Sea-level rise and coastal change: Causes and implications for the future of coasts and low-lying regions

By

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ABSTRACT

According to climate change assessment reports published in 2008 and 2009 by the U.S. Global Change Research Program and the U.S. Climate Change Science Program, observations show that recent increase in global temperature is unequivocal; and that warming and widespread environmental change primarily result from increase in greenhouse gas emissions from anthropogenic fossil fuel burning. Additional contributions to climate change are from land-use activities since the late 19th century.

One of the most significant climate-change impacts is sea-level rise. Direct sea-level rise impacts include: increased coastal erosion, more frequent tidal and storm-surge flooding, inundation of low-lying areas, saltwater intrusion, wetland loss, and threats to human infrastructure in coastal zones. Climate-change assessments, such as the United Nation's Intergovernmental Panel on Climate Change Fourth Report, suggest that global sea level for this century will rise 18-59 cm (IPCC 2007). More recent modeling studies suggest that sea-level rise rates may be significantly higher in the decades ahead due to climate processes that appear to be stronger than previously thought (e.g. Greenland and West Antarctica ice-sheet melting, ocean current disruption). These recent studies suggest that global sea-level rise could be 1 m or more by the year 2100 and continued accelerated melting in Greenland and West Antarctica could lead to 4 m to 6 m rise over the next several hundred years.

Accelerated sea-level rise will have significant impacts on coastal and wetland systems, natural resources and habitats, and societies world-wide. Coastal scientists have developed conceptual and qualitative frameworks based on field studies and modeling to understand the primary factors and processes that drive coastal change. However, current techniques used to predict coastal change such as inundation modeling, historical shoreline-change analysis, and equilibrium-profile modeling can not yet provide reliable long-term predictions at spatial and temporal scales considered optimal for local coastal planning and decision making. With substantial acceleration of sea-level rise, some coastal management and engineering practices (i.e. maintaining shoreline position with hard structures, beach nourishment) will become more difficult for society and may not be economically or environmentally sustainable. Sea-level rise projections and implications need to be fully considered in coastal management plans and engineering design. Options such as relocation of infrastructures to higher elevations and conversion of low-lying developed areas to parks for open-space conservation and recreation may be more appropriate for adapting to coming coastal change.

Global climate has been highly variable throughout Earth's history. The causes for this variability result from complex interactions between the land, ocean, and atmosphere which involve positive and negative feedback. Geologic and historical records show cyclical fluctuations in global sea level associated with global climate change (e.g. Lambeck *et al.* 2002; Miller *et al.* 2005; IPCC 2001; IPCC 2007; Hansen *et al.* 2007; Broecker and Kunzig 2008). For example, during the last interglacial warm period (~125,000 yrs BP) sea level was approximately 5 m higher than present, and during the Last Glacial Maximum (~21,000 yrs BP), sea level was about 120 m lower than present (Figure 1) (Fairbanks 1989; Muhs *et al.* 2004).

ADDITIONAL KEYWORDS: Subsidence, wetlands, climate change, global warming, coastal erosion, barrier islands, spits, bluffs, thresholds, storms, waves, beach nourishment, sand resources, coastal zone management, coastal adaptation.

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Analyses of historic sea-level measurements show that sea level rose on average 19 cm during the 20th century (Jevrejeva *et al.* 2008). Moreover, a number of studies and assessments conducted in recent years continue to suggest that the rate of sea-level rise is likely to increase during the 21st century (IPCC 2007; Rahmstorf 2007; Pfeffer *et al.* 2008). While uncertainty exists in predicting quantitatively the magnitude and rates of future change in sea level, a solid body of scientific evidence suggests that sea level has risen over the recent geologic past, is currently rising and is thought to contribute to various effects such as coastal erosion, increased tidal flooding, and inundation. There is consensus among climate scientists that sea level is very likely to rise at an accelerated rate this century and for centuries beyond (IPCC 2007).

Accelerated global sea-level rise is a major long-term outcome of climate change which will have impacts on all coastal regions. The effects of climate change on coasts are not uniform, but vary considerably from region to region and over a range of temporal scale (Nicholls *et al.* 2007).

