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Past, Present, and Future Sea Level Rise and Effects on Coasts Under Changing Global Climate

Chapter C of

Sand Resources, Regional Geology, and Coastal Processes of the Chandeleur Islands Coastal System: an Evaluation of the Breton National Wildlife Refuge

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U.S. Department of the Interior
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Edited by Dawn Lavoie

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Chapter C. Past, Present, and Future Sea Level Rise and Effects on Coasts Under Changing Global Climate

By S. Jeffress Williams[1]

Abstract

Coastal regions, at the interface between the land, oceans, and atmosphere, are highly dynamic because of storms, sea level change, and other processes that act together in complex ways. The geologic record shows that sea level has risen and fallen in cycles of more than 120 m as the climate has shifted because of natural processes from glacial cold periods to interglacial warm periods. Humans are altering the global climate through greenhouse gas emissions to the atmosphere, and observations show that climate is warming on a global average, as well as becoming more variable, and that sea level rise is accelerating. Earth's climate system this century and beyond is likely to be quite different from how it was in the 20th century. Coastal regions are especially vulnerable to climate change effects and sea level rise, and increased storminess will affect the entire Gulf of Mexico region including the Chandeleur Islands, La. Projections of sea level rise for the 21st century vary, ranging from one-half meter to more than a meter. Rising sea level can inundate low-lying areas and increase flooding, coastal erosion, wetland loss, and saltwater intrusion into estuaries and freshwater aquifers. The coastal zone is dynamic because of erosion and accretion, and the response of coastal areas to sea level rise is more complex than simple inundation. Much of the United States, and especially the northern Gulf of Mexico region, consists of coastal environments and landforms such as barrier islands and wetlands that will respond to sea level rise by changing shape, size, or position. The combined effects of sea level rise and other climate change factors such as storms may cause rapid and irreversible coastal change when geomorphic thresholds are exceeded. Such changes are likely to dramatically affect coastal landforms, coastal habitats, and species for the Chandeleur Islands, as well as other regions around the Nation.

Introduction

The Mississippi River Delta Plain and coastal features of the northern Gulf of Mexico region, including the Chandeleur Islands, La., are products of complex and highly variable physical processes and interactions (for example, sediment budgets, storms, sea level change, land subsidence) among the land, the ocean, the atmosphere, and human activities over the past century and longer. Global climate, a primary driver of many processes, has considerable natural variability. Climate conditions affecting the Chandeleur Islands region specifically—in the way of temperature, storm intensity and frequency (for example, wave character and surge flooding), and rates of relative sea level rise—are highly likely to be quite different for the rest of this century and beyond compared to the climate condition effects on the islands over the 20th century. Scientific evidence and observations over the past several decades are unequivocal in demonstrating that the warming of Earth's atmosphere and oceans are very likely the result of carbon emissions from fossil fuel burning and land-use changes. Worldwide observations and data also show that changing rates of global sea level rise are consistent with increasing greenhouse gas concentrations and global warming (IPCC, 2001, 2007; Hansen and others, 2007; Broecker and Kunzig, 2008). Global climate change is underway and already having significant effects on Earth's ecosystems and human populations (Nicholls and others, 2007).

Effects from climate change are not uniform but vary considerably from region to region and over a range of time periods (Nicholls and others, 2007). These variations are caused by regional and local differences in atmospheric, terrestrial, and oceanographic processes. The processes driving climate change are complex, and so-called feedback interactions among the various processes can either enhance or diminish sea level rise impacts, making quantitative prediction of long-term effects difficult. Accelerated global sea level rise, a major outcome of climate warming, will have increasingly far-reaching impacts on all coastal regions of the United States and around the world (Nicholls and others, 2007). Impacts will be particularly dramatic on the very low relief north-central delta plain of the Gulf Coast, including the Chandeleur Islands, where land subsidence adds significantly to the rate of global sea level rise.

Sea-level rise impacts are already evident for many coastal regions (southern Louisiana, Chesapeake Bay, North Carolina) and are likely to increase significantly during this century and beyond. Future sea level rise will cause further changes to coastal landforms (for example, barrier islands,

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beaches, dunes, marshes), as well as to estuaries, waterways, and human populations and development (Nicholls and others, 2007; FitzGerald and others, 2008; Rosenzweig and others, 2008). Low-lying coastal plain regions—particularly those that are densely populated, including the north-central Gulf of Mexico—are especially vulnerable to sea level rise and its associated impacts (for example, Day and others, 2007; McGranahan and others, 2007).

As stated above, the effects of sea level rise are evident in many ways. Arguably, the most visible effect is seen in changing coastal landscapes, which are altered through inundation and coastal erosion as beaches and sand dunes change shape and move landward (Nordstrom, 2000). In addition, the alteration or loss of coastal habitats such as wetlands, bays, and estuaries has negative impacts on many animal and plant species that depend on these coastal ecosystems.

The analyses of long-term sea level measurements show that sea level rose globally on average 19 cm during the 20th century (Jevrejeva and others, 2008). In addition, satellite data show that global sea level rise has accelerated over the past 15 years but at highly variable rates on regional scales. Analyses indicate that future sea level rise will likely exceed 20th century observations by the end of the 21st century (Meehl and others, 2007; Rahmstorf, 2007; Jevrejeva and others, 2008).

