it is expected that accelerations in sea-level rise will enhance beach erosion globally, but on a local scale this response will depend on the sediment budget (Nicholls *et al.*, 2007).



13.2.3 Coastal Marshes, Mangroves, and Mud Flat Shorelines

Coastal wetlands include swamps and tidal flats, salt and brackish marshes, mangroves, and bayous. They form in low-relief, low-energy sheltered coastal environments, often in conjunction with river deltas, landward of barrier islands, and along the flanks of estuaries (*e.g.*, Delaware Bay, Chesapeake Bay, Everglades, Lake Pontchartrain, Galveston Bay, San Francisco Bay, and Puget Sound). Most coastal wetlands are in Louisiana, North and South Carolina, south Florida, and Alaska (Dahl, 1990; NRC, 1995a). Wetlands are extremely vulnerable to sea-level rise and can maintain their elevation and viability only if sediment accumulation (both mineral and organic matter) keeps pace with sea-level rise (Cahoon *et al.*, 2006; Nyman *et al.*, 2006; Morris *et al.*, 2002; Rybczyk and Cahoon, 2002). Future wetland area will also be determined, in part, by the amount of space (*e.g.*, mud flat or tidal flat area) available for landward migration and the rates of lateral erosion of the seaward edge of the marsh (see Chapter 4; Poulter, 2005). Wetlands will be especially vulnerable to the higher projected rates of future sea-level rise (*e.g.*, greater than 70 cm by the year 2100), but some will survive a 1-meter rise (Morris *et al.*, 2002). Even under lower accelerated sea-level rise rates, wetlands may be sustained only where conditions are optimal for vertical wetland development (*e.g.*, abundant sediment supply and low regional subsidence rate) (Rybczyk and Cahoon, 2002).

Mud flat shorelines represent a relatively small portion of U.S. coasts, but are important in providing the foundation for wetlands and marshes (Mitsch and Gosselink, 1986). They are frequently associated with wetlands, and occur predominately in low-energy, low-relief regions with high inputs of fine-grained, river-born sediments and organic materials and large tidal ranges. These shoreline types are common in western Louisiana (*i.e.*, Chenier Plain) and along northeastern parts of the Gulf Coast of Florida. Muddy coasts may be drowned with sea-level rise unless sediment inputs are sufficiently large, such as the Atchafalaya River delta region of southwestern Louisiana, where the flats are able to be colonized by plants.



13.2.4 Tropical Coral Reef Coasts

Tropical coral reefs, made up of living organisms very sensitive to ocean temperature and chemistry, are found in the U.S. along the south coast of Florida; around the Hawaiian Islands, Puerto Rico, the Virgin Islands, and many of the U.S. territories in the Pacific (Riegl and Dodge, 2008). In tropical environments, living coral organisms build reefs that are important ecological resources (Smith and Buddemeier, 1992; Boesch *et al.*, 2000). Most corals are able to tolerate rates of sea-level rise of 10 to 20 mm per year or more (Smith and Buddemeier, 1992; Bird, 1995; Wells, 1995; Hallock, 2005). Nonetheless, the ability of coral reef systems to survive future sea-level rise will depend heavily on other climate change impacts such as increase in ocean temperature and/or acidity, sediment runoff from the land, as well as episodic storm erosion (Hallock, 2005; Nicholls *et al.*, 2007). In addition, human caused stresses such as overfishing or pollution can contribute to the vulnerability of these systems to climate change (Buddemeier *et al.*, 2004; Mimura *et al.*, 2007).

13.3 POTENTIAL FOR FUTURE SHORELINE CHANGE

Over the next century and beyond, with an expected acceleration in sea-level rise, the potential for coastal change will increase and coastal change is likely to be more widespread and variable than has been observed in the historic past (NRC, 1987; Brown and McLachlan, 2002; Nicholls *et al.*, 2007). However, it is difficult at present to quantitatively attribute shoreline changes directly to sea-level rise (Rosenzweig *et al.*, 2007). The potential changes include

increased coastal erosion, more frequent tidal and storm-surge flooding of low-relief areas, and wetland deterioration and losses. Many of these changes will occur in all coastal states. These changes to the coastal zone can be expected to have especially large impacts to developed areas (Nicholls *et al*., 2007). Some portions of the U.S. coast will be subject principally to inundation from sea-level rise over the next century, including upper reaches of bays and estuaries (*e.g.*, Chesapeake and Delaware Bays, Tampa Bay, Lake Pontchartrain, San Francisco Bay), and hardened urban shorelines. Erosion, sediment transport, and sediment deposition in coastal environments are active processes and will drive coastal change in concert with the combined effects of future sea-level rise and storms (Stive, 2004).