Understanding how sea-level rise will affect coastal regions and how society

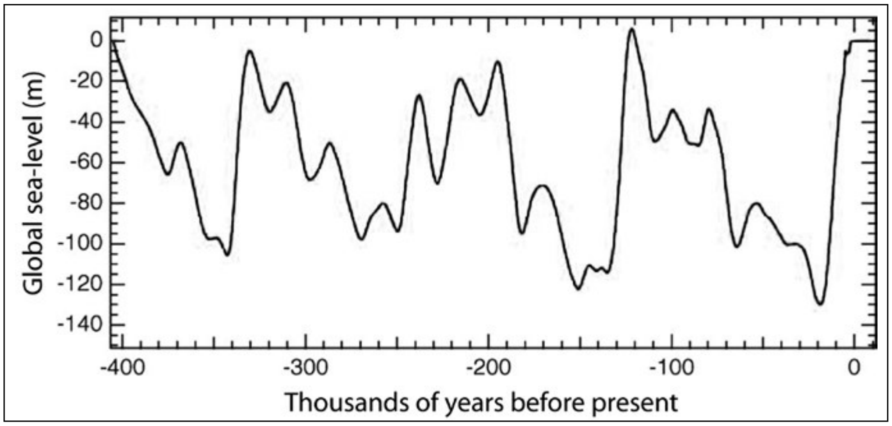

Figure 1. Plot of large variations in global sea-level elevation over the past 400,000 years resulting from four glacial and interglacial global climate cycles. Evidence suggests that sea level was about 4-6 m higher than present during the last interglacial warm period 125,000 years ago, and 120 m lower during the Last Glacial Maximum, 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, Huybrechts (2002), 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.

will choose to address it in ways that are sustainable for the long term is a major challenge for both scientists and policy-makers. Over the past several thousand years, global climate and sea level have been relatively stable and some have suggested that this has enabled the expansion of human populations (~6.8 billion people presently) and the development of modern society (Day *et al.* 2007). In coastal regions of the U.S. and also globally, human populations (~130 million people and ~600 million people, respectively) are substantial, continue to expand rapidly, and are increasingly at risk from natural hazards (Crossett *et al.* 2004; McGranahan, *et al.* 2007).

Coastal lands will not simply be inundated, but will be modified by a variety of dynamic processes whose impacts will vary by location and geologic setting. Several driving forces influence the evolution of the coast in response to sea-level rise: 1) framework geology, 2) oceanographic processes, 3) sediment supply, and 4) human activity (Carter and Woodroffe 1994; Morton 2003; FitzGerald *et al.* 2008). All of these factors interact in complex ways driving the response of coastal landforms to sea level change.

One of the most important sea-level rise impacts is shoreline change. On sandy coasts such as much of the U.S. coast, shoreline changes result from changes in beach morphology. These changes do not occur directly as the result of sea-level rise, but shores are in an almost continual state of change in response to waves and currents, as well as sediment availability (Carter and Woodroffe 1994; 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 (~30 cm to 40 cm along the U.S. mid-Atlantic coast). During this time, major storms, variations in sediment supply to the coast, and human activity have had more direct effects on shoreline change. 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 underlying geology, the mechanics of which are not yet understood, also influence the behavior of beach morphology over time (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, mitigate erosion, and maintain navigation channels have altered the behavior of some portions of the coast considerably (Dean and Perlin 1977; Leatherman 1984; Nordstrom 1994, 2000; Nicholls *et al.* 2007).

During the 20th century, coastal management and planning have been based on the premise that coastal change and sea-level rise are modest and fairly predictable, but recently several states and organizations (e.g. Coastal States Organization, The Nature Conservancy, American Society of Civil Engineers [ASCE], Canadian Society of Civil Engineers [CSCE], British Institution of Civil Engineers[BICE]) are recognizing that climate change is an important issue and that adaptation to climate change effects need to be integrated into coastal zone management and coastal engineering planning and practice (e.g. Civil Engineering and Climate Change Protocol signed by ASCE, CSCE and BICE in June 2009).

The focus of this paper is on sea-level rise, its causes and effects on U.S. coasts and implications for planning and management. It complements the paper by Charles Fletcher in this volume. This paper is based partly on findings and results presented in chapters 1, 2, 3, 4, and 13 of the recently published Synthesis and Assessment Product 4.1 from the U.S. Climate Change Science Program (CCSP 2009).