Understanding Climate Change

The scientific study of climate change and associated global sea level rise are complicated because of differences in observations, data quality, cumulative effects, and many other factors. Both direct and indirect methods are useful for studying past climate change (Peltier, 2001). Instrument records and historical documents are the most accurate but are limited to the past 100–150 years in the United States. Geological information from analyses of continuous cores sampled from ice sheets and glaciers, sea and lake sediments, and sea corals provides useful proxies that have allowed researchers to decipher past climate conditions and a record of climate changes stretching back several million years (Miller and others, 2005; Jansen and others, 2007). The most precise methods are annually age-dated paleorecords from ice cores that provide accurate high-resolution data on the climate (for example, global temperature, atmospheric composition) dating back more than 400,000 years. Other paleorecords can extend back even further but provide lower resolution records.

The Intergovernmental Panel on Climate Change (IPCC) in its Fourth Assessment Report provided a comprehensive scientific review and assessment of global climate change trends, expected changes over this century, and the impacts and challenges that both humans and the rest of the natural world are likely to be confronted with (IPCC, 2007). Some key findings from this report are summarized in the IPCC text box. A U.S. Climate Change Science Program (CCSP) report (CENR, 2008) provided a general assessment of current scientific understanding of climate change impacts to the United States, and the recently published CCSP Science and Assessment Product (SAP) 4.1 specifically addressed sea level rise effects on the United States (CCSP, 2009). This chapter is based on chapter 1 of the CCSP SAP 4.1 report.

Global Sea Level Change

The elevation of global sea level is determined in large part by the dynamic balance between the mass of ice on land and the mass of water in ocean basins. This balance is largely determined by Earth's atmospheric temperature. During the last 800,000 years, global sea level has repeatedly risen and fallen about 120 m in response to the alternating accumulation and decline of large continental ice sheets as the climate warmed and cooled in naturally occurring 80,000- to 120,000-year astronomical cycles (Imbrie and Imbrie, 1986; Lambeck and others, 2002). A record of large global sea level change over the past 400,000 years during the last four cycles consists of glacial maximums with low sea levels and interglacial warm periods with high sea levels (fig. 1). The last interglacial period, about 125,000 years ago, lasted about 10,000 to 12,000 years, and global sea level was 4–6 m higher than present (Imbrie and Imbrie, 1986). Following the peak of the Last Glacial Maximum (LGM) about 18,000 to 20,000 years ago, Earth entered the present interglacial warm period. Global sea level rose very rapidly at rates as high as 50 mm/yr and a mean rate of about 10 mm/yr between about 15,000 and 6,000 years ago. The rate of sea level slowed to about 0.5 mm/yr over the past 6,000 years. During the past 3,000 to 2,000 years the rate appears to have slowed further to approximately 0.1 to 0.2 mm/yr (IPCC, 2001).

There is growing scientific evidence that during the transition from the LGM to the present interglacial warm period about 12,000 years ago (see fig. 1) Earth underwent abrupt changes when the climate system crossed some thresholds or tipping points (points or levels in the evolution of Earth's climate) that triggered abrupt changes in temperature, precipitation, ice cover, and sea level over decades or less. The causes are not well understood (National Academy of Sciences, 2002; Alley and others, 2003), but one plausible cause is thought to be disruption of major ocean currents by catastrophic influxes of freshwater from glacial lakes, which disrupted ocean circulation and heat transport processes. It is unknown how anthropogenic climate change may alter the natural glacial-interglacial cycle or the forcings that drive abrupt change in Earth's climate system.

At the peak of the LGM, global sea level was approximately 120 m lower than it is today (fig. 2), so coastlines were far seaward of their present locations near the margins of the continental shelf. As the global climate warmed and ice sheets melted, sea level rose rapidly but at highly

Selected Findings of the Intergovernmental Panel on Climate Change (IPCC) on Climate and Global Sea Level Rise

Recent Global Climate Change

As discussed in IPCC (2007), warming of Earth's climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level.

Human-induced increase in atmospheric carbon dioxide is the most important factor affecting the warming of Earth's climate since the mid-19th century. The atmospheric concentration of carbon dioxide in 2005 exceeds by far the natural range over the last 650,000 years.

Most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in human-caused greenhouse gas concentrations. Discernible human influences now extend to other aspects of climate, including ocean warming, continental average temperatures, temperature extremes, and wind patterns.

Recent Global Sea Level Rise

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

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

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

Global average sea level rose at an average rate of 1.8 (a range of 1.3–2.3) mm/yr between 1961 and 2003. The rate was faster between 1993 and 2003: about 3.1 (2.4–3.8) mm/yr. Whether the faster rate for 1993–2003 reflects decadal variability or an increase in the longer term trend is unclear.

Global average sea level in the last interglacial period (about 125,000 years ago) was likely 4–6 m higher than during the 20th century, mainly because of the retreat of polar ice. Ice core data indicate that average polar temperatures at that time were 3°C–5°C higher than present because of differences in Earth's orbit. The Greenland ice sheet and other arctic ice fields likely contributed no more than 4 m of the observed global sea level rise. There may also have been contributions from Antarctica ice sheet melting.

Projections for the Future

Continued greenhouse gas emissions at or above current rates would cause further warming and induce many changes in the global climate system during the 21st century that would very likely be larger than those observed during the 20th century.

On the basis of a range of possible greenhouse gas emission scenarios for the next century, the IPCC estimates that the global increase in temperature will likely be between 1.1ºC and 6.4ºC. Estimates of sea level rise for the same scenarios are 0.18–0.59 m, excluding the contribution from accelerated ice discharges from the Greenland and Antarctica ice sheets.

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

In addition to global sea level rise, the storms that lead to coastal storm surges could become more intense. The IPCC indicates that on the basis of a range of computer models it is likely that tropical storms such as hurricanes will become more intense, with larger peak windspeeds and more heavy precipitation associated with ongoing increases of tropical sea surface temperatures, while the tracks of "winter" or nontropical storms are projected to shift toward the poles and increase in intensity in the North Atlantic.

