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Sea-Level Rise Implications for Coastal Regions

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ABSTRACT

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Sea-level rise, a dominant driving force of change for coastal regions, is becoming increasingly important as a hazard to humans and urban areas in the coastal zone worldwide as global climate change takes effect. The geologic record shows that sea level, due to past natural climate factors, has been highly variable, as much as 6–8 m higher than present during the last interglacial warm period and 130 m lower during the last glacial period. Sea level was fairly stable for the past 3,000 years until about the mid-19th century. During the 20th century, sea level began rising at a global average rate of 1.7 mm/yr. The current average rise rate is 3.1 mm/yr, a 50% increase over the past two decades. Many regions are experiencing even greater rise rates due to local geophysical (*e.g.*, Louisiana, Chesapeake Bay) and oceanographic (Mid-Atlantic coast) forces. A few regions experience rise rates less than the global average due to land uplift. Observations show the increase of carbon emissions since the Industrial Revolution has increased global mean temperature of the air and ocean, which is responsible for sea-level rise due to ice sheet melting and steric expansion, and many related environmental changes. Sea-level rise, with high regional variability, is exhibiting acceleration and is expected to continue for centuries unless mitigation is enacted to reduce atmospheric carbon. Low-lying coastal plain regions, deltas, and most islands are highly vulnerable. Adaptation planning on local, state and national scales for projected sea-level rise of 0.5–2 m by A.D. 2100 is advisable. Sustained global rise in sea level of 4 m to as much as 8 m is possible, but not likely until well after A.D. 2100.

ADDITIONAL INDEX WORDS: *Global mean sea level, relative sea level, sea-level rise, coast, climate change, coastal erosion, barrier island, coastal vulnerability, adaptation, coastal hazards.*

INTRODUCTION

Managing the hazard risks posed by climate change and impacts such as sea-level rise to coastal regions is becoming increasingly recognized as a major challenge for the 21st century by U.S. federal agencies and most coastal states. Rising water levels and increased risk of flooding along the coasts of United States and worldwide poses significant challenges (Moser, Williams and Boesch, 2012). Over 8 million people live in vulnerable coastal regions in the U.S. and development continues (Crowell *et al.,* 2010). The majority of the most vulnerable coastal regions are within 1-m elevation of sea level. A key to planning and developing strategies for adaptation is understanding the driving forces of sea-level change and past impacts of varying sea level. Geologic history shows that Earth's global climate has been highly variable in both time and space. The causes for this result from complex interactions between the continental land masses, ocean, atmosphere, and solar radiation–the Earth System (Figure 1). These involve positive and negative feedback mechanisms that can trigger tipping points of physical processes. Small changes, such as with atmospheric temperature, can have cumulative, multiplying, and irreversible effects across regions and even globally.

These feedback mechanisms are important in regulating global climate, but many are neither well understood nor predictable with high confidence. Physicists have been aware of the importance of solar radiation, both incoming and radiated, greenhouse gases in the atmosphere and the affects of increasing carbon dioxide

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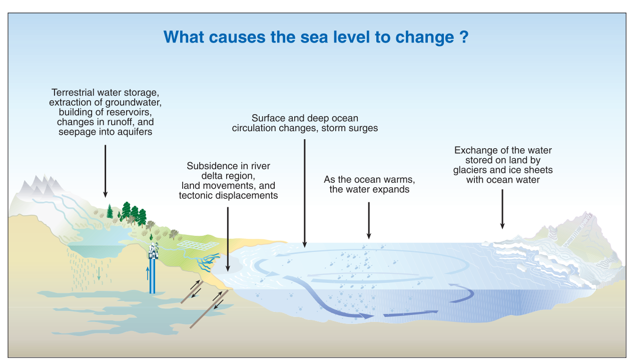

Figure 1. Processes that contribute to sea level change. Adapted from Rekacewicz (2005).

on energy levels and warming of Earth since the early 1900s, but growing scientific understanding based on observations and improved modeling over the past 50 years has led to increased understanding of both natural factors and human influences on Earth's climate. One of the early papers discussing human effects on climate change was by Professor Roger Revelle (1983), who discussed the steady increase of atmospheric carbon dioxide and potential impacts of global warming on the atmosphere and the oceans, including sea-level rise. Another important study that discussed sea-level rise, effects on coasts, and included global sea-level rise projections, was published by the U.S. National Academy of Sciences (NRC, 1987).

Over the past approximately 3,000 years, global climate and global sea level have been relatively stable. Some suggest that a benign climate has enabled the expansion of human populations (7 billion people currently) and the development of our modern society (Day *et al.,* 2007). In coastal regions of the U.S. and globally, human populations are substantial. Population continues to expand in many regions, and people are increasingly at risk from a variety of natural hazards such as sea-level rise, storms, and flooding, which are exacerbated by global warming (Crossett *et al.,* 2004; McGranahan, Balk, and Anderson, 2007; Nicholls *et al.,* 2011). Understanding and predicting with confidence how sea-level rise will affect coastal regions and how society may choose to address it in ways that are cost-effective and sustainable for the long term is a major challenge, but vitally important. The public needs to be informed about the reality of climate warming impacts such as sea-level rise, but also about alternatives for adaptation, which are available.

The objective of this paper is to review the literature on the topic of sea-level change, the causes and processes responsible on regional to global scales, the implications of projected sea-level rise due to global warming in coastal and low-elevation regions, and the need for adaptation planning. While this review is focused on the United States, much may be applicable to coastal regions worldwide.