GLOBAL SEA-LEVEL CHANGE

Sea level has varied throughout Earth's history due to a variety of processes that operate over a range of spatial and temporal scales (Douglas *et al.* 2001; Miller *et al.* 2005). On a global scale, sea level varies as the volume and mass of ocean water changes, and as the volume of the ocean basins changes. Two primary contributors to ocean volume and mass are from thermal expansion through heat uptake and the addition of melt water from grounded ice sheets and glaciers (IPCC 2007; Bindoff *et al.* 2007). Over the last 3 million years, oxygen isotope records have provided evidence that sea level has varied primarily in response to shifts from glacial to interglacial periods such that mass exchange between land based ice and the ocean dominates long-term sea-level variability (Lambeck *et al.* 2002). These records indicate that over the last 800,000 years the magnitude of the sea-level changes has been on the order of 120 m to 140 m with a period of about 100,000 years (Figure 1).

Since the last glacial maximum 21,000 years ago, sea level rose approximately 120 m (Figure 2, Fairbanks 1989). Evidence from the coral record constructed by Fairbanks (1989) indicates that sea-level rise between 21,000 to 6,000 years ago averaged 10 mm/yr and was punctuated with two distinct "meltwater pulses" when rates may have reached 50 mm/yr (Fairbanks 1989; CCSP 2008). Sea-level rise then slowed to a rate of about 0.5 mm/yr from 6,000 to 3,000 years ago (Fairbanks 1989; Rohling *et al.* 2008). The rate of global sea-level rise has slowed episodically with rates eventually reaching a near still-stand (0 to 0.2 mm/yr) 2,000 to 3,000 years ago approaching the current position (Lambeck and Bard 2000). Rates increased in the late 19th and early 20th centuries, (Bindoff *et al.* 2007; Lambeck *et al.* 2004; Gehrels *et al.* 2008), and some studies indicate that acceleration in sea-level rise may have begun earlier, in the 18th century (Figure 3) (Jevrejeva *et al.* 2008).

Analyses of tide-gauge data indicate that the 20th century rate of sea-level rise averaged 1.7 mm/yr on a global scale (Bindoff *et al.* 2007), with decadal fluctuations occurring over 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). Given this short 10-year record, it is not yet possible to determine with certainty whether this is a natural decadal variation or a definitive acceleration in sea-level rise due to climate warming (Bindoff *et al.* 2007). The IPCC (2007) estimates that the increase is due to equal contributions from ocean thermal expansion and ice-sheet melting. Recent studies of the global sea-level rise budget (years 2003 to 2008) by Cazenave *et al.* (2009) found that the rate of sea-level is about 2.5 mm/yr and reflects mainly glacial melt contributions, while thermal expansion has leveled off in comparison to observations from the previous decade.

The recent climate change assessment by the IPCC (2007) included model-based forecasts of sea-level rise by the end of the 21st century. The results indicated that sea level could rise 18-59 cm, but these projections did not include acceleration in melting of major land-based ice masses (Meehl *et al.* 2007). More recent studies suggest that sea-level rise may accelerate in decades ahead as Greenland ice-sheet melting and West Antarctic ice-sheet breakup occur more rapidly than previously anticipated (see review in CCSP 2008). These studies indicate that global sea-level rise may be 1 m or more by the year 2100, but rates of rise will be regionally highly variable. Additional modeling studies conclude that gravitational effects and shifts in ocean currents will result in nonuniform rise in sea level, possibly an additional 30-51 cm rise along the northeast coast of the U.S. and Canada (Hu *et al.* 2009) On a longer time frame, some climate scientists have argued that accelerated melting in Greenland and Antarctica could lead to sea-level rise of 4 m to 6 m over the next several hundred years, possibly reaching levels attained during the last interglacial warm period (Overpeck *et al.* 2006).