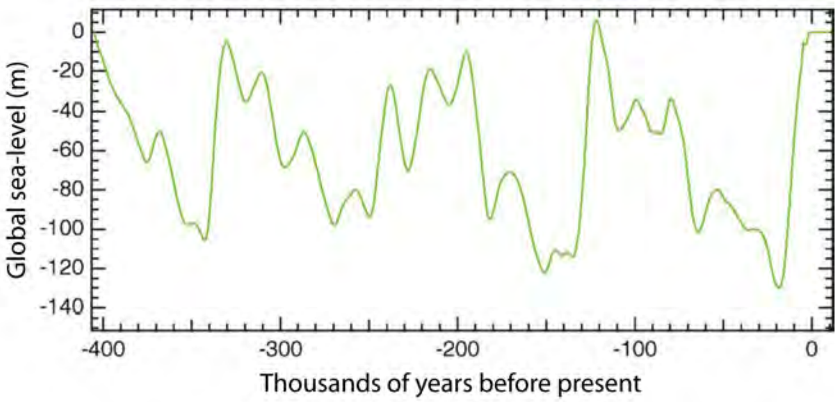

Figure 1. Plot of large variations in global sea level elevation over the past 400,000 years resulting from four glacial and interglacial global climate cycles. Evidence suggests that sea level was about 4–6 m higher than present during the last interglacial warm period 125,000 years ago and 120 m lower during the Last Glacial Maximum, about 21,000 years ago (see reviews in Muhs and others, 2004, and Overpeck and others, 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.

variable rates, eroding and submerging the continental shelves, drowning ancestral river valleys, and creating major estuaries such as Long Island Sound, Delaware Bay, Chesapeake Bay, Tampa Bay, Lake Pontchartrain, Galveston Bay, and San Francisco Bay. With one model of sea level rise (as described above) based on sea level data compiled from salt marsh deposits, global sea level rise slowed considerably 6,000 years ago and was within a couple of meters of its current elevation about 3,000 years ago (fig. 2).

Global sea level was relatively stable, with rates of rise averaging 0–0.2 mm/yr until increasing in the late 19th and early 20th centuries (Lambeck and others, 2004; Bindoff and others, 2007; Gehrels and others, 2008). Some studies indicated that acceleration in sea level rise may have begun earlier, in the late 18th century (Jevrejeva and others, 2008). Analyses of tide gage data indicate that the 20th century rate of sea level rise averaged 1.7 mm/yr on a global scale (fig. 3) (Bindoff and others, 2007) but that the rate fluctuated over decadal periods throughout the century (Church and White, 2006; Jevrejeva and others, 2006, 2008). Between 1993 and 2003, both satellite altimeter and tide gage data indicate that the global average rate of sea level rise increased to 3.1 mm/yr (Bindoff and others, 2007); however, with such a short record, it is not yet possible to determine with certainty whether this is a natural decadal variation or an accelerated rise that is due to climate warming or some combination of the two (Bindoff and others, 2007).

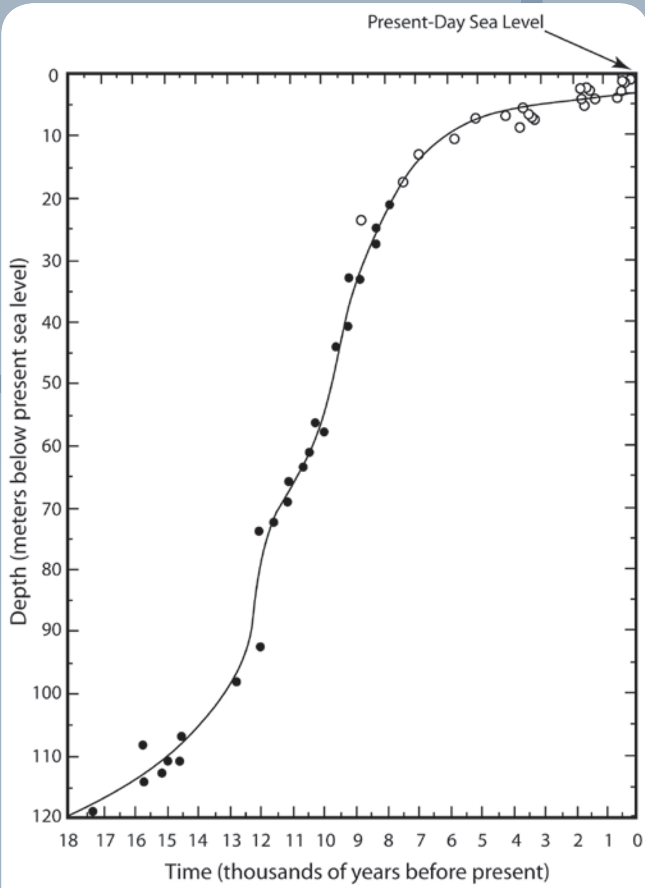

Figure 2. Generalized plot of the rise in global sea level at variable rates over the last 18,000 years as Earth moved from a glacial period to the present interglacial warm period. This curve is reconstructed from geologic samples, shown as data points. Rise was rapid but highly variable for much of 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).