CAUSES OF SEA-LEVEL CHANGE

In this paper the following abbreviations are used for sea level terms:

GSL= global or eustatic or absolute mean sea level (global average corrected for regional and local factors)

LRSL= local relative sea level (rates determined by tide gage records and other observations that include a combination of global mean rates and effects of regional and local geophysical and oceanographic factors).

Sea-level rise is a major impact of global climate warming. Its causes, however, are complex and result from not only warming but also regional and local effects of geologic, oceanographic, and atmospheric conditions that are highly variable on both spatial and temporal scales. Several important regional factors include: land subsidence and uplift due to isostatic adjustment of the crust; tectonic forces; sediment compaction and consolidation; gravitational changes; and changes in ocean circulation patterns and wind patterns. Global mean sea level (GSL) or eustatic sea level is the elevation of the ocean used in describing effects of climate warming. Relative local sea level (LRSL) elevation of the ocean relative to the land surface is used to describe the combination of global plus the various regional and local factors. The distinction between GSL and LRSL is important for understanding projections of future sea-level rise and how regional factors can increase or decrease effects of future rise on coasts. While GSL is used in discussing future rise scenarios, LRSL is most important in understanding the likely regional and local impacts on coasts and is most applicable for planning and management.

Sea level has varied throughout Earth's history due to a variety of processes that operate over a range of spatial and temporal scales (*e.g*., Broecker and Kunzig, 2008; Church *et al.,* 2010, 2011; Douglas, Kearney, and Leatherman, 2001; Hansen *et al.,* 2007; IPCC, 2001, 2007; Lambeck, Esat, and Potter, 2002; Miller *et al.,* 2005). On a global scale, sea level varies as the volume and mass of ocean water changes, and also as the volume of the ocean basins changes. Two primary contributors to ocean volume and mass are from thermal steric expansion through heat uptake and the addition of melt water from grounded ice sheets and glaciers (Bindoff *et al.,* 2007; Church *et al.,* 2010; IPCC, 2007; Milne *et al.,* 2009; Mitchum *et al.,* 2010; Woodworth *et al.,* 2008). Oxygen isotope records from cores provide evidence that sea level has varied over the past 3 million years, primarily in response to cyclic shifts between glacial and interglacial periods (Lambeck, Esat, and Potter, 2002). These records indicate that over the last 800,000 years the magnitude of the sea-level changes has been in the range of 120–140 m with a cyclicity of about 100,000 years as determined by variances in Earth's orbital motion. During the last interglacial warm period (~125,000 years before present (yr BP)), when most of the world's glaciers and many ice sheets on

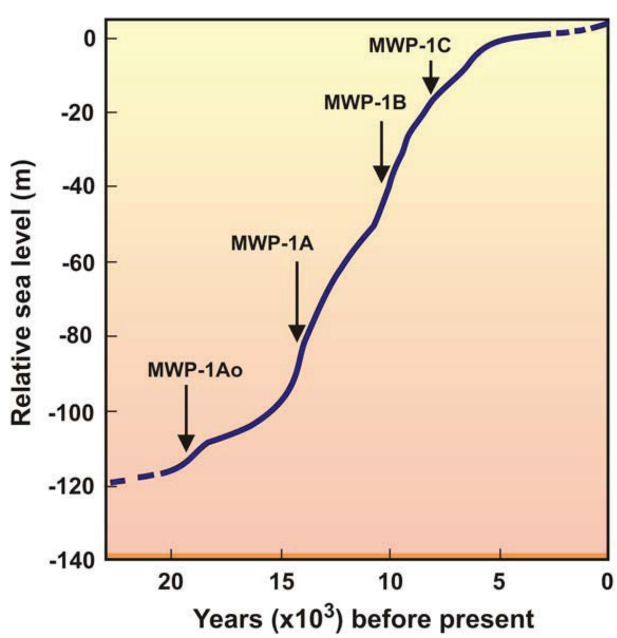

Figure 2. Generalized curve of sea-level rise since the last ice age. Abbreviations: MWP=meltwater pulse. MWP-1Ao, c. 19,000 years ago; MWP-1A, 14,600 to 13,500 years ago; MWP-1B, 11,500 to 11,000 years ago; MWP-1C, ~8,200 to 7,600 years ago (Gornitz, 2007).

Greenland were depleted, sea level was approximately 6–8 m higher than present (Kopp *et al.,* 2009). In contrast, during the Last Glacial Maximum (LGM, ~21,000 years before present) when much of North America and northern Europe were covered with ice sheets, sea level was 120–130 m lower than present and many present-day continental shelf areas were exposed coastal plains (Figure 2) (Fairbanks, 1989; Muhs *et al.,* 2004).

Evidence from the coral record constructed by Fairbanks (1989) indicates that GSL rise rates between 21,000 to 6,000 years ago averaged 10 mm/yr and were punctuated by two meltwater pulses when rise rates may have reached 40–50 mm/yr (USCCSP, 2008; Fairbanks, 1989). 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 GSL rise slowed episodically with rates eventually reaching a near stillstand (0 to 0.2 mm/yr) 2,000 to 3,000 years ago (Lambeck and Bard, 2000).

HISTORICAL SEA-LEVEL CHANGE

Mapping of ancient coastal landforms and radiocarbon age dating and analysis of organic material in sediment cores and coral reefs are indirect proxy methods used for determining sea-level elevations in the recent geologic past. However, long-term (>50 years) tide gage data from well located sites are the best source of measurements of relative sea-level trends over the past century and longer (Figure 3; Douglas, 1992). The Permanent Service for Mean Sea Level (http://www.psmsl.org/) is the best source of global tide data and NOAA (2009) is a source for U.S. tide gage data (Zervas, 2009).