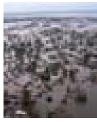
Coastal landforms may become even more dynamic and that erosion will dominate changes in shoreline position over the next century and beyond (Nicholls *et al*., 2007). Wetlands with sufficient sediment supply and available land for inland migration may be able to maintain elevation, keeping pace with sea-level rise, but sediment starved wetlands and those constrained by engineering structures (*e.g.*, seawalls, revetments) or steep uplands are likely to deteriorate and convert to open water through vertical accretion deficits and lateral erosion (see Chapter 4). On barrier island shores, erosion is likely to occur on both the ocean front and the landward side of the island due to a combination of storm activity, changes in sediment budget, more frequent tidal flooding, and rising water levels (Nicholls *et al*., 2007).

Sea-level rise is a particular concern for islands (Mimura *et al*., 2007). Especially at risk are islands comprised of coral atolls (*e.g.*, Midway Atoll), which are typically low-lying and dependent on the health of coral reefs that fringe the atolls. Populated islands with higher elevations (*e.g.*, the Northern Mariana Islands) are also frequently at risk as the infrastructure is frequently located in low-lying coastal regions along the periphery of the islands.

Many coastal areas in the United States will likely experience an increased frequency and magnitude of storm-surge flooding, greater wave heights, and more erosion due to storms as part of the response to sea-level rise (NRC, 1987; Woodworth and Blackman, 2004; Nicholls *et al*., 2007; Gutowski *et al*., 2008). Impacts from these storm events may extend farther inland than those that would be affected by sea-level rise alone. Many regions may also experience large changes to coastal systems, such as increased rates of erosion, barrier island and dune landward migration, and potential barrier island collapse (Nicholls *et al*., 2007; see also Chapters 1, 3, and 14 for discussion of geomorphic thresholds). The potential of crossing thresholds, potentially leading to barrier and wetland collapse, may increase with higher rates of sea-level rise.

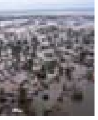
The use of so called “soft” coastal engineering mitigation measures, such as beach nourishment, usually using sand dredged from offshore Holocene-age sand bodies, may reduce the risk of storm flooding and coastal erosion temporarily (NRC, 1987, 1995b). However, an important issue is whether or not these practices are able to be maintained into the future to provide sustainable and economical shoreline protection in the face of high cost, need for periodic renourishment, and limited sand resources of suitable quality for nourishment for many regions of the country (NRC, 1995b; Magoon et al., 2004). Results from offshore geologic mapping studies indicate that most continental shelf regions of the United States have relatively limited Holocene-age sediment that can be deemed available and suitable for uses such as beach nourishment (Schwab *et al*., 2000; Gayes *et al*., 2003; Pilkey *et al*., 1981; Kraft, 1971). In some cases, potential sand volumes are reduced because of economic and environmental factors such as water depth, benthic environmental concerns, and concerns that sand removal may alter sediment exchange with the adjacent coast (Bliss *et al*., 2009). The result is limited volumes of high-quality offshore sand resources readily available for beach nourishment. The issue of relying long term on using offshore sand for beach nourishment to mitigate erosion is important and needs to be addressed.

More widespread implementation of regional sediment or best sediment management practices to conserve valuable coastal clean sandy dredged spoils can enhance the long-term sustainability of sandy coastal landforms (NRC, 2007). The use of so called “hard” engineering structures (*e.g.*, seawalls, breakwaters) to protect property from erosion and flooding may be justified for urban coasts, but their use on sandy shores can further exacerbate erosion over time due to disruption of sediment transport processes. Alternatives, such as relocation landward, strategic removal of development or limiting redevelopment following storm disasters in highly vulnerable parts of the coast, may provide longer term sustainability of both coastal landforms and development, especially if the higher rates of sea-level rise are realized (NRC, 1987). An example of abandonment of an island in Chesapeake Bay due to sea-level rise is detailed in Gibbons and Nicholls (2006). If coastal development is relocated, those areas could be converted to marine protected areas, public open-space lands that would serve to buffer sea-level rise effects landward and also provide recreation benefits and wildlife habitat values (see Salm and Clark, 2000).



13.4 CONCLUSIONS

Global climate is changing, largely due to carbon emissions from human activities (IPCC, 2001, 2007). Sea-level rise is one of the impacts of climate change that will affect all coastal regions of the United States over the next century and beyond (NRC, 1987; Nicholls *et al*., 2007). The scientific tools and techniques for assessing the effects of future sea-level rise on coastal systems are improving, but much remains to be done in order to develop useful forecasts of potential effects. Chapter 14 of this Product identifies research opportunities that, if implemented, would lead to better understanding and prediction of sea-level rise effects that are likely to further impact the United States in the near future. Planning for accelerating sea-level rise should include thorough evaluation of a number of alternatives, such as cost-effective and sustainable shore protection and strategic relocation of development within urban centers. Important decisions like these should ideally be based on the best available science and careful consideration of long-term benefits for a sustainable future, and the total economic, social, and environmental costs of various methods of shore protection, relocation, and adaptation.