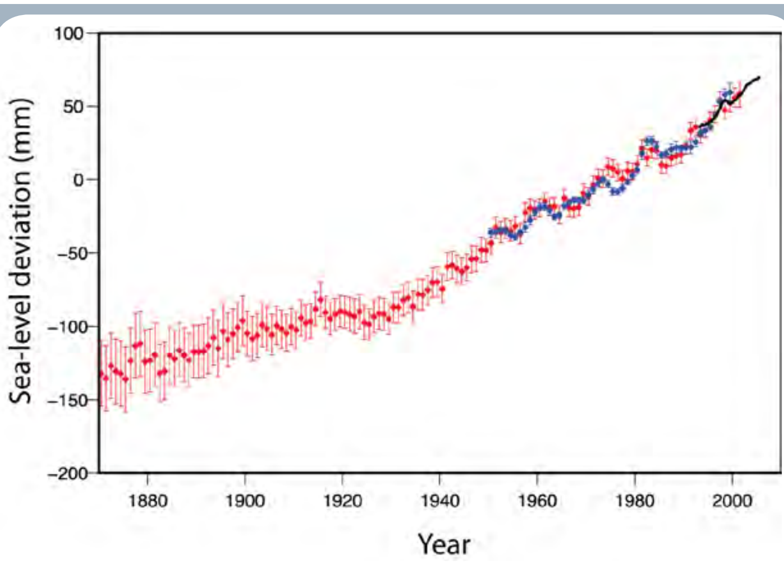

Figure 3. Annual averages of global mean sea level in millimeters from IPCC (2007). The red curve shows sea level fields since 1870 (updated from Church and White, 2006), the blue curve displays tide gage data from Holgate and Woodworth (2004), and the black curve is based on satellite observations from Leuliette and others (2004). The red and blue curves are deviations from their averages for 1961–90, and the black curve is the deviation from the average of the red curve for the period 1993–2001. 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.

Relative Sea Level Rise

Geologic data from age-dating organic sediments in sediment cores and coral reefs are methods used for determining sea level elevations over the past 40,000 years, but the records from long-term (the past 50–100 years) tide gage stations have been the primary direct measurements of relative sea level trends over the past century (Douglas, 2001).

Large variations for relative sea level rise (and fall) around the United States range from a fall of 16.7 mm/yr at Skagway in southeast Alaska that was caused by tectonic processes and land rebound upward as a result of glacier melting to a rise of 9.9 mm/yr at Grand Isle, La., west of the Mississippi River Delta, that was caused by land subsidence from natural compaction and oil and gas and water extraction. Most of the U.S. northern Gulf of Mexico coast undergoes higher rates of sea level rise (2–10 mm/yr) than the current global average (1.7 mm/yr) (Zervas, 2001). Unfortunately, there are no long-term tide gages along the Chandeleur Islands chain. The closest long-term tide gages to the Chandeleur Islands are at Grand Isle with a 60-year record of 9.9 mm/yr and at Dauphin Island, Ala., with a 39-year record of 2.9 mm/yr (Zervas, 2001). The Chandeleur Islands are approximately

Relative Sea Level

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

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

Vertical changes of the land surface result from many factors including tectonic processes and subsidence (sinking of the land) that is due to compaction of sediments and extraction of subsurface fluids such as oil, gas, and water. A principal contributor to this change along the northern Gulf Coast is sediment loading, which also contributes to regional subsidence of the land surface. Subsidence contributes to high rates of relative sea level rise (9.9 mm/yr) in the Mississippi River Delta, where thick sediments have accumulated and are compacting. Likewise, fluid withdrawal from coastal aquifers causes the sediments to compact locally as the water is extracted. In Louisiana and Texas, oil, gas, and groundwater extractions have contributed markedly to subsidence and relative sea level rise (Gornitz and Lebedeff, 1987; Emery and Aubrey, 1991; Galloway and others, 1999; Morton and others, 2004). In locations where the land surface is subsiding, rates of relative sea level rise exceed the average rate of global rise.

midway between the gages, yielding an extrapolated rate of 6.4 mm/yr; however, because the subsurface geology of the islands and adjacent sea floor are thought to be more stable than those west of the delta, this rate is likely an upper limit.

The IPCC (2007) estimated on the basis of modeling studies that global sea level is likely to rise 18–59 cm over the next century (fig. 4); however, an important caveat in the IPCC predictions is that possible increased meltwater contributions from Greenland and the Antarctica have been excluded because of limited capability at the time the report was being prepared to understand and model ice flow processes (IPCC, 2007; Meehl and others, 2007). The IPCC projections (fig. 4) represent a likely range of sea level rise that inherently allows for the possibility that the actual rise may be higher or lower. Recent satellite data suggest that sea level rise rates (about 3.1 mm/yr) may already be approaching the higher end of the IPCC estimates (Rahmstorf and others, 2007; Jevrejeva and others, 2008), and scientific consensus is growing that the IPCC estimates are conservative and should be considered low estimates because meltwater contributions from Greenland and Antarctica—which are increasingly recognized as important—were excluded. Rahmstorf (2007), as well as other climate scientists, has suggested that a global sea level rise of about 1 m or more is plausible within this century; therefore, prudence suggests that this value be considered for planning and management of the coast, including the Chandeleur Islands region. As climate data and scientific understanding improves, this prediction may likely change.

This discussion focuses on the effects of sea level rise on U.S. coasts, including the Chandeleur Islands, over this century, but climate warming and its effects are likely to continue and accelerate in effects well into the future because of the amount of greenhouse gases already in the atmosphere (IPCC, 2007). Currently, potential ice melting from land-based ice masses (primarily Greenland and west Antarctica) has some scientific uncertainty and therefore may not be adequately incorporated into sea level rise model projections. Recent observations of changes in ice cover and glacial melting on Greenland, west Antarctica, and smaller glaciers and ice caps around the world indicate that ice loss could be more rapid than the trends evaluated for the IPCC (2007) report (Chen and others, 2006; Fettweis and others, 2007; Meier and others, 2007; Shepherd and Wingham, 2007). The science needed to assign probability to these high scenarios is not yet established, but this topic is worthy of continued study because of the grave implications for coastal and low-lying areas in the United States and around the world.