Analyses of tide gage records worldwide indicate that sea-level rise rates increased in the 20th century (Bindoff *et al.,* 2007; Gehrels *et al.,* 2008; Kemp *et al.,* 2011; Mitchum *et al.,* 2010), and that acceleration in GSL rise rates may have begun earlier (Jevrejeva *et al.,* 2008). The 20th century rate of GSL rise averaged 1.7 mm/yr (Bindoff *et al.,* 2007), with decadal fluctuations occurring throughout the century (Church and White, 2011; Jevrejeva *et al.,* 2006; 2008; Woodworth *et al.,* 2008). Since the early 1990s, both satellite altimetry, as shown in Figure 4, and tide gage observations indicate that the rate of GSL rise increased to 3 mm/yr (Bindoff *et al.,* 2007; Cazenave and Llovel, 2010). While this is a significant increase, it is not yet possible to determine with certainty whether this is a natural decadal variation that has occurred in the past, or a definitive acceleration in response to climate warming (Bindoff *et al.,* 2007).The IPCC (2007) reports, however, that the increase is likely due to equal contributions from ocean thermal expansion and ice-sheet melting. Studies by Cazenave *et al.* (2009) found that the rate mainly reflects glacial melt contributions, whereas thermal expansion has apparently leveled off in comparison to the previous decade. Recent studies of global sea-level change and energy budgets from 1961 to 2008 by Church *et al.* (2011) show that of the observed rise, ocean expansion accounts for 0.8 mm/yr, melting glaciers and ice caps accounts for 0.7 mm/yr, and Greenland and Antarctica melt rates account for 0.4 mm/yr. Other factors such as groundwater depletion and water retention behind dams, which offset GSL rise rates are discussed by Church *et al.* (2011) and Konikow (2011).

It should be emphasized that calculating a rate for historical GSL rise is highly dependent on the specific time period selected for measurement due to the changing contributions of the steric and eustatic components to the average global sea-level change, and the number and spatial distribution of gage stations used (Jevrejeva *et al.,* 2006). Much of the debate about the historical GSL trends and apparent accelerations or decelerations in the rate of change over time is due to different statistical trends in data within specific time frames. Excellent reviews discussing the complexity of methods for studying and reporting sea level are provided by Baart *et al.* (2012), Church *et al.* (2010), and Woodworth *et al.* (2008). An important question to address is whether there is evidence that acceleration in GSL rise has

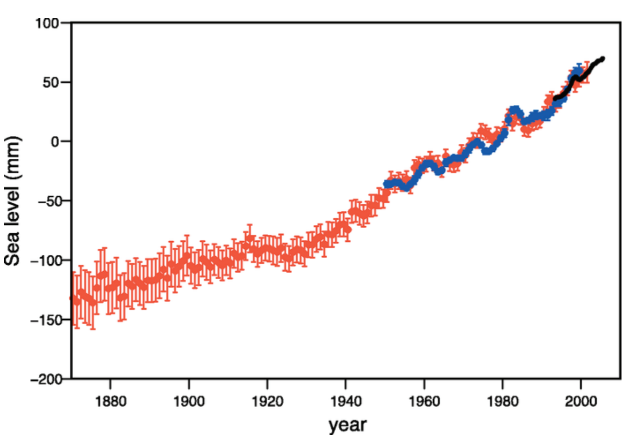

Figure 3. Global mean sea-level rise from 1870 to 2001 reported in IPCC (2007). The red curve shows sea level since 1870 (from Church and White, 2006); the blue curve shows tide gage data from Holgate and Woodworth (2004), and the black curve is based on satellite altimeter data from Leuliette, Nerem, and Mitchum (2004). The red and blue curves are deviations from their averages for 1961–1990, and the black curve is the deviation from the average of the red curve for the period 1993–2001 (IPCC, 2007).

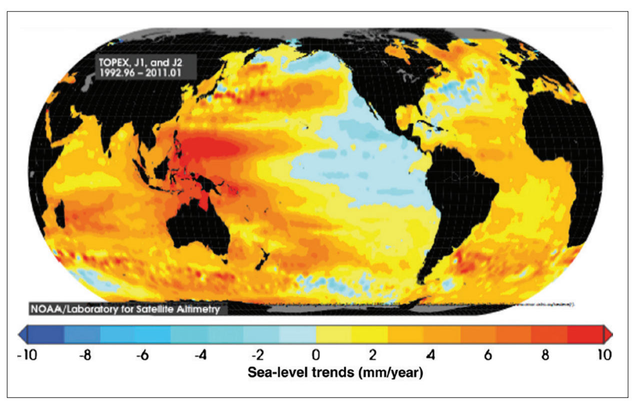

Figure 4. The highly variable spatial distribution of the rates of sea-level change, plotted about the globally averaged rate of change for the period 1992–2011, as measured from satellite altimeter data and processed by NOAA (CSIRO, 2012).

started as predicted from semiempirical models and can be linked to observed global warming? And is it a global acceleration, a region-specific acceleration due to warming, the product of a multidecadal variation, or some combination of these?