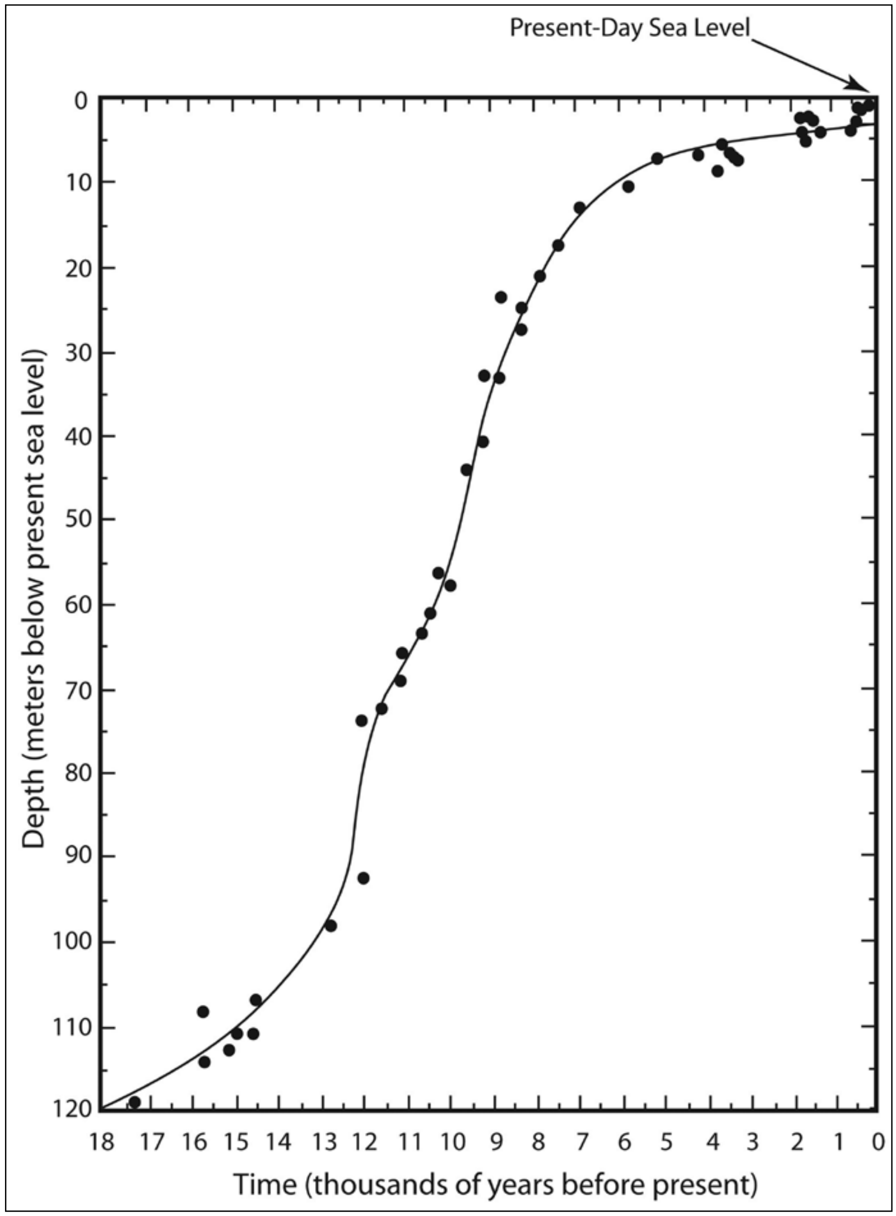

Figure 2. Generalized plot of the rise in global sea level at variable rates over the last 18,000 years as the Earth moved from a glacial period to the present interglacial warm period. This curve is reconstructed from geologic samples, shown as data points. Rise was rapid but highly variable for much of the time and slowed about 3,000 years ago. Recent acceleration is not shown at this scale. Reprinted by permission and adapted from Macmillan Publishers Ltd: *Nature* (Fairbanks, 1989), A 17,000-year glacio-eustatic sea level record — influence of glacial melting rates on the Younger Dryas event and deep-sea circulation, copyright (1989).

TWENTIETH CENTURY SEA-LEVEL CHANGE AROUND THE U.S.

Radiocarbon age-dating of organic sediments in cores and coral reefs are indirect methods used for determining sea-level elevations over the past 40,000 years. However, long-term (>50 yrs) tide-