Impacts of Sea Level Rise on the U.S. Coast

Coastal communities and habitats will be increasingly stressed by climate change impacts that are due to sea level rise and storms (Field and others, 2007). To varying degrees over decades, rising sea level will affect entire coastal systems from the ocean shoreline well landward across the coastal plain. The physical and ecological changes that are likely to occur in the near future will impact people, coastal development, and natural ecosystem resources. Impacts from sea level rise include land loss through submergence and erosion of lands in coastal areas, migration of coastal landforms and habitats, increased frequency and extent of storm-related flooding, wetland losses, and increased salinity in estuaries and coastal freshwater aquifers. Each of these effects can have impacts on both natural ecosystems and human development. Often the impacts act together, and the effects can be cumulative over time.

Other impacts of climate change, such as increasingly severe droughts and storm intensity—combined with continued rapid coastal development—could increase the extent of sea level rise impacts (Nicholls and others, 2007). To deal with these impacts, several things should be considered: new practices in managing coasts, the combined

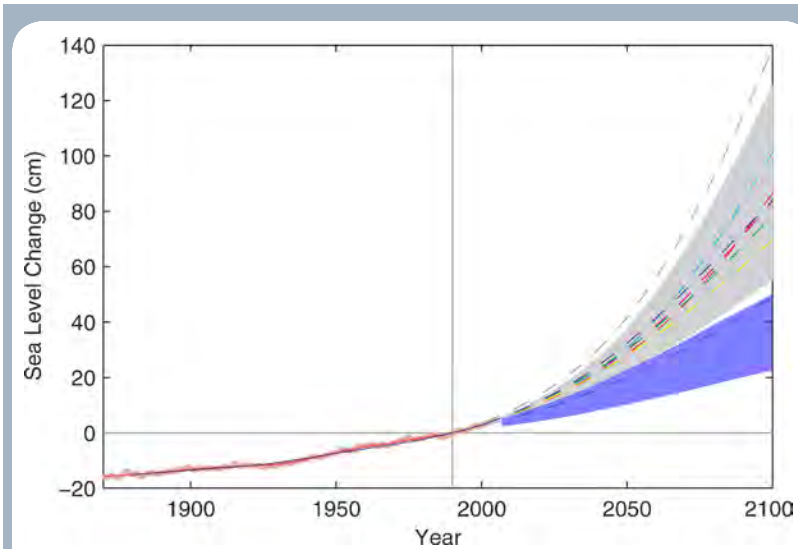

Figure 4. Plot in centimeters rise over time of past sea level observations and several future sea level projections to the year 2100 based on various computer models. The blue shaded area is the projection by Bindoff and others (2007) and the basis for the IPCC (2007) estimates. The higher gray and dashed line projections are from Rahmstorf (2007) considering the factors used in the IPCC estimates and also potentially increased melting of ice sheets in Greenland and Antarctica. From: Rahmstorf, S., 2007: A semi-empirical approach to projecting future sea-level rise. Science, 315(5810), 368–370. Reprinted with permission from AAAS.

impacts of mitigating changes to the physical system (for example, coastal erosion or migration, wetland losses), and the combination of impacts to the environment as well as to humans (for example, property losses, more frequent flood damage).

Global sea level rise, in combination with the factors above, is already having significant effects on many U.S. coastal areas. Flooding of low-lying regions by storm surges and spring tides is becoming more frequent. In many areas around the United States (for example New Jersey, North Carolina, Chesapeake Bay, Louisiana), wetland losses are occurring, fringe forests are dying and being converted to marsh, farmland and lawns are being converted to marsh (for example, see Riggs and Ames, 2003), and some roads and urban areas (Charleston, Chesapeake Bay) in low-elevation areas are more frequently flooded during spring high tides (Douglas, 2001). Rising sea level is causing saltwater intrusion into estuaries and threatening freshwater resources.

Climate Change and Storms

Although storms occur episodically, they can have long-term impacts to the physical environment and human populations. Coupled with rise in sea level, the effects of storms could be more extensive in the future because of changes in storm character, such as intensity, frequency, and storm tracking. In addition to higher sea level, coastal storm surge from hurricanes could become higher, and more intense rainfall could raise the potential for flooding from land runoff. Recent studies (for example, Emanuel and others, 2004; Emanuel, 2005, 2008; Elsner and others, 2008; Komar and Allan, 2008) concluded that there is evidence that hurricane intensity has increased during the past 30 years over the Atlantic Ocean; however, it is unknown whether this trend will continue into the future. There is currently no scientific consensus on changes in the frequency of major storms. Emanuel (2008) suggested that increased wind shear (which weakens hurricanes) resulting from global warming may reduce the global frequency of hurricanes. The topic of storm effects resulting from climate warming is being studied but is very much unsettled at the present time.

Extratropical storms can also produce significant storm surges. Over the last 50 years, the pattern of these storms shows a northward shift in track (Karl and others, 2008), which has reduced storm frequencies and intensities in the middle latitudes and increased storm frequencies and intensities at high latitudes (Gutowski and others, 2008). Karl and others (2008) concluded that future intense nontropical storms will become more frequent and will have stronger winds and greater wave heights. Projections for changes in extratropical storm activity for the Gulf of Mexico are not available. Thus, while increased storm intensity is a serious risk in concert with sea level rise, storm predictions are not so well established that planners can yet rely on them.