This topic is subject of debate in the literature; however, observations show that acceleration of rise rates started in the mid-19th century, increasing to a current global average rise rate (over the past 20 years) of 3 mm/yr, a 50% increase, but with high regional variability (Gehrels, 2010; Holgate and Woodworth, 2004; Merrifield, Merrifield, and Mitchum, 2009; Sallenger, Doran, and Howd, 2012; Yin *et al.*, 2010). In contrast to papers reporting evidence for acceleration, Douglas (1992) was one of the first to look for evidence of acceleration using tide gage data and reported none. Munk (2002) offered insights on the enigma of warming and lack of definitive GSL rise. More recently Houston and Dean (2011a, b) used tide gage data to conclude a slight deceleration in sea-level rise rates. Subsequent rebuttal papers by Rahmstorf and Vermeer (2011), Rignot *et al.* (2011), Donoghue and Parkinson (2011), and Sallenger, Doran and Howd (2012), have raised issues with the data selection, statistical analysis, and conclusions of Houston and Dean (2011a, b). Baart, van Koningsveld, and Stive (2012) provide a useful discussion of the debate and offer constructive suggestions on methods of research for addressing and reporting on the topic of sea level. This is an important topic and longer-term satellite altimetry observations and additional careful statistical analysis of the data are needed to resolve the question of whether sea-level-rise rates are accelerating in response to warming effects.

Tide gage records, and more recently, satellite observations show that LRSL has very large spatial and temporal variability due to many geophysical and oceanographic drivers. The high variability is due to regional factors such as subsidence, uplift, and changes in ocean circulation, and shows the difficulty of determining average rates from such diverse data. Most of the U.S. coast is undergoing LRSL rise; however, there are exceptions where uplift of the land is greater than GSL. The rate of LRSL rise, as measured by tide gages along the Atlantic coast of the U.S., varies from 1.8 mm/yr to as much as 4.4 mm/yr (Zervas, 2009). The lower rise rates, which occur along New England and from Georgia to Florida, are close to the global average rate of 1.7 mm/yr and indicate that the land is stable (Bindoff *et al.,* 2007). The higher LRSL rise rates, however, along the Mid-Atlantic region from New Jersey to Virginia, are attributed to global rise in combination with land subsidence, due mainly to glacio-isostatic adjustment (GIA) (*i.e.*, vertical change of the Earth's crust in response to the melting of the Laurentide ice sheet), to local compaction of sediments due to freshwater withdrawal from aquifers (Douglas, 2001; Emery and Aubrey, 1991; Gornitz and Lebedeff, 1987; Kearney and Stevenson, 1991; Peltier, 2001), and to changes in ocean circulation patterns (Sallenger, Doran, and Howd, 2012).

For the northern Gulf of Mexico coast, rates of LRSL rise are relatively modest along the Florida coast (2.0 to 2.4 mm/yr). Rates are significantly higher at tide gage stations in Louisiana and Texas. Galveston, Texas has rates of 6.5 mm/yr and rates increase eastward to 9.9 mm/yr at Grand Isle, Louisiana (Zervas, 2009). The higher than average rates along the Texas and Louisiana coast are the result of down warping of the crust due to sediment loading and land subsidence due to sediment compaction and consolidation, groundwater withdrawal, and oil and gas production (Gabrysch, 1984; Galloway, Jones, and Ingebritsen, 1999; Morton, Buster, and Krohn, 2002; Williams *et al.,* 2011).

Along the U.S. Pacific coast, tectonic activity and GIA influence LRSL rise rates. At some locations, like San Diego and Santa Barbara, California, and Port Townsend, Washington, LRSL rise rates exceed the global average (2.2–2.8 mm/yr). At other locations, tectonic uplift causes LRSL to fall (*e.g.*, Crescent City, California, -0.5 mm/yr; Astoria, Oregon, -0.2 mm/yr; and Neah Bay, Washington, -1.4 mm/yr) (Zervas, 2009). Tide gages along the coast of Alaska record that LRSL is falling as a result of a combination of GIA of the land as glaciers and ice sheets melt and tectonic uplift (Cohen and Freymueller, 2001). This uplift is determined by Global Positioning System (GPS) mapping of raised shorelines and gage data and use of viscoelastic models of crustal movement (Larsen *et al.,* 2003). The greatest uplift is observed at Skagway, Alaska, where relative rise rates are -16.7 mm/yr and Glacier Bay, Alaska, where relative rise rates are -28 mm/yr (Zervas, 2009).

COASTAL LANDFORM RESPONSE TO DRIVING FORCES

Coastal landforms are not simply inundated as sea level rises, but rather are modified by a variety of processes with cumulative impacts that vary greatly over time and location, and are determined by geophysical processes and geologic character. Conditions and driving forces that influence the evolution of coasts include:

- Geologic framework and character of coastal landforms
- Coastal and nearshore oceanographic processes (waves, currents, circulation)
- Sediment supply to the coast by erosion and rivers and sediment transport along the coast
- Effects of human activity that alter sediment movement (Carter and Woodroffe, 1994; FitzGerald *et al.,* 2008; Williams and Gutierrez, 2009).

These factors interact in complex ways, influencing the response of coastal landforms to sea-level change and tropical and extratropical storms.

One of the most evident impacts of sea-level rise is shoreline change resulting from inundation, erosion, and transgression of the shoreline. On sandy coasts, shoreline change results from changes to the morphology of the beach–dune system and shoreface. These changes do not occur as a direct result of sea-level rise, but rather, coasts exist in an almost continual state of change in response to waves, currents, tidal action, and sediment availability (Carter and Woodroffe, 1994; Nicholls *et al.,* 2007, 2010; Stive *et al.,* 2002). This is especially evident for shoreline change observed over the past century, when the increase in global sea level has been modest (1.7 mm/yr). During this time, major storms, variations in sediment supply to the coast, and a variety of human activities seem to have had more direct influence on shoreline change.