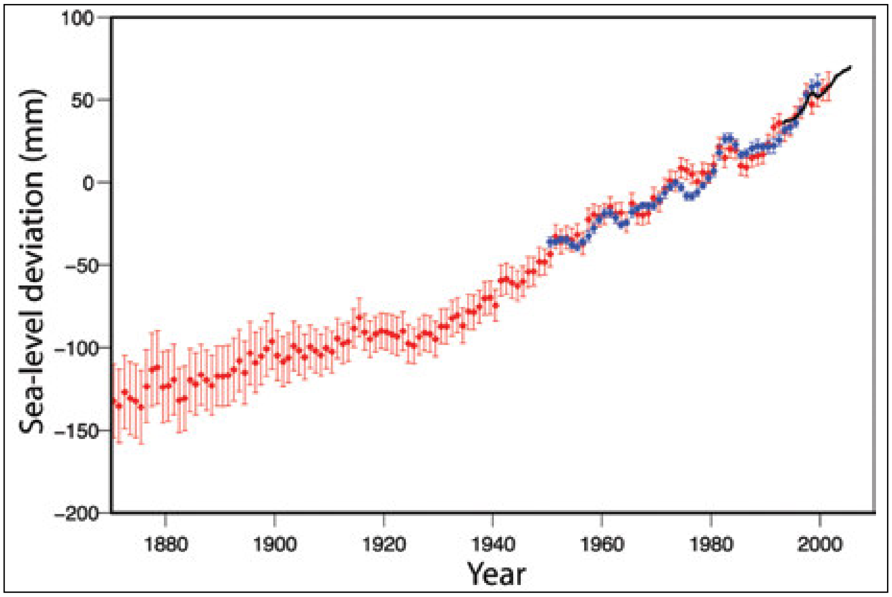

Figure 3. Annual averages of global mean sea level in millimeters from IPCC (2007). The red curve shows sea-level fields since 1870 (updated from Church and White 2006); the blue curve displays tide gauge data from Holgate and Woodworth (2004), and the black curve is based on satellite observations from 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. 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.

gauge data have been the primary source of measurements of relative sea-level trends over the past century (Douglas 2001). The rate of relative sea-level rise measured by tide gauges at specific locations along the Atlantic Coast of the U.S. varies from 1.8 mm to as much as 4.4 mm/yr (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 mm/yr (Bindoff *et al.* 2007). The highest rates are in the mid-Atlantic region between northern New Jersey and southern Virginia. The high rates of relative sea-level rise are attributed to subsidence of the land surface, which are due mainly to adjustments of 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 (Gornitz and Lebedeff 1987; Emery and Aubrey 1991; Kearney and Stevenson 1991; Douglas 2001; Peltier 2001).

On the Gulf Coast of the U.S., rates of relative sea-level rise are relatively modest along the Florida coast (2.0 to 2.4 mm/yr). However, rates of relative sea level change are significantly higher at stations in Louisiana and Texas. Galveston, Texas experiences sea-level rise rates of 6.5 mm/yr and increase to reach as much as 9.9 mm/yr at Grand Isle, Louisiana (Zervas 2001). The higher rise rates along the Texas and Louisiana coast are the result of land subsidence due to groundwater withdrawal, sediment compaction, and oil and gas production, in addition to global sea-level rise contributions (Gabrysch 1984, Galloway *et al.* 1999, Morton *et al.* 2002).

Along the Pacific Coast of the U.S., tectonic activity in addition to glacio-isostatic adjustment influence relative sea-level rise trends. At some locations, like San Diego and Santa Barbara, California, and Port Townsend, Washington, relative SLR rates exceed the global average (2.2 to 2.8 mm/yr). At other locations, tectonic uplift is believed to cause relative sea level observations that indicate sea-level has fallen (e.g. Crescent City, California, -0.5 mm/yr; Astoria, Oregon, -0.2 mm/yr; and Neah Bay, Washington, 1.4 mm/yr) (Zervas 2001).

Many of the tide gauges along the coast of Alaska indicate relative sea level is falling due to glacio-isostatic rebound and tectonic uplift of the land (Cohen and Freymueller 2001). The most extreme example has been observed at Skagway in southeastern Alaska where rates are -16.7 mm/yr. Parts of Glacier Bay are experiencing some of the highest rates of uplift (28 mm/yr). These uplift rates are determined from raised shorelines, GPS measurements, water-level recorders, and ice load and viscoelastic earth models (Larsen *et al.* 2003).

IMPACTS OF SEA-LEVEL RISE ON THE U.S. COAST

Sea-level rise has the potential to affect all coastal regions in the U.S (Gornitz *et al.* 2002; CCSP 2009). In some areas, wetland losses are occurring, fringe forests are dying and being converted to marsh, farmland and lawns are being converted to marsh (Riggs and Ames 2003, 2007). In addition, some roads and urban centers in low elevation areas are more frequently flooded during spring high tides (Douglas *et al.* 2001). Recent examples are Charleston, South Carolina, and parts of the Eastern Shore, Chesapeake Bay, Maryland (D. Marcy and C. Larsen, pers. comm.). Moreover, "ghost forests" of standing dead trees killed by salt water intrusion are becoming increasingly common in southern New Jersey, Maryland, Virginia, Louisiana, and North Carolina (Riggs and Ames 2003). Relative sea-level rise is also causing salt water intrusion into estuaries and threatening freshwater resources in some parts of the mid-Atlantic region (Barlow 2003). In addition, research over the last decade has shown that storms such as hurricanes, winter storms, especially during El Niño periods on the west coast, continue to have substantial impacts to coastal regions (Flick 1998, Allan and Komar 2006; Sallenger *et al.* 2007). With higher sea level, storm impacts from surge and waves have the potential to be greater and reach farther inland from the coast (CCSP 2009).