Shoreline Change and Coastal Erosion

The diverse landforms that make up the more than 150,000 km of U.S. tidal coastline reflect a dynamic interaction between (1) natural factors and physical processes that act on the coast (for example, storms, waves, currents, sand sources and sinks, relative sea level), (2) human activity (for example, dredging, dams, coastal engineering), and (3) the geological character of the coast and nearshore. Variations of these physical processes in both location and time, as well as the local geology along the coast, result in the majority of U.S. coastlines undergoing overall long-term net erosion at highly varying rates.

The complex interactions between these factors make it difficult to relate sea level rise and shoreline change and to reach agreement among coastal scientists on approaches to predict how shorelines will change in response to sea level rise. The difficulty in linking sea level rise to coastal change stems from the fact that shoreline change is not driven solely by sea level rise. Instead, coasts are in dynamic flux, responding to many driving forces, such as storm activity, dominant winds, the coastal geological character, changes in tidal flow, and volume of sediment (that is, sediment budget) in the coastal system. For example, FitzGerald and others (2008) reported 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 in predicting in any detail how the coast will respond to future sea level rise in concert with the other driving processes.

Some scientific evidence suggests that barrier islands, wetlands, and other landforms within coastal systems might have tipping points or thresholds, such that when limits are exceeded the landforms become unstable and undergo large irreversible changes (National Academy of Sciences, 2002; Riggs and Ames, 2003; Nicholls and others, 2007). These changes are thought to occur rapidly and are thus far unpredictable. It is possible that this process is happening to barrier islands and wetlands along the Louisiana coast, including the Chandeleur Islands, which have been subject to high rates of sea level rise, frequent major storms over the past decade, land subsidence, high rates of erosion, and limited sediment supply as detailed in the other chapters of this report and in Sallenger and others (2007).

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References

Alley, R.B., Marotzke, J., Nordhaus, W.D., Overpeck, J.T., Peteet, D.M., Pielke, R.A., Jr., Pierrehumbert, R.T., Rhines, P.B., Stocker, T.F., Talley, L.D., and Wallace, J.M., 2003, Abrupt climate change: Science, v. 299, no. 5615, p. 2005–2010.

Bindoff, N.L., Willebrand, J., Artale, V., Cazenave, A., Gregory, J., Gulev, S., Hanawa, K., C. Le Quéré, Levitus, S., Nojiri, Y., Shum, C.K., Talley, L.D., and Unnikrishnan, A., 2007, Observations—oceanic climate change and sea level, *in* Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Avery, K.B., Tignor, M., and Miller, H.L., eds., Climate change 2007—the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change: Cambridge, U.K., and New York, Cambridge University Press, p. 385–432.

Broecker, W.S., and Kunzig, R., 2008, Fixing climate—what past climate changes reveal about the current threat—and how to counter it: New York, Hill and Wang, 253 p.

CCSP (Climate Change Science Program), 2009, Coastal sensitivity to sea-level rise—a focus on the mid-Atlantic region. A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research (James G. Titus [Coordinating Lead Author], K. Eric Anderson, Donald R. Cahoon, Stephen K. Gill, E. Robert Thieler, S. Jeffress Williams [Lead Authors]): Washington, D.C., U.S. Environmental Protection Agency, 320 p.

CENR (Committee on Environment and Natural Resources), 2008, Scientific assessment of the effects of global change on the United States: Washington, D.C., National Science and Technology Council, Committee on Environment and Natural Resources, 261 p.

Chen, J.L., Wilson, C.R., and Tapley, B.D., 2006, Satellite gravity measurements confirm accelerated melting of Greenland ice sheet: Science, v. 313, no. 5795, p. 1958–1960.

Church, J.A., and White, N.J., 2006, A 20th century acceleration in global sea-level rise: Geophysical Research Letters, v. 33, L01602, doi:10.1029/2005GL024826.

Day, J.W., Jr., Biesch, D.F., Clairain, E.J., Kemp, G.P., Laska, S.B., Mitsch, W.J., Orth, K., Mashriqui, H., Reed, D.J., Shabman, L., Simenstad, C.A., Streever, B.J., Twilley, R.R., Watson, C.C., Wells, J.T., and Whigham, D.F., 2007, Restoration of the Mississippi Delta—lessons from Hurricanes Katrina and Rita: Science, v. 315, no. 5819, p. 1679–1684.

Douglas, B.C., 2001, Sea level change in the era of the recording tide gauges, *in* Douglas, B.C., Kearney, M.S., and Leatherman, S.P., eds., Sea level rise—history and consequences: San Diego, Academic Press, International Geophysics Series, v. 75, p. 37–64.

Elsner, J.B., Kossin, J.P., and Jagger, T.H., 2008, The increasing intensity of the strongest tropical cyclones: Nature, v. 455, no. 7209, p. 92–95.

Emanuel, K.A., 2005, Increasing destructiveness of tropical cyclones over the past 30 years: Nature, v. 436, no. 7051, p. 686–688.

Emanuel, K., 2008, The hurricane-climate connection: Bulletin of the American Meteorological Society, v. 89, no. 5, p. ES10–ES20.

Emanuel, K., DesAutels, C., Holloway, C., and Korty, R., 2004, Environmental control of tropical cyclone intensity: Journal of the Atmospheric Sciences, v. 61, no. 7, p. 843–858.

Emery, K.O., and Aubrey, D.G., 1991, Sea levels, land levels, and tide gauges: New York, Springer-Verlag, 237 p.

Fairbanks, R.G., 1989, A 17,000-year glacio-eustatic sea level record—influence of glacial melting rates on the Younger Dryas event and deep-sea circulation: Nature, v. 342, no. 6250, p. 637–642.