Major storms often cause changes in the character of the coast that may persist for weeks to a decade or more (List, Farris, and Sullivan, 2006; Riggs and Ames, 2007; Zhang, Douglas, and Leatherman, 2002, 2004). Complex interactions between nearshore sand bodies and underlying geology along the coast also influence the behavior of beach morphology over time (Honeycutt and Krantz, 2003; Miselis and McNinch, 2006; Riggs, Cleary, and Snyder, 1995; Schupp, McNinch, and List, 2006). In addition, a variety of human actions intended to protect coastal development from waves and flooding, mitigate erosion, and maintain navigation channels have often altered the behavior of coasts considerably (Dean and Perlin 1977; Leatherman 1984; Nicholls *et al.,* 2007, 2011; Nordstrom 1994, 2000).

Until recently, coastal management and planning have been based on the premise that coastal change and sea-level rise are modest and predictable based on linear extrapolation of historical records, but that is changing based on improved climate science. Federal agencies, coastal states, and many organizations recognize that climate change and its impacts are compelling societal issues that should be addressed. An example is the U.S. Army Corps of Engineers (USACE) issued Engineering Circular 1165-2-212 that provides guidance to districts for incorporating the effects of projected future sea-level change in all aspects of Corps projects. It directs that impacts resulting from sea-level change must be considered using three scenarios (low-medium-high) specific to project details (USACE, 2011). And most recently, a panel of experts for the latest U.S national climate assessment, using peer literature, is projecting a range of GSL rise scenarios ranging from 0.2 to 2 m by A.D. 2100. They use 0.2 mm/yr as a baseline projection of the 20th century rise rate. This new assessment is expected to be released in 2013.

IMPACTS OF SEA-LEVEL RISE

Sea-level rise is impacting coasts now with increased tidal-flood frequency during routine astronomical spring high tides and erosion; and, these effects will increase in the future (Church *et al.,* 2010; Gornitz *et al.,* 2002; Moser, Williams and Boesch, 2012; Nicholls *et al.,* 2011; Nicholls and Cazavene, 2010; Weiss, Overpeck, and Strauss, 2011; USCCSP, 2009; Williams, 2010; Williams *et al.*, 2009a, b). The effects of sea-level rise on coasts are not uniform, but vary considerably from region to region and over a range of temporal scales (Nicholls *et al.,* 2007; Nicholls *et al.,* 2010; Weiss *et al.,* 2011). The effects are greatest on low-relief, low-elevation coasts such as deltas, coastal plains, and islands, as well as urban areas on the coast (Nicholls *et al.,* 2011; Moser, Williams and Boesch 2012, Weiss *et al.,* 2011). With higher sea level, storm impacts from surge and waves have the potential to be greater and reach farther inland from the coast (USCCSP, 2009). In some regions, wetlands are drowning, fringe forests are dying from saltwater exposure, and farmland is being converted to tidal marsh and salt flats (Riggs and Ames, 2003, 2007). In addition, some roadways and urban centers in low-elevation areas close to the coast experience more frequent flooding during spring high tides (Douglas, 2001). Examples are Alexandria, Virginia, Charleston, South Carolina, and the Eastern Shore, Chesapeake Bay, Maryland. Moreover, ghost forests of standing dead trees killed by saltwater intrusion are becoming increasingly common in southern New Jersey, Maryland, Virginia, Louisiana, and North Carolina (Riggs and Ames, 2003). Sea-level rise is also increasing saltwater intrusion into estuaries and threatening freshwater resources in some parts of the Mid-Atlantic region (Barlow, 2003).

The complex interactions among many driving forces make it difficult to directly relate sea-level rise to shoreline change and thus to reach agreement on best approaches to predict shoreline response to LRSL rise. The difficulty in linking LRSL rise to coastal change stems from the fact that shoreline change is not driven solely by sea level. Instead, coasts are in dynamic flux, responding to factors such as the underlying geological character, changes in tidal flow, and volume of sediment in the coastal system (*e.g.*, FitzGerald *et al.,* 2008; Riggs, Cleary, and Snyder, 1995; Sallenger *et al.,* 2000). Consequently, while there is strong scientific consensus that climate change is affecting coasts, there are still uncertainties when predicting, in any detail, how the coast will respond to future GSL rise in concert with the other driving forces. Some promising results using geomorphic modeling of sea-level rise effects along ocean coasts are reported by Moore *et al.* (2010, 2011).

The challenge in defining the relationship between sea-level rise and shoreline change lies in the difficulty of measuring a direct cause and effect 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, Zhang, and Douglas, 2000a, 2000b; Pilkey, Young, and Bush, 2000; Sallenger *et al.,* 2000; Zhang, Douglas, and Leatherman, 2004). Nonetheless, there is an abundance of geological evidence preserved on the continental shelf that indicates that the shoreline was several tens of kilometers seaward about 5,000 years ago when sea level was lower and that since then the shoreline has transgressed landward (Fletcher, Knebel, and Kraft, 1990; Kraft, 1971).