The complex interactions between a variety of factors make it difficult to relate sea-level rise and shoreline change and to reach agreement among coastal scientists on best approach to predicting shoreline 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 (e.g. Riggs *et al.* 1995; Sallenger *et al.* 2000; FitzGerald *et al.* 2008). 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.

The challenge in clearly defining a relationship between sea-level rise and shoreline change lies in the difficulty measuring a direct relationship between these two factors. The few studies that have attempted to constrain this relationship by examining shoreline changes during the 19th and 20th centuries have provoked debate (Leatherman *et al.* 2000a, 2000b, Pilkey *et al.* 2000; Sallenger *et al.* 2000; Zhang *et al.* 2004). Nonetheless, there is a wealth of geological evidence preserved on the continental shelf that indicates that the shoreline was several 10s of kilometers seaward 3,000 to 4,000 years ago when sea level was lower and since then the shore has transgressed landward and reworked the shelf surface (Kraft 1971; Moslow and Heron 1979; Belknap and Kraft 1985; Fletcher *et al.* 1990).

Some scientists contend that barrier islands, wetlands, and other parts of coastal systems might have a threshold or tipping point, such that when limits are exceeded, the landforms become unstable and prone to irreversible changes in form and position (NRC 2002; Riggs and Ames 2003). For barrier island systems, which make up a large portion of the U.S. shores, these changes would likely result in landward migration, change to the barrier island dimensions such as reduction in size or an increased presence of tidal inlets, or transformation into a subaqueous sand shoal (i.e. drowning of the barrier island). The topic of storm effects on barriers, thresholds for coastal landforms, and implications for future coastal change conditions is addressed in a recent book by Sallenger (2009). Although it is difficult to precisely define a barrier close to a threshold, several possible indicators discussed in Gutierrez *et al.* (2007) are:

- Rapid landward migration of the barrier
- Decreased barrier width and elevation
- Increased frequency of storm overwash
- Increased frequency of barrier breaching and inlet formation
- Segmentation of the barrier

Recent mapping and observations suggest that the Chandeleur Islands, off the Louisiana coast, subject to high rates of sea-level rise, subsidence, frequent major storms over the past decade, and limited sediment supply, may be crossing a threshold of stability (Sallenger *et al.* 2007). Similar deterioration of the barrier islands and wetlands may also occur in the near future along the North Carolina's Outer Banks coast as a result of increased sea-level rise and storm activity (Culver *et al.* 2007, 2008; Riggs and Ames 2003).

To investigate possible impacts to mid-Atlantic coastal landforms under three sea-level rise scenarios (30-100 cm by year 2100), Gutierrez *et al.* (2007)