Fettweis, X., van Ypersele, J.-P., Gallee, H., Lefebre, F., and Lefebvre, W., 2007, The 1979–2005 Greenland ice sheet melt extent from passive microwave data using and improved version of the melt retrieval XPGR algorithm: Geophysical Research Letters, v. 34, L05502, doi:10.1029/2006GL028787.

Field, C.B., Mortsch, L.D., Brklacich, M., Forbes, D.L., Kovacs, P., Patz, J.A., Running, S.W., and Scott, M.J., 2007, North America, *in* Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., and Hanson, C.E., eds., Climate change 2007—impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change: Cambridge, U.K., and New York, Cambridge University Press, p. 617–652.

FitzGerald, D.M., Fenster, M.S., Argow, B.A., and Buynevich, I.V., 2008, Coastal impacts due to sea-level rise: Annual Review of Earth and Planetary Sciences, v. 36, p. 601–647.

FitzGerald, D.M., Fenster, M.S., Argow, B.A., and Buynevich, I.V., 2008, Coastal impacts due to sea-level rise: Annual Review of Earth and Planetary Sciences, v. 36, p. 601–647.

Galloway, D., Jones, D.R., and Ingebritsen, S.E., 1999, Land subsidence in the United States: Reston, Va., U.S. Geological Survey Circular 1182, 177 p.

Gehrels, W.R., Hayward, B.W., Newnham, R.M., and Southall, K.E., 2008, A 20th century acceleration in sea-level rise in New Zealand: Geophysical Research Letters, v. 35, L02717, doi:10.1029/2007GL032632.

Gornitz, V., and Lebedeff, S., 1987, Global sea-level changes during the past century, *in* Nummedal, D., Pilkey, O.H., and Howard, J.D., eds., Sea-level fluctuation and coastal evolution: Tulsa, Okla., Society of Economic Paleontologists and Mineralogists, Special Publication 41, p. 3–16.

Gutowski, W.J., Hegerl, G.C., Holland, G.J., Knutson, T.R., Mearns, L.O., Stouffer, R.J., Webster, P.J., Wehner, M.F., and Zwiers, F.W., 2008, Causes of observed changes in extremes and projections of future changes, *in* Karl, T.R., Meehl, G.A., Miller, C.D., Hassol, S.J., Waple, A.M., and Murray, W.L., eds., Weather and climate extremes in a changing climate—regions of focus—North America, Hawaii, Caribbean, and U.S. Pacific Islands. Synthesis and Assessment Product 3.3: Washington D.C., U.S. Climate Change Science Program, p. 81–116.

Hansen, J., Sato, M., Kharecha, P., Russell, G., Lea, D.W., and Siddall, M., 2007, Climate change and trace gases: Philosophical Transactions of the Royal Society A, v. 365, no. 1856, p. 1925–1954.

Huybrechts, P., 2002, Sea-level changes at the LGM from ice-dynamic reconstructions of the Greenland and Antarctic ice sheets during the glacial cycles, Quaternary Science Reviews, v. 21, nos. 1–3, p. 203–231.

Holgate, S.J., and Woodworth, P.L., 2004, Evidence for enhanced coastal sea level rise during the 1990s: Geophysical Research Letters, v. 31, L07305, doi:10.1029/2004GL019626.

Imbrie, J., and Imbrie, K.P., 1986, Ice ages—solving the mystery: Cambridge, Mass., Harvard University Press, 224 p.

IPCC (Intergovernmental Panel on Climate Change), 2001, Climate change 2001—the scientific basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., and Johnson, C.A., eds.): Cambridge, U.K., and New York, Cambridge University Press, 881 p.

IPCC (Intergovernmental Panel on Climate Change), 2007, Climate change 2007—the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., and Miller, H.L., eds.): Cambridge, U.K., and New York, Cambridge University Press, 996 p.

Jansen, E., Overpeck, J., Briffa, K.R., Duplessy, J.-C., Joos, F., Masson-Delmotte, V., Olago, D., Otto-Bliesner, B., Peltier, W.R., Rahmstorf, S., Ramesh, R., Raynaud, D., Rind, D., Solomina, O., Villalba, R., and Zhang, D., 2007, Palaeoclimate, *in* Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., and H.L. Miller, H.L., eds., Climate change 2007—the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change: Cambridge, U.K., and New York, Cambridge University Press, p. 433–497.

Jevrejeva, S., Grinsted, A., Moore, J.C., and Holgate, S., 2006, Nonlinear trends and multiyear cycles in sea level records: Journal of Geophysical Research, v. 111, C09012, doi:10.1029/2005JC003229.

Jevrejeva, S., Moore, J.C., Grinsted, A., and Woodworth, P.L., 2008, Recent global sea level acceleration started over 200 years ago?: Geophysical Research Letters, v. 35, L08715, doi:10.1029/2008GL033611.

Karl, T.R., Meehl, G.A., Peterson, T.C., Kunkel, K.E., Gutowski, W.J., Jr., and Easterling, D.R., 2008, Executive summary, *in* Karl, T.R., Meehl, G.A., Miller, C.D., Hassol, S.J., Waple, A.M., and Murray, W.L., eds., Weather and climate extremes in a changing climate—regions of focus—North America, Hawaii, Caribbean, and U.S. Pacific Islands. Synthesis and Assessment Product 3.3: Washington, D.C., U.S. Climate Change Science Program, p. 1–9.

Komar, P.D., and Allan, J.C., 2008, Increasing hurricane-generated wave heights along the U.S. east coast and their climate controls*:* Journal of Coastal Research, v. 24, no. 2, p. 479–488.