CHAPTER 14

A Science Strategy for Improving the Understanding of Sea-Level Rise and Its Impacts on U.S. Coasts

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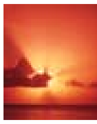
KEY FINDINGS

- Understanding, predicting, and responding to the environmental and human effects of sea-level rise requires an integrated program of research that includes natural and social sciences.
- Monitoring of modern processes and environments could be improved by expanding the network of basic observations and observing systems, developing time series data on environmental and landscape changes, and assembling baseline data for the coastal zone.
- The historic and geologic record of coastal change should be used to improve the understanding of natural and human-influenced coastal systems, increase knowledge of sea-level rise and coastal change over the past few millennia, identify thresholds or tipping points in coastal systems, and more closely relate past changes in climate to coastal change.
- Increases in predictive capabilities can be achieved by improving quantitative assessment methods and integrating studies of the past and present into predictive models.
- Research on adaptation, mitigation, and avoidance measures will enable better understanding of the societal impacts of sea-level rise.
- Decision making in the coastal zone can be supported by providing easy access to data and resources, transferring knowledge of vulnerability and risk that affect decision making, and educating the public about consequences and alternatives.



14.1 INTRODUCTION

Chapter 14 identifies several major themes that present opportunities to improve the scientific understanding of future sea-level rise and its impacts on U.S. coastal regions. Advances in scientific understanding will enable the development of higher quality and more reliable information for planners and decision makers at all levels of government, as well as the public.

A number of recent studies have focused specifically on research needs in coastal areas. Two National Research Council (NRC) studies, *Science for Decision-making* (NRC, 1999) and *A Geospatial Framework for the Coastal Zone* (NRC, 2004) contain recommendations for science activities that can be applied to sea-level rise studies. Other relevant NRC reports include *Responding to Changes in Sea Level* (NRC, 1987), *Sea Level Change* (NRC, 1990b), and *Abrupt Climate Change* (NRC, 2002). The Marine Board of the European Science Foundation's Impacts of Climate Change on the European Marine and Coastal Environment (Philippart *et al*., 2007) identified numerous research needs, many of which have application to the United States. Recent studies on global climate change by the Pew Charitable Trusts also included the coastal zone (*e.g*., Neumann *et al*., 2000; Panetta, 2003; Kennedy *et al*., 2002). Other studies by the NRC (1990a, b, c, 2001, 2006a, 2007) and the Heinz Center (2000, 2002a, b, 2006) have addressed issues relevant to the impacts of sea-level rise on the coastal zone. These reports and related publications have helped guide the development of the potential research and decision-support activities described in the following sections.

14.2 A SCIENCE STRATEGY TO ADDRESS SEA-LEVEL RISE

An integrated scientific program of sea level studies that seeks to learn from the historic and geologic past, and monitors ongoing physical and environmental changes, will improve the level of knowledge and reduce the uncertainty about potential responses of coasts, estuaries, and wetlands to sea-level rise. Outcomes of both natural and social scientific research will support decision making and adaptive management in the coastal zone. The main elements of a potential science strategy and their interrelationships are shown in Figure 14.1.

Building on and complementing ongoing efforts at federal agencies and universities, a research and observation program could incorporate new technologies to address the complex scientific and societal issues highlighted in this Product. These studies could include further development of a robust monitoring program for all coastal regions, leveraging the existing network of site observations, as well as the growing array of coastal observing systems. Research should also include studies of the historic and recent geologic past to understand how coastal systems evolved in response to past changes in sea level. The availability of higher resolution data collected over appropriate time spans, coupled with conceptual and numerical models of coastal evolution, will provide the basis for improved quantitative assessments and the development of predictive models useful for decision making. Providing ready access to interpretations from scientific research—as well as the underlying data—by means of publications, data portals, and decision-support systems will allow coastal managers to evaluate alternative strategies for mitigation, develop appropriate responses to sea-level rise, and practice adaptive management as new information becomes available.

14.2.1 Learn from the Historic and Recent Geologic Past

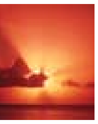
Studies of the recent geologic and historical record of sea-level rise and coastal and environmental change are needed to improve the state of knowledge of the key physical and biological processes involved in coastal change. As described throughout this Product, particularly in Chapters 1 through 5, significant knowledge gaps exist that inhibit useful prediction of future changes. The following research activities will help refine our knowledge of past changes and their causes.

Improve understanding of natural and human-influenced coastal systems

Significant opportunities exist to improve predictions of coastal response to sea-level rise. For example, scientists' understanding of the processes controlling rates of sediment flux in both natural and especially in human-modified coastal systems is still evolving. This is particularly true at the regional (littoral cell) scale, which is often the same scale at which management decisions are made. As described in Chapters 3 and 6, the human impact on coastal processes at management scales is not well understood. Shoreline engineering such as bulkheads, revetments, seawalls, groins, jetties, and beach nourishment can fundamentally alter the way a coastal system behaves by changing the transport, storage, and dispersal of sediment. The same is true of development and infrastructure on mobile landforms such as the barrier islands that comprise much of the mid-Atlantic coast.

