Part VI: A Science Strategy for Improving Our Understanding of Sea-Level Rise and its Impacts on U.S. Coasts

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VI.1 INTRODUCTION

This section of the report identifies several major themes that present opportunities to improve our 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. An integrated scientific program of sea level studies that seeks to learn from the historic and geologic past, and monitor ongoing physical and environmental changes will improve our knowledge and reduce the uncertainty about potential responses of coasts, estuaries and wetlands to sea-level rise. Outcomes of 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 VI-1.

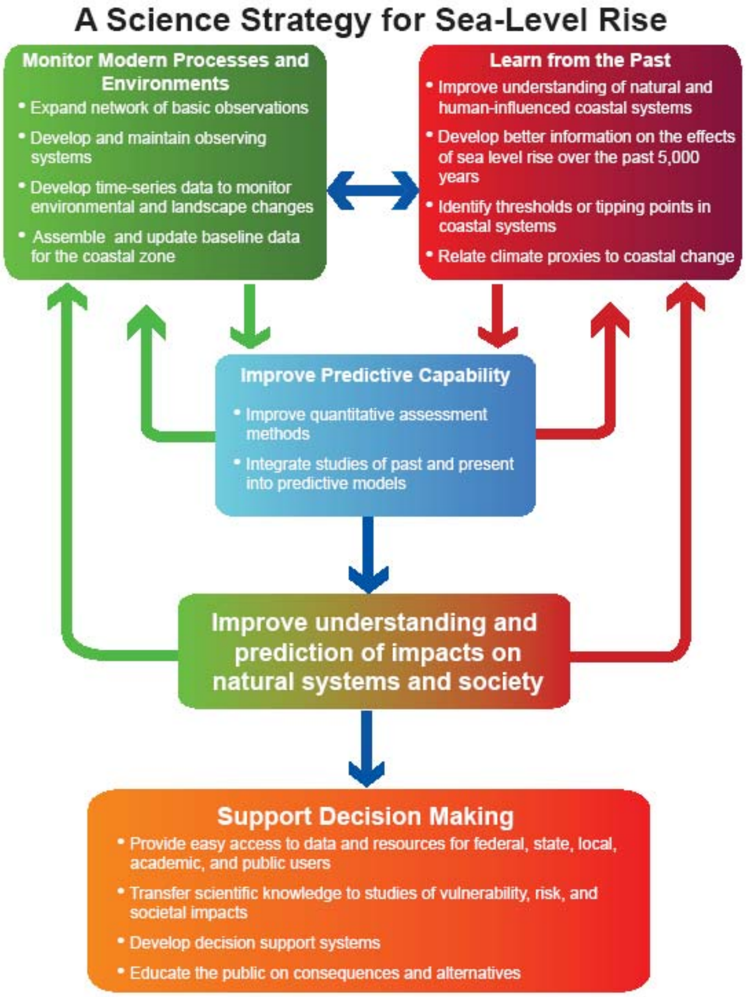

Figure VI.1 Schematic flow diagram summarizing a science strategy for improvement of scientific knowledge and decision making capability needed to address the impacts of future sea level rise.

Building on and complementing ongoing efforts at federal agencies and universities, a research and observation program should incorporate new technologies to address the complex scientific and societal issues highlighted in this report. These studies should 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 sufficient time spans, coupled with conceptual and numerical models of coastal evolution should 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.

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 numerous 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, 1990) 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 U.S. Recent Pew Trust studies (Panetta, 2003, Kennedy, *et al.*, 2002) on global climate change included the coastal zone. Other recent studies by the NRC (1990a, 1990b, 1990c, 2001, 2006a, 2006b) and the Heinz

Center (2000, 2002a, 2002b, 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 below.

VI.1.1 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 our understanding of the key physical and biological processes involved in coastal change. As described throughout this report, and particularly in Chapters 2 and 3, significant knowledge gaps exist that inhibit useful prediction of future changes.

- Improve understanding of natural and human-influenced coastal systems

Significant opportunities exist to improve predictions of coastal response to sea-level rise. For example, our understanding of the processes controlling and 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. 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 alter fundamentally 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

Broadly speaking, 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. 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 stratigraphic sampling and analytical techniques over the past 15 years have improved significantly the centennial to millennial scale record of sea-level rise and coastal environmental change (*e.g.*, Gehrels, 1994; Gehrels *et al.*, 1995; van de Plassche, 1997; Donnelly *et al.*, 2001; Horton *et al.*, 2006) and provide a basis for future work.

- 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 glaciers and ice cap responses to temperature and precipitation, involve understanding the potential for abrupt climate change or ‘climate surprises’ (Meehl *et al.*, 2007). Coastal systems may also respond abruptly to changes in sea-level rise or other physical and biological processes (see Box 2.1 in Chapter 2). 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). Coastal responses could result in: a) landward migration or roll-over, b) barrier segmentation, or c) barrier disintegration. If the barrier were to disintegrate, portions of the ocean shoreline could migrate or back-step toward and/or merge with the mainland.

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.*, 2003; FitzGerald *et al.*, 2006; Reed *et al.*, 2007). It has been suggested that a reduction of salt marsh in back-barrier regions could change the hydraulics of back-barrier systems, altering local sediment budgets and leading to a reduction in sandy materials available to sustain barrier systems (FitzGerald *et al.*, 2003, 2006).