There is some indication that coastal landforms have thresholds or tipping points of geomorphic stability, such that when limits are exceeded, they become unstable and prone to irreversible changes in form and position (Moore *et al.,* 2011; NRC, 2002; Riggs and Ames, 2003). For barrier islands, these changes may result in increased landward migration, geomorphic change such as reduction in size or segmentation, or in extreme cases, transformation of a barrier into a subaqueous sand shoal (*i.e.*, drowning of the barrier island). Although it is not yet possible to define when a barrier island is close to a tipping point, several possible indicators are discussed by Gutierrez, Williams, and Thieler (2007):

- Increased rate of landward migration of the barrier
- Decreased barrier width and elevation of barrier and sand dunes
- Increased frequency of storm overwash
- Increased frequency of barrier breaching and inlet formation and widening
- Segmentation of the barrier

As discussed earlier, the Mississippi River Delta plain region of Louisiana has much higher than average rates of LRSL rise due to geologic factors such as subsidence and man-made alterations to the delta plain, wetlands, and coast (Williams, 2010). As a result the entire coast is highly erosional and highly vulnerable to sea-level rise and storms (Pendleton *et al.,* 2010). Detailed mapping studies over the past two decades show that the Chandeleur Islands off the southeastern Louisiana coast are subject to sea-level rise, subsidence, frequent major storms, and reduced sediment budget. These factors suggest that the Chandeleur Islands may be close to crossing a threshold of stability, ultimately leading to their demise (Moore *et al.,* 2011; Sallenger *et al.,* 2007). Geologic evidence for barrier island deterioration and submergence off other parts of the Louisiana coast during the late Holocene marine transgression has been reported by Williams *et al.* (2011, 2012) among others. Loss of these barrier landforms might be the result of past threshold crossings and perhaps are analogues for the Chandeleur Islands. Similar pervasive deterioration of barrier islands may also occur along the North Carolina Outer Banks as a result of sea-level rise and storm activity (Culver *et al.,* 2007, 2008; Moore *et al.,* 2010, 2011; Riggs and Ames, 2003).

To investigate possible impacts to Mid-Atlantic coastal landforms under three GSL rise scenarios (30 cm, 50 cm, and 100 cm by A.D. 2100), a panel of coastal scientists produced a qualitative assessment of what might happen as reported in USCCSP (2009) and Gutierrez, Williams, and Thieler (2007). Results shown in Figure 5 indicate increased coastal erosion, overwash and breaching are likely at moderate rates of rise, and possible threshold crossing of barrier islands at higher rise values (~1 m).

Also discussed in USCCSP (2009) and other reports, many U.S. tidal wetlands (*e.g.*, Mississippi River Delta Plain, Louisiana, and Blackwater Marshes, Chesapeake Bay, Maryland) are already experiencing submergence and land loss because LRSL rise rates are exceeding sedimentation rates. Mid-Atlantic wetlands are expected to keep pace with moderate sea-level rise, but with higher values (~1 m) most tidal wetlands are likely to convert to open water bays and lagoons (see chapter 4, USCCSP, 2009). Tidal wetlands with sufficient sediment input may prevail under higher rates. The current wetland response models appear quite good for site-specific applications where local land elevations (*i.e.*, lidar) and sediment accretion processes are well known, but model results at regional and national scales for wetland response currently lack reliability (USCCSP, 2009).

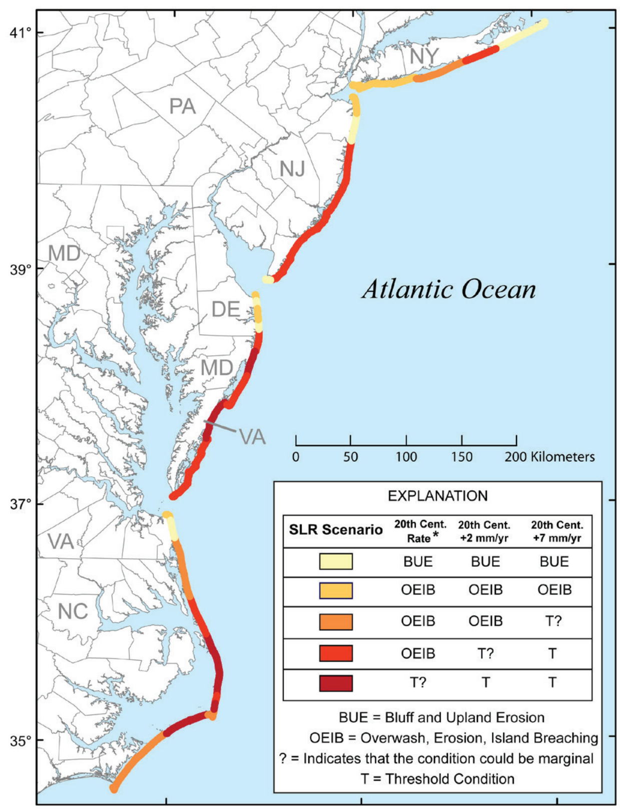

Figure 5. Map showing potential sea-level rise responses of coastal landforms in the Mid-Atlantic region. Colored portions of the coastline indicate the potential response for each of the three sea-level rise scenarios shown in the table (USCCSP, 2009).