Lambeck, K., Esat, T.M., and Potter, E.-K., 2002, Links between climate and sea levels for the past three million years: Nature, v. 419, no. 6903, p. 199–206.

Lambeck, K., Anzidei, M., Antonioli, F., Benini, A., and Esposito, A., 2004, Sea level in Roman time in the central Mediterranean and implications for recent change: Earth and Planetary Science Letters, v. 224, nos. 3–4, p. 563–575.

Leuliette, E.W., Nerem, R.S., and Mitchum, G.T., 2004, Calibration of TOPEX/Poseidon and Jason altimeter data to construct a continuous record of mean sea level change: Marine Geodesy, v. 27, nos. 1–2, p. 79–94.

McGranahan, G., Balk, D., and Anderson, B., 2007, The rising tide—assessing the risks of climate change and human settlements in low elevation coastal zones: Environment & Urbanization, v. 19, no. 1, p. 17–37.

Meehl, G.A., Stocker, T.F., Collins, W.D., Friedlingstein, P., Gaye, A.T., Gregory, J.M., Kitoh, A., Knutti, R., Murphy, J.M., Noda, A., Raper, S.C.B., Watterson, I.G., Weaver, A.J., and Zhao, Z.-C., 2007, Global climate projections, *in* Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., and Miller, H.L., eds., Climate change 2007—the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change: Cambridge, U.K., and New York, Cambridge University Press, p. 747–845.

Meier, M.F., Dyurgerov, M.B., Ursula, K.R., O'Neel, S., Pfeffer, W.T., Anderson, R.S., Anderson, S.P., and Glazovsky, A.F., 2007, Glaciers dominate eustatic sea-level rise in the 21st century: Science, v. 317, no. 5841, p. 1064–1067.

Miller, K.G., Kominz, M.A., Browning, J.V., Wright, J.D., Mountain, G.S., Katz, M.E., Sugarman, P.J., Cramer, B.S., Christie-Blick, N., and Pekar, S.F., 2005, The Phanerozoic record of global sea-level change: Science, v. 310, no. 5752, p. 1293–1298.

Morton, R.A., Miller, T.L., and Moore, L.J., 2004, National assessment of shoreline change—part 1, historical shoreline changes and associated coastal land loss along the U.S. Gulf of Mexico: Reston, Va., U.S. Geological Survey Open-File Report 2004–1043, 44 p.

Muhs, D.R., Wehmiller, J.F., Simmons, K.R., and York, L.L., 2004, Quaternary sea level history of the U.S., *in* Gillespie, A.R., Porter, S.C., and Atwater, B.F., eds., The Quaternary Period of the United States: Amsterdam, Elsevier, p. 147–183.

National Academy of Sciences, 2002, Abrupt climate change—inevitable surprises: Washington, D.C., National Academy Press, 230 p.

Nicholls, R.J., Wong, P.P., Burkett, V.R., Codignotto, J.O., Hay, J.E., McLean, R.F., Ragoonaden, S., and Woodroffe, C.D., 2007, Coastal systems and low-lying areas, *in* Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., and Hanson, C.E., eds., Climate change 2007—impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change: Cambridge, U.K., and New York, Cambridge University Press, p. 315–356.

Nordstrom, K.F., 2000, Beaches and dunes of developed coasts: New York, Cambridge University Press, 338 p.

Overpeck, J.T., Otto-Bliesner, B.L., Miller, G.H., Muhs, D.R., Alley, R.B., and Keihl, J.T., 2006, Paleo-climatic evidence for the future ice-sheet instability and rapid sea level rise: Science, v. 311, no. 5768, p. 1747–1750.

Peltier, W.R., 2001, Global glacial isostatic adjustment and modern instrumental records of relative sea level history, *in* Douglas, B.C., Kearney, M.S., and Leatherman, S.P., eds., Sea level rise—history and consequences: San Diego, Academic Press, International Geophysics Series, v. 75, p. 65–95.

Rahmstorf, S., 2007, A semi-empirical approach to projecting future sea-level rise: Science, v. 315, no. 5810, p. 368–370.

Rahmstorf, S., Cazenave, A., Church, J.A., Hansen, J.E., Keeling, R.F., Parker, D.E., and Somerville, R.C.J., 2007, Recent climate observations compared to projections: Science, v. 316, no. 5825, p. 709.

Riggs, S.R., and Ames, D.V., 2003, Drowning of North Carolina—sea-level rise and estuarine dynamics: Raleigh, North Carolina Sea Grant College Program, Publication no. UNC-SG-03-04, 152 p.

Rosenzweig, C., Karoly, D., Vicarelli, M., Neofotis, P., Wu, Q., Casassa, G., Menzel, A., Root, T.L., Estrella, N., Seguin, B., Tryjanowski, P., Liu, C., Rawlins, S., and Imeson, A., 2008, Attributing physical and biological impacts to anthropogenic climate change: Nature, v. 453, no. 7193, p. 353–358.

Sallenger, A.S., Wright, C.W., and Lillycrop, J., 2007, Coastal-change impacts during Hurricane Katrina—an overview, *in* Kraus, N.C., and Rosati, J.D., eds., Coastal sediments '07: Reston, Va., America Society of Civil Engineers, p. 888–896.

Shepherd, A., and Wingham, D., 2007, Recent sea-level contributions of the Antarctic and Greenland ice sheets: Science, v. 315, no. 5818, p. 1529–1532.

Zervas, C., 2001, Sea level variations of the United States 1854–1999: Silver Spring, Md., National Oceanic and Atmospheric Administration (NOAA) National Ocean Service, NOAA technical report NOS CO-OPS 36.

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