- 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, sea level high-stands 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 our understanding 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 (MIS 11), and rapid sea level fluctuations during a high-stand (MIS 5) (Neumann and Hearty, 1996).

VI.1.2 Monitor Modern Coastal Conditions

The status and trends of sea level change and changes in coastal environments should be better monitored by expanding the existing network of observation sites, as well as through the continued development of coastal and ocean observing systems. There are numerous ongoing efforts that could be leveraged to contribute to understanding spatial and temporal patterns of sea level rise and the response of coastal environments.

- Expand the network of basic observations

The coverage and quality of the U.S. network of basic observations of sea level should be improved. Tide gauges are a primary source of information for sea-level rise data at a wide range of temporal scales, from minutes to centuries. These data contribute to a multitude of studies on local to global sea level trends. U.S. tide gauge data include some of the longest such data sets in the world and have been especially valuable for monitoring long-term trends.

A denser network of high-resolution gauges is needed to rigorously assess regional trends and effects. The addition of tide gauges along the open ocean coast of the U.S. 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 also be connected to GPS-based Continuously Operating Reference Systems (CORS) to enable the coupling of the geodetic and oceanographic vertical reference frames at the land-sea interface. Long time series data from CORS can provide precise local vertical land movement information (*e.g.*, Snay et al, 2007; Woppelmann *et al*, 2007) that contribute to the delineation of eustatic and non-eustatic sea level change.

- 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, such as that for the Gulf of Maine) that cover an entire region. Oceanographic observations also need to be integrated with observations of habitats biological processes.

An example of place-based observing systems is the National Estuarine Research Reserve System (NERRS: http://www.ners.noaa.gov/, accessed 21 September 2007), 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 biological processes, such as species changes or ecosystem impacts. Important contributions are also made by the Long Term Ecological Research sites (http://www.lternet.edu/, accessed 21 September 2007) such as the Virginia Coast Reserve. The sites combine long-term data with current research to closely 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/, accessed 21 September 2007) 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 spatial and temporal changes in sea-level rise. These observing systems bring together 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 major new initiative began in 2005 with a worldwide effort to build a Global Earth Observation System of Systems (GEOSS) (http://www.earthobservations.org/, accessed 21 September 2007) over the next 10 years. GEOSS will work with and build upon existing national, regional, and international systems to provide comprehensive, coordinated Earth observations from thousands of instruments worldwide, and should 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) have provided new and important insights into the temporal and spatial patterns of sea level change. 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 *et al.*, 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 should include a robust satellite observation program.

Studies of environmental and landscape change also need to be expanded across larger spatial scales and longer time scales. Examples include systematic mapping of shoreline changes and coastal barrier and dunes around the U.S. (*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, accessed 21 September 2007). It is also important to undertake a rigorous study of land movements beyond the point scale of tide gauges and Global Positioning System networks. A good example is the application of an emerging technology—Interferometric Synthetic Aperture Radar (InSAR)—which 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 the 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 essential.

Coastal process studies require a long time series of data to evaluate changes in beach and barrier profiles to track morphological changes over a period 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 bathymetry 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, new remote sensing and *in-situ* technologies and techniques should be developed to 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, ecosystem and habitat boundaries, should be collected at high spatial resolution. Existing 30-meter digital elevation models are generally inadequate for meaningful mapping and analyses in the coastal zone. The use of lidar data, with much closer data spacing and better vertical resolution, is essential. While some of these mapping data are being collected now, there are significant areas around the U.S. that need higher quality data. More accurate bathymetric data, especially in the near-shore, is required for site specific analyses and to develop a complete topographic-bathymetric model of the coastal zone to be able to predict with confidence wave and current actions, inundation, shoreline 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 near shore areas are needed to accurately judge the effects of habitat loss or transformation. More extensive and detailed areas of habitat mapping will enable preservation efforts to be focused on the most important areas.

VI.1.3 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.

- Develop quantitative assessment methods that identify high-priority areas (geographic or topical) 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 U.S. and elsewhere (*e.g.*, Gornitz and White, 1992; Shaw *et al.*, 1998; Thieler and Hammar-Klose, 1999; 2000a; 200b). Although the CVI is a fairly simplistic technique, it offers useful insights and has found application as a coastal planning and management tool (Thieler *et al.*, 2002).

Projecting long-term wetland sustainability to future sea-level rise requires data on accretionary events over sufficiently long time scales that encompass return frequencies 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 3). 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

As summarized by Gutierrez *et al.* (2007), 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. As a result, the usefulness of these modeling approaches has been debated in the coastal science community (see Chapter 2). Newer models that include better representations of real-world settings and processes (*e.g.*, Cowell and Roy, 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.

Although 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 is needed 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 Late Pleistocene to Holocene coastal evolution should be explored to identify the position and timing of former shorelines and coastal environments.

VI.1.4 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 of assessing options and alternatives for management strategies. Geospatial information on a wide range of themes that is maintained on regular cycle will be a key component of planning for mitigation and adaptation strategies. For example, specialized themes of data such as hydric 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. A regular process of undertaking vulnerability assessments and reviews will be necessary 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 (NRC, 2004).

In order to combine terrestrial and marine data in a seamless geospatial framework, a national project to develop and apply data integration tools should be initiated. This will involve the collection of real-time tide 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.

- 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 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

Feedback from stakeholder meetings during the preparation of this report made it clear that 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, stakeholders recognize the 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 will be required 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 mix 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.

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