SEA-LEVEL RISE SCENARIOS FOR THE FUTURE

While the evidence for recent GSL rise due to climate warming is debated, consensus is strong among climate scientists that sea level is very likely to rise at accelerated rates for the rest of the 21st century and for centuries beyond (Anderson *et al.,* 2010; IPCC, 2007; Jevrejeva, Moore, and Grinsted, 2011; Mitchum *et al.,* 2010; Pfeffer, Harper, and O'Neel, 2008; Rahmstorf, 2007, 2010; USGCRP, 2009). The latest climate change assessment by the Intergovernmental Panel on Climate Change (IPCC, 2007; Meehl *et al.,* 2007) included physical model-based forecasts of sea-level rise by the end of the 21st century. They reported that sea level could rise 18–59 cm; however it is important to recognize that the IPCC authors emphasized that the projections did not include the potential for melting of major land-based ice sheets on Greenland or West Antarctica due to a lack of understanding of ice sheet dynamics at the time (Meehl *et al.,* 2007). These ice sheets account for a very large amount of potential sea-level rise but could not be modeled with high confidence at the time of the 2007 report writing. A new IPCC assessment (AR 5) is being prepared and is expected to include refined model results of ice sheet dynamics and their contributions to GSL rise.

As shown in Figure 6 from Moser, Williams, and Boesch (2012), modeling studies by many since IPCC (2007) suggest that GSL is likely to increase by AD 2100 considerably more than the IPCC's 59 cm predicted upper limit. Many believe that Greenland and West Antarctic ice sheet melting is likely to be more rapid than previously thought (see review in USCCSP, 2008; Woodworth *et al*., 2008). These studies suggest that average GSL rise will be in a range of 0.5–2 m (Figure 6) by AD 2100; however, the rates of rise will have high regional and temporal variability due to the geophysical and oceanographic factors discussed earlier. For example, modeling studies have been used to predict that gravitational effects and shifts in ocean circulation patterns are likely to result in a 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, 2011; Yin, Schlesinger, and Stouffer, 2009; Yin, 2010). These model results of sea-level acceleration have recently been supported by observations and analyses from gage data from the Mid-Atlantic coast (Sallenger, Doran, and Howd, 2012). Many assessment studies over the past several years are projecting a 1-m global

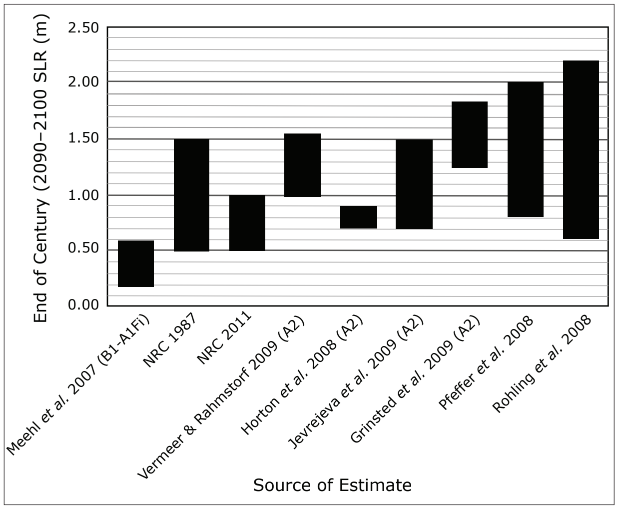

Figure 6. Graphic summary of the range of average global sea-level rise projections by end of this century (2090-2100) from the peer-reviewed literature. Notations "B1", "A2" and "A1Fi" refer to IPCC emissions scenarios. Details on methods used and assumptions are in the original references (Moser, Williams, and Boesch, 2012).

average sea-level rise by year A.D. 2100 as a reasonable value to be used for planning purposes. Having precise LRSL rise values for each region of the coast would be useful but is not possible at present because of so many variables and a lack of local data. As scientific understanding improves with new data, planning values, such as 1 m, can be adjusted downward or upward to meet needs.

Over longer time frames, with continued warming, some climate scientists feel that accelerated melting in Greenland and West Antarctica could lead to sea-level rise of 4 m or more over the next several hundred years. Sea-level rise may even approach levels attained during the last interglacial warm period, which was 6–8 m higher than modern day (Hansen *et al.,* 2007; Overpeck *et al.,* 2006). A paper by Jevrejeva, Moore, and Grinsted (2011) suggests GSL rise in the range of 1.8–5.5 m is possible by AD 2500. At the extreme, a maximum rise of about 70 m is possible, if global warming continues such that all ice sheets melt. Total melting has happened in the geologic past, but would likely require several centuries of high global temperatures. Temperatures at this level (~4 C) are predicted by IPCC (2007) in some atmospheric model scenarios if carbon emissions are not reduced.

IMPLICATIONS OF SEA-LEVEL RISE

The record of humans living at the coast is long, whether for resources, commerce, or personal appeal. And, throughout history, humans have responded to eroding shorelines and frequent flooding. The usual response was to avoid permanent habitation in low-lying coastal areas and to relocate village sites inland to higher ground when the shoreline encroached. More recently, as population has grown and coastal development increased, a variety of hard and soft engineering measures (*e.g.*, seawalls, revetments, groins, beach nourishment) have been implemented to mitigate erosion and protect threatened upland property. Some measures can afford protection to upland areas but hard structures can also exacerbate erosion by disrupting sediment transport processes (USCCSP, 2009; NRC, 2007). Most engineering structures have been designed based on simple extrapolation of historical parameters of sea-level change, waves and currents, and hurricanes; however, with future sea-level rise, calls for addressing increased coastal flooding and erosion will become more widespread and ultimately more expensive for society (Nicholls and Cazenave, 2010; Nicholls *et al.,* 2007, 2011; Weiss *et al.,* 2011). Coastal plain regions such as northeastern North Carolina and southern Virginia as well as the Louisiana delta plain, are particularly at risk and highly vulnerable to rising seas due to the low and narrow character of the barrier islands, the flat coastal plain surface extending from the coast many kilometers landward, and the fact that relative LRSL rise is occurring in these regions at higher than GSL rise rates due to regional geophysical factors. Cities along the coast are especially highly vulnerable, (*e.g.*, Norfolk–Virginia Beach, New Orleans, Boston, New York, Washington, D.C., Miami, Houston–Galveston, San Francisco, and Honolulu).