Develop better information on the effects of sea-level rise over the past 5,000 years

The foundation of modern coastal barrier island and wetland systems has evolved over the past 5,000 years as the rate of sea-level rise slowed significantly (see Chapters 1, 3, and 4). More detailed investigation of coastal sedimentary deposits is needed to understand the rates and patterns of change during this part of the recent geologic past. Advances in



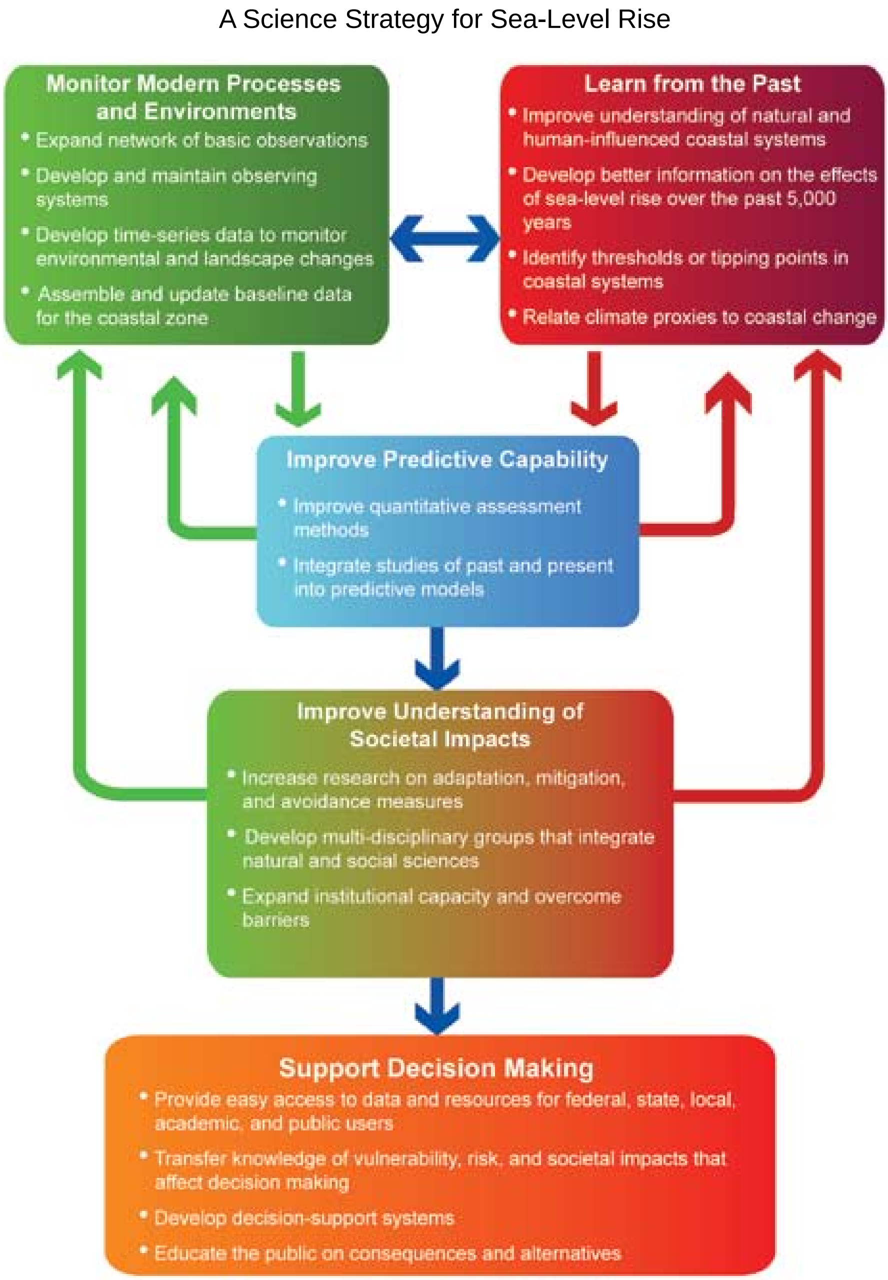
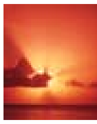


Figure 14.1 Schematic flow diagram summarizing a science strategy for improvement of scientific knowledge and decision-making capability that can address the impacts of future sea-level rise.

methods to obtain samples of the geologic record, along with improvements in analytical laboratory techniques since the early 1990s, have significantly increased the resolution of the centennial-to-millennial scale record of sea-level rise and coastal environmental change (*e.g.*, Gehrels, 1994; Gehrels *et al.*, 1996; van de Plassche *et al.*, 1998; Donnelly *et al.*, 2001; Horton *et al.*, 2006) and provide a basis for future work. Archaeological records of past sea-level change also exist in many locales, and provide additional opportunities to understand coastal change and impacts on human activity.