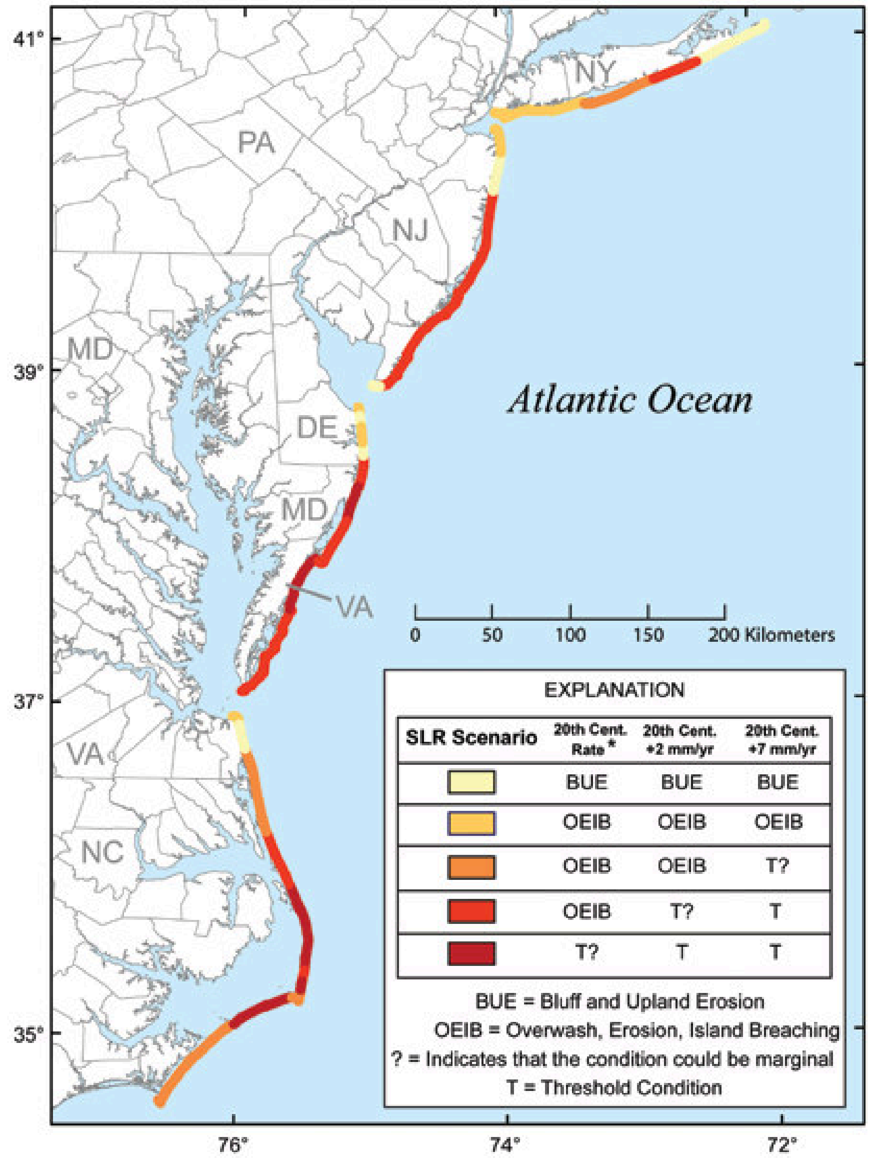

Figure 4. Map showing the potential sea-level rise responses for coastal landforms in the mid-Atlantic region. Colored portions of the coastline indicate the potential response for each of three rise scenarios shown in the inset table (Gutierrez *et. al.* 2007; CCSP 2009).

consulted a panel of coastal scientists with expert knowledge of coastal processes to produce a qualitative assessment of what might happen by the year 2100. Some results shown in Figure 4 and discussed in chapter 3 of CCSP (2009) indicate increased coastal erosion, overwash and breaching at moderate rates of sea-level rise, and possible threshold crossing of barrier islands at higher rise rates (~1 m). As discussed in chapter 4 of CCSP (2009), U.S., tidal wetlands (e.g. Mississippi River delta plain, Louisiana, and Blackwater marshes, Chesapeake Bay, Maryland) are already experiencing submergence and associated land loss by sea-level rise. These observed changes in wetlands are expected to continue in these regions and others around the U.S. in response to changing climate over this century. The current wetland response models appear quite good for site-specific applications where local elevations and sediment accretionary processes are well known, but model results for regional and national scales are uncertain and lack reliability. Mid-Atlantic wetlands are expected to keep pace with moderate sea-level rise, but under higher rates (~1 m) most would not survive and convert to open water (CCSP 2009).

DISCUSSION: IMPLICATIONS FOR COASTAL ZONE MANAGEMENT

Throughout history, humans have generally responded to eroding shorelines and flooding by implementing a variety of engineering measures to protect threatened property or by relocating settlement and 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).

A key issue for coastal zone management is to identify 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 is limited policy and regulation that explicitly addresses or incorporates sea-level rise into the decision making process (CCSP 2009). This situation is changing for some states (e.g. Massachusetts, Delaware, North Carolina, Florida, California, and Washington) and federal agencies (e.g. National Oceanic and Atmospheric Administration, Fish and Wildlife Service, National Park Service, Army Corps of Engineers).

Many property owners and government agency 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 have negative effects on the natural behavior of coastal landforms and disrupt coastal ecosystems (NRC, 2007; CCSP, 2009). In the short term (~10 to 50 yrs), an acceleration of sea-level rise may simply increase the cost of current shore protection practices (Nordstrom 2000). In the longer term (>50 yrs), policy makers might evaluate whether current approaches and justifications for coastal development and protection should be modified to reflect the increasing vulnerability to accelerating rates of sea-level rise.