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 using methods that benefit or minimize impacts to both the natural environment and human populations. Shore protection policies have been developed in response to shoreline retreat issues that affect coastal property or erosion of recreational beaches. While it is widely recognized that sea-level rise is an underlying cause of these changes, there has been limited policy and regulation that explicitly addresses or incorporates sea-level rise into the decisionmaking process (USCCSP, 2009). Fortunately, this situation is changing as the importance of addressing the need for developing adaptation alternatives is recognized. In the short term (10–50 years), a low to modest acceleration in rise rates may simply increase the cost of current shore protection practices (Nordstrom, 2000). For longer term (>50 years) planning or if GSL rise rates become high, policy makers might evaluate whether current approaches and justifications for coastal protection need to be modified to reflect the increasing vulnerability (USCCSP, 2009). The use of rolling easements as described in Titus (2011) to accommodate sea-level rise and maintain public access to the coast might have application in regions where development is limited and open space is available to accommodate marine transgression.

With the recognition of increasing coastal vulnerability, there is 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 Bruun Rule, empirical models based on historical water-level data, or more simply extrapolation of historical shoreline change rates (Bruun, 1962). 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 shoreline response may depend on the influence of previous events. The use of semiquantitative geomorphic models to predict coastal change offers promise (Moore *et al.,* 2010, 2011). Incorporating probabilistic methods such as Bayesian Networks (Borsuk, Stow, and Reckhow, 2004; Gutierrez, Plant, and Thieler, 2011; Jensen, 1996) also may help account for the complexities involved in assigning probabilities to coastal change.

Sea-level rise projections should 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 required for local decisionmaking (see chapter 2, USCCSP, 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 elevation data for much of the U.S. do not scientifically support assessment mapping using a rise increment of 1 m or less. Nationwide collection of high-quality lidar-elevation data across the coastal zone would improve the ability to conduct assessments of coastal vulnerability that can reliably be used for planning and decisionmaking (USCCSP, 2009).

To cope with sea-level rise, current policies and economic considerations should be examined and modified when necessary so that society and natural systems are better able to adapt. Plans and policy need to be based on the best available science. To enhance scientific understanding, needs include more continuous and long-term observations of glaciers and ice sheets, coastal and sea-level change, and continued improvement in models that are able to resolve regional variability in coastal change.

SUMMARY AND CONCLUSIONS

The geologic record shows that global mean sea level has been 6–8 m higher in the past due to natural climate change. Global climate change now, however, is due largely to carbon emissions from human activities and land use change. Sea-level rise is one of the most pervasive impacts of climate change and is already affecting many coastal regions with erosion and increased tidal flooding. These effects will continue and are very likely to increase in the future. High population densities in many coastal regions make it more expensive and complex to protect development in the face of natural hazards. These conditions are leading to an increase in vulnerability of natural systems and human populations, resulting in significant economic and societal risk. Our scientific understanding for predicting GSL rise and the effects on coastal systems is improving, but much work remains to develop reliable and useful forecasts of risk and quantified probabilities.

For much of the U.S. coast, more frequent tidal flooding, erosion, and inundation will be the dominant responses to sea-level rise throughout the 21st century and beyond. The actual responses will vary greatly depending on many local factors. Some coastal landforms may undergo large changes in shape and location, and wetlands may drown if higher rise rates are realized. Increased inundation and more frequent tidal and storm-surge flooding will especially affect estuaries and low-lying coastal areas. Regions undergoing subsidence will experience the greatest land loss. The response of coastal landforms to these driving forces will vary depending on the geologic character of coastal landform and local conditions, but the impacts are likely to be more extreme, more variable, and less predictable than the changes observed in the past century. For higher GSL rise scenarios, some barrier islands and spits, and wetlands may cross thresholds and undergo irreversible change, such as rapid landward migration, segmentation of barrier islands, and drowning of wetlands.

Observations that sea-level rise rates are accelerating due to warming are becoming conclusive. Analyses suggest GSL rise rate acceleration started in the mid-19th century. The 20th century average rise rate was 1.7 mm/yr and the current GSL rise rate is 3 mm/yr. Important questions still to be answered are: how much is sea level likely to rise during this century, at what rates, and what levels are expected beyond A.D. 2100? The range of projections for very likely GSL rise by the end of this century is 0.5–2 m. Local rates, however, will have high spatial and temporal variability. Assessments from several studies suggest that using a rise value of 1 m by A.D. 2100 for planning is sensible. More rapid warming and greater ice losses in Greenland and West Antarctica could result in rise of 2 m or even more. Warming beyond A.D. 2100 will continue along with accelerated but highly variable GSL rise.

Coastal management plans should include evaluations of potential responses to higher rates of GSL rise and cost-effective alternatives. Plans might include some combination of sustainable coastal protection, and strategic landward relocation of infrastructure and development for particularly vulnerable areas or if very high rise rates are realized.

In closing, planning for projected sea-level rise increases should be based on credible science, engineering, and economics to ensure careful consideration of cost-effective methods for sustaining the coast. Plans should be flexible to accommodate new information on rise projections and changes to coastal management and policy. And last, planning should also be inclusive by fully considering the long term economic, social, and environmental costs and benefits of various methods of adaptation.

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