Understand thresholds in coastal systems that, if crossed, could lead to rapid changes to coastal and wetland systems

Several aspects of climate change studies, such as atmosphere-ocean interactions, vegetation change, sea ice extent, and glacier and ice cap responses to temperature and precipitation, involve understanding the potential for abrupt climate change or “climate surprises” (NRC, 2002; Meehl *et al.*, 2007). Coastal systems may also respond abruptly to changes in sea-level rise or other physical and biological processes (see Box 3.1 in Chapter 3). Coastal regions that may respond rapidly to even modest changes in future



external forcing need to be identified, as well as the important variables driving the changes. For example, limited sediment supply, and/or permanent sand removal from the barrier system, in combination with an acceleration in the rate of sea-level rise, could result in the development of an unstable state for some barrier island systems (*i.e.*, a behavioral threshold or tipping point, as described in Chapters 1 and 3). Coastal responses could result in landward migration or rollover, or barrier segmentation. Understanding and communicating the potential for such dramatic changes in the form and rate of coastal change will be crucial for the development of adaptation, mitigation, and other strategies for addressing sea-level rise.

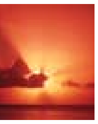
The future evolution of low-elevation, narrow barriers will likely depend in part on the ability of salt marshes in back-barrier lagoons and estuaries to keep pace with sea-level rise (FitzGerald *et al*., 2004, 2008; Reed *et al*., 2008). It has been suggested that a reduction of salt marsh in back-barrier regions could change the hydrodynamics of back-barrier systems, altering local sediment budgets and leading to a reduction in sandy materials available to sustain barrier systems (FitzGerald *et al*., 2004, 2008).

Relate climate proxies to coastal change

Links between paleoclimate proxies (*e.g.*, atmospheric gases in ice cores, isotopic composition of marine microfossils, tree rings), sea-level rise, and coastal change should be explored. Previous periods of high sea level, such as those during the last several interglacial periods, provide tangible evidence of higher-than-present sea levels that are broadly illustrative of the potential for future shoreline changes. For example, high stands of sea level approximately 420,000 and 125,000 years ago left distinct shoreline and other coastal features on the U.S. Atlantic coastal plain (Colquhoun *et al*., 1991; Baldwin *et al*., 2006). While the sedimentary record of these high stands is fragmentary, opportunities exist to relate past shoreline positions with climate proxies to improve the state of knowledge of the relationships between the atmosphere, sea level, and coastal evolution. Future studies may also provide insight into how coastal systems respond to prolonged periods of high sea level and rapid sea-level fluctuations during a high stand. Examples of both exist in the geologic record and have potential application to understanding and forecasting future coastal evolution.

14.2.2 Monitor Modern Coastal Conditions

The status and trends of sea-level change, and changes in the coastal environment, are monitored through a network of observation sites, as well as through coastal and ocean observing systems. Monitoring of modern processes and environments could be improved by expanding the network of basic observations, as well as the continued development of coastal and ocean observing systems. There are numerous ongoing efforts that could be leveraged to contribute to understanding patterns of sea-level rise over space and time and the response of coastal environments.



Expand the network of basic observations

An improvement in the coverage and quality of the U.S. network of basic sea-level observations could better inform researchers about the rate of sea-level rise in various geographic areas. Tide gauges are a primary source of information for sea-level rise data at a wide range of time scales, from minutes to centuries. These data contribute to a multitude of studies on local to global sea-level trends. Tide gauge data from the United States include some of the longest such datasets in the world and have been especially valuable for monitoring long-term trends. A denser network of high-resolution gauges would more rigorously assess regional trends and effects. The addition of tide gauges along the open ocean coast of the United States would be valuable in some regions. These data can be used in concert with satellite altimetry observations.

Tide-gauge observations also provide records of terrestrial elevation change that contributes to relative sea-level change, and can be coupled with field- or model-based measurements or estimates of land elevation changes. Existing and new gauges should be co-located with continuously operating Global Positioning System (GPS) reference stations (CORS) or surveyed periodically using GPS and other Global Navigation Satellite System technology. This will enable the coupling of the geodetic (earth-based) reference frame and the oceanographic reference frame at the land-sea interface. Long time series from CORS can provide precise local vertical land movement information in the ellipsoidal frame (*e.g.*, Snay *et al*., 2007; Woppelmann *et al*., 2007). Through a combined effort of monitoring ellipsoid heights and the geoid, as well as through gravity field monitoring, changes in coastal elevations can be adequately tracked.

Develop and maintain coastal observing systems

Observing systems have become an important tool for examining environmental change. They can be place-based (*e.g.*, specific estuaries or ocean locations) or consist of regional aggregations of data and scientific resources (*e.g.*, the developing network of coastal observing systems) that cover an entire region. Oceanographic observations also need to be integrated with observations of the physical environment, as well as habitats and biological processes.