To facilitate these decisions, policymakers require credible scientific data and information. Predicting sea-level rise impacts such as shoreline changes or wetland losses with a high degree of confidence and precision is often not possible (Cooper and Pilkey 2004; CCSP 2009). 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.

With the recognition of the hazards facing coasts, there is growing need for predictive models that can be used to forecast where erosion hazards are highest. Existing models that forecast shoreline response to sea-level rise include geometric models such as the Brunn Rule, empirical models based on historical water level data, or more simply extrapolation of historic shoreline change rates. These methods provide deterministic predictions, but often do not account for the spatial and temporal variability of coastal processes, or for the fact that erosion is episodic and does not necessarily respond quickly to forcing. Furthermore, the response may depend on the influence of previous events. Incorporating probabilistic methods (e.g. Bayesian Networks; Jensen 1996; Borsuk *et al.* 2004) may be useful to account for the complexity of coastal change.

Marine geophysical investigations show that offshore regions may have abundant sediments, but often sand-size sediment suitable in texture and composition for beach nourishment is very limited for many regions due to geologic factors. Also, while marine sand may potentially be available, it is often considered "excluded" due to overlapping resource uses and factors such as dredging limitations, preemptive uses of the seafloor, and economic and environmental factors. As a result, only a portion of potential offshore sand resources may ultimately be available for beach nourishment (Bliss *et al.* 2009). To resolve competing interests in use of the sea floor and to establish priorities, the use of integrated, forward-looking decision making planning tools, such as "marine spatial planning" is an option.

Coastal regions are generally managed under the premise that sea-level rise, shoreline change, and storms are modest, regular and predictable. New strategies for coastal planning and management that will be effective as sea-level rise accelerates are needed. For example, 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/) in order to conserve sediment resources and maintain natural sediment transport processes (NRC 2007).

Sea-level rise projections need to be fully considered in coastal management plans and engineering design, however, existing studies of vulnerability based on extant elevation data do not provide the degree of confidence that is optimal for local decision making (see chapter 2 in CCSP 2009). Studies that use elevation data for risk maps need to include statements about the vertical accuracy of the data and, importantly, the current best available data for much of the U.S. do not scientifically support assessment mapping using a sea-level rise increment of 1 m or less. Nationwide collection of high-quality LIDAR (LIght Detection And Ranging) elevation data across the coastal zone would improve the ability to conduct assessments of coastal vulnerability that can reliably be used for planning and decision making (CCSP 2009).

To effectively cope with sea-level rise and its impacts, current policies and economic considerations should be examined, and possible options for modifying planning and management activities are warranted so that society and the environment are better able to adapt to potential accelerated rise in sea level.

CONCLUSIONS

Global climate is changing and becoming more variable, due largely to carbon emissions from human activities and land-use change. Sea-level rise is judged to be one of the most pervasive and important impacts of climate change affecting all coastal regions of the U.S. and around the world over this century and into the future. The high population densities in many coastal regions make it difficult to balance human interests and natural hazards. These conditions will lead to an increase in vulnerability of natural systems and human populations, resulting in significant economic and societal impacts. The scientific tools and techniques for assessing and predicting the effects of sea-level rise on coastal systems are improving, but much remains to be done to develop reliable and useful forecasts of potential risks.

For much of the U.S., coastal regions composed of barrier islands, dunes, spits, sandy bluffs, and wetlands, erosion and inundation will be the dominate responses at highly variable rates to sea-level rise and storms over this century and beyond. Some coastal land forms in the U.S. may undergo large changes in shape and location, and wetlands may drown, if the rate of sea-level rise increases as predicted. Increased inundation and more frequent tidal and storm-surge flooding will especially affect estuaries and low-lying coastal areas. The response to these driving forces will vary depending on the type of coastal land form 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 islands and spits 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. For some regions of the U.S., tidal wetlands, already experiencing submergence and associated land loss by sea-level rise, in concert with other factors, will continue to deteriorate in response to changing climate.

Planning for accelerating sea-level rise of 1 m or more by the year 2100 should begin now and include thorough evaluation of all of the potential responses to sea-level rise and the viable alternatives. These include cost-effective and sustainable coastal protection and strategic landward relocation of infrastructure and development. Important planning decisions for sea-level rise should be based on the best available science and careful consideration of long-term benefits for a sustainable future, as well as all inclusive economic, social, and environmental costs of various methods of shore protection, relocation, and adaptation (CCSP 2009).

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