An example of place-based observing systems is the National Estuarine Research Reserve System (NERRS: <http://www.nerrs.noaa.gov>), a network of 27 reserves for long-term research, monitoring, education, and resource stewardship. Targeted experiments in such settings can potentially elucidate impacts of sea-level rise on the physical environment, such as shoreline change or impacts to groundwater systems, or on biological processes, such as species changes or ecosystem impacts. Important contributions can also be made by the Long Term Ecological Research sites (<http://www.lternet.edu>) such as the Virginia Coast Reserve in the mid-Atlantic area (part of the focus area of this Product). The sites combine long-term data with current research to examine ecosystem change over time. Integration of these ecological monitoring networks with the geodetic and tide gauge networks mentioned previously would also be an important enhancement.

The Integrated Ocean Observing System (IOOS) (<http://www.ocean.us>) will bring together observing systems and data collection efforts to understand and predict changes in the marine environment. Many of these efforts can contribute to understanding changes in sea-level rise over space and time. These observing systems incorporate a wide range of data types and sources, and provide an integrated approach to ocean studies. Such an approach should enable sea-level rise-induced changes to be distinguished from the diverse processes that drive changes in the coastal and marine environment.

A new initiative began in 2005 with a worldwide effort to build a Global Earth Observation System of Systems (GEOSS) (<http://www.earthobservations.org>) over the next 10 years. GEOSS builds upon existing national, regional, and international systems to provide comprehensive, coordinated Earth observations from thousands of instruments worldwide, which have broad application to sea-level rise studies.

Develop time series data to monitor environmental and landscape changes

Observations of sea level using satellite altimetry (*e.g.*, TOPEX/Poseidon and Jason-1) have provided new and important insights into the patterns of sea-level change across space and time. Such observations have allowed scientists to examine sea-level trends and compare them to the instrumental record (Church *et al*., 2001, 2004), as well as predictions made by previous climate change assessments (Rahmstorf, 2007). The satellite data provide spatial coverage not available with ground-based methods such as tide gauges, and provide an efficient means for making global observations. Plans for future research could include a robust satellite observation program to ensure comprehensive coverage.

Studies of environmental and landscape change can also be expanded across larger spatial scales and longer time scales. Examples include systematic mapping of shoreline changes and coastal barriers and dunes around the United States (*e.g.*, Morton and Miller, 2005), and other national mapping efforts to document land-use and land-cover changes (*e.g.*, the NOAA Coastal Change Analysis Program: <http://www.csc.noaa.gov/crs/lca/ccap.html>). It is also important to undertake a rigorous study of land movements beyond the point scale of tide gauges and GPS networks. For example, the application of an emerging technology—Interferometric Synthetic Aperture Radar (InSAR)—enables the development of spatially-detailed maps of land-surface displacement over broad areas (Brooks *et al*., 2007).

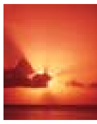
Determining wetland sustainability to current and future sea-level rise requires a broader foundation of observations if they are to be applied with high confidence at regional and national scales. In addition, there is a significant knowledge gap concerning the viability or sustainability of human-impacted and restored wetlands in a time of accelerating sea-level rise. The maintenance of a network of sites that utilize surface elevation tables and soil marker horizons for measuring marsh accretion or loss will be essential in understanding the impacts on areas of critical wetland habitat. The addition of sites to the network would aid in delineating regional variations (Cahoon *et al*., 2006). Similar long-term studies for coastal erosion, habitat change, and water quality are also essential.

Coastal process studies require data to be collected over a long period of time in order to evaluate changes in beach and barrier profiles and track morphological changes over a time interval where there has been a significant rise in sea level. These data will also reflect the effects of storms and the sediment budget that frequently make it difficult to extract the coastal response to sea-level change. For example, routine lidar mapping updates to track morphological changes and changes in barrier island area above mean high water (*e.g.*, Morton and Sallenger, 2003), as well as dune degradation and recovery, and shore-face profile and near-shore bathymetric evolution may provide insight into how to distinguish various time and space scales of coastal change and their relationship to sea-level rise.

Time series observations can also be distributed across the landscape and need not be tied to specific observing systems or data networks. They do, however, need a means to have their data assimilated into a larger context. For example, development of new remote sensing and *in situ* technologies and techniques would help fill critical data gaps at the land-water interface.

Assemble and update baseline data for the coastal zone

Baseline data for the coastal zone, including elevation, bathymetry, shoreline position, and geologic composition of the coast, as well as biologic and ecologic parameters such as vegetation and species distribution, and ecosystem and habitat boundaries, should be collected at high spatial resolu-



tion. As described in Chapter 2, existing 30-m (100-ft) digital elevation models are generally inadequate for meaningful mapping and analyses in the coastal zone. The use of lidar data, with much better horizontal and vertical accuracy, is essential. While some of these mapping data are being collected now, there are substantial areas around the United States that would benefit from higher quality data. More accurate bathymetric data, especially in the nearshore, is needed for site-specific analyses and to develop a complete topographic-bathymetric model of the coastal zone to be able to predict with greater confidence wave and current actions, inundation, coastal erosion, sediment transport, and storm effects.

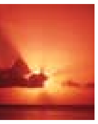
To improve confidence in model predictions of wetland vulnerability to sea-level rise, more information is needed on: (1) maximum accretion rates (*i.e.*, thresholds) regionally and among vegetative communities; (2) wetland dynamics across larger landscape scales; (3) the interaction of feedback controls on flooding with other accretion drivers (*e.g.*, nutrient supply and soil organic matter accumulation); (4) fine-grained, cohesive sediment supplies; and (5) changing land use in the watershed (*i.e.*, altered river flows and accommodation space for landward migration of wetlands). In addition, population data on different species in nearshore areas are needed to accurately judge the effects of habitat loss or transformation. More extensive and detailed habitat mapping will enable preservation efforts to be focused on the most important areas.

14.2.3 Predict Future Coastal Conditions

Studies of the past history of sea-level rise and coastal response, combined with extensive monitoring of present conditions, will enable more robust predictions of future sea-level rise impacts. Substantial opportunities exist to improve methods of coastal impact assessment and prediction of future changes.

Develop quantitative assessment methods that identify high-priority areas needing useful predictions

Assessment methods are needed to identify both geographic and topical areas most in need of useful predictions of sea-level rise impacts. For example, an assessment technique for objectively assessing potential effects of sea-level rise on open coasts, the Coastal Vulnerability Index (CVI), has been employed in the United States and elsewhere (*e.g.*, Gornitz *et al*., 1997; Shaw *et al*., 1998; Thieler and Hammar-Klose, 1999, 2000a, 2000b). Although the CVI is a fairly simplistic technique, it can provide useful insights and has found application as a coastal planning and management tool (Thieler *et al*., 2002). Such assessments have also been integrated with socioeconomic vulnerability criteria to yield a more integrative measure of community vulnerability (Boruff *et al*., 2005).



Projecting long-term wetland sustainability to future sea-level rise requires data on accretionary events over sufficiently long time scales that include the return periods of major storms, floods, and droughts, as well as information on the effects of wetland elevation feedback on inundation and sedimentation processes that affect wetland vertical accretion. Numerical models can be applied to predict wetland sustainability at the local scale, but there is not sufficient data to populate these models at the regional or national scale (see Chapter 4). Given this data constraint, current numerical modeling approaches will need to improve or adapt such that they can be applied at broader spatial scales with more confidence.

Integrate studies of past and present coastal behavior into predictive models

Existing shoreline-change prediction techniques are typically based on assumptions that are either difficult to validate or too simplistic to be reliable for many real-world applications (see Appendix 2). As a result, the usefulness of these modeling approaches has been debated in the coastal science community (see Chapter 3). Newer models that include better representations of real-world settings and processes (*e.g.*, Cowell *et al*., 1992; Stolper *et al*., 2005; Pietrafesa *et al*., 2007) have shown promise in predicting coastal evolution. Informing these models with improved data on past coastal changes should result in better predictions of future changes.

The process of marine transgression across the continental shelf has left an incomplete record of sea-level and environmental change. An improved understanding of the rate and timing of coastal evolution will need to draw on this incomplete record, however, in order to improve models of coastal change. Using a range of techniques, such as high-resolution seafloor and geologic framework mapping coupled with geochronologic and paleoenvironmental studies, the record of coastal evolution during the Pleistocene (1.8 million to 11,500 years ago) and the Holocene (the last 11,500 years) can be explored to identify the position and timing of former shorelines and coastal environments.

14.2.4 Improve Understanding of Societal Impacts

Research in the social sciences will be critical to understanding the potential effects on society and social systems resulting from sea-level rise.

Increase research on adaptation, mitigation, and avoidance measures

This Product describes a wide variety of potential impacts of sea-level rise, including the effects on the physical environment, biological systems, and coastal development and infrastructure. While the ability to predict future changes is currently inadequate for many decisions, adaptation, mitigation, and avoidance strategies must evolve as scientific knowledge and predictive ability increase. For example, expanded research and assessments of the economic and environmental costs of present and future actions are needed to allow a more complete analysis of the tradeoffs involved in sea-level rise decision making. In addition, opportunities to engage stakeholders such as federal agencies, states, counties, towns, non-government organizations, and private landowners in the design and implementation of sea-level rise impact and response planning should be created.

Develop multi-disciplinary groups that integrate natural and social sciences
Interdisciplinary research that combines natural and social sciences will be crucial to understanding the interplay of the physical, environmental, and societal impacts of sea-level rise. Development of programs that facilitate such collaborations should be encouraged.

Expand institutional capacity and overcome barriers
Substantial opportunities exist to expand and improve upon the ability of institutions to respond to sea-level rise (see Chapters 10, 11, and 12). Research is needed to define the capacity needed for decision making, as well as the methods that can be best employed (*e.g.*, command and control, economic incentive) to achieve management goals. Overcoming the institutional barriers described in Chapter 12 is also necessary for effective response to the management challenges presented by sea-level rise.

14.2.5 Develop Coastal Decision-Support Systems for Planning and Policy Making

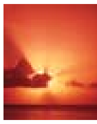
For coastal zone managers in all levels of government, there is a pressing need for more scientific information, a reduction in the ranges of uncertainty for processes and impacts, and new methods for assessing options and alternatives for management strategies. Geospatial information on a wide range of themes such as topography, bathymetry, land cover, population, and infrastructure, that is maintained on a regular cycle will be a key component of planning for mitigation and adaptation strategies. For example, specialized themes of data such as hydric (abundantly moist) soils may be critical to understanding the potential for wetland survival in specific areas. Developing and maintaining high-resolution maps that incorporate changes in hazard type and distribution, coastal development, and societal risk will be critical. Regularly conducting vulnerability assessments and reviews will be necessary in order to adapt to changing conditions.

Provide easy access to data and information resources for federal, state, local, academic, and public users
Understanding and acting on scientific information about sea-level rise and its impacts will depend upon common, consistent, shared databases for integrating knowledge and providing a basis for decision making. Thematic data and other value-added products should adhere to predetermined standards to make them universally accessible and transferable through internet portals. All data should be accompanied by appropriate metadata describing its method of production, extent, quality, spatial reference, limitations of use, and other characteristics (NRC, 2004).

An opportunity exists to undertake a national effort to develop and apply data integration tools to combine terrestrial and marine data into a seamless geospatial framework. For example, this could involve the collection of real-time oceanographic data and the development of more sophisticated hydrodynamic models for the entire U.S. coastline, as well as the establishment of protocols and tools for merging bathymetric and topographic datasets (NRC, 2004). Modern and updated digital flood insurance rate maps (DFIRM) that incorporate future sea-level rise are needed in the coastal zone (see Chapter 9).

Transfer scientific knowledge to studies of vulnerability, risk, and societal impacts
In addition to basic scientific research and environmental monitoring, a significant need exists to integrate the results of these efforts into comprehensive vulnerability and risk assessments. Tools are needed for mapping, modeling, and communicating risk to help public agencies and communities understand and reduce their vulnerability to, and risk of, sea-level rise hazards. Social science research activities are also needed that examine societal consequences and economic impacts of sea-level rise, as well as identify institutional frameworks needed to adapt to changes in the coastal zone. For example, analyses of the economic costs of armoring shores at risk of erosion and the expected lifespan of such efforts will be required, as will studies on the durability of armored shorefronts under different sea-level rise scenarios. The physical and biological consequences of armoring shores will need to be quantified and the tradeoffs communicated. Effective planning for sea-level rise will also require integrated economic assessments on the impact to fisheries, tourism, and commerce.

Applied research in the development of coastal flooding models for the subsequent study of ecosystem response to sea-level rise is underway in coastal states such as North Carolina (Feyen *et al.*, 2006). There is also a need for focused study on the ecological impacts of sea-level rise and in how the transfer of this knowledge can be made to coastal managers for decision making.



Develop decision-support systems
Local, county, and state planners need tools to analyze vulnerabilities, explore the implications of alternative response measures, assess the costs and benefits of options, and provide decision-making support. These might take the form of guidelines, checklists, or software tools. In addition, there is a need to examine issues in a landscape or ecosystem context rather than only administrative boundaries.

In addition to new and maintained data, models, and research, detailed site studies are needed to assess potential impacts on a site-specific basis and provide information that allows informed decision making. Appropriate methodologies need to be developed and made available. These will have to look at a full range of possible impacts including aquifer loss by saltwater intrusion, wetland loss, coastal erosion, and infrastructure implications, as well as the impact of adaptation measures themselves. Alternative strategies of adaptive management will be required. Each locality may need a slightly different set of responses to provide a balanced policy of preserving ecosystems, protecting critical infrastructure, and adjusting to property loss or protection. Providing a science-based set of decision support tools will provide a sound basis for making these important decisions.

Educate the public on consequences and alternatives
Relative to other natural hazards such as earthquakes, volcanic eruptions, and severe weather (*e.g.*, hurricanes, tornadoes) that typically occur in a time frame of minutes to days, sea-level rise has a long time horizon over which effects become clear. Thus, it is often difficult to communicate the consequences of this sometimes slow process that occurs over many years. The impacts of sea-level rise, however, are already being felt across the United States (see Chapter 13). Public education will be crucial for adapting to physical, environmental, economic, and social changes resulting from sea-level rise. Research activities that result in effective means to conduct public education and outreach concerning sea-level rise consequence and alternatives should be encouraged.