Sea-level **rise** & Global **climate change:**

A Review of Impacts to U.S. Coasts

Prepared for the Pew Center on Global Climate Change

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Foreword *Eileen Claussen, President, Pew Center on Global Climate Change*

Coastal regions play an integral role in the United States, serving as home to over half of the U.S. population, providing recreational opportunities to many, and supplying numerous valuable ecological services. At the same time, these areas are constantly evolving and face a wide range of natural and human-induced stresses, including erosion, storms, and pressures from development and recreational uses.

Current scientific research shows that climate change will lead to substantial sea-level rise along much of the U.S. coastline. Sea levels have already risen between 10 and 25 cm over the last century. Global warming will accelerate these rates, with sea levels projected to rise by 50 cm by 2100.

"Sea-Level Rise and Global Climate Change" is the fourth in a series of reports examining the potential impacts of climate change on the U.S. environment and society. This report finds that the vulnerability of a coastal area to sea-level rise varies according to the physical characteristics of the coastline, the population size and amount of development, and the responsiveness of land-use and infrastructure planning at the local level. The authors conclude the following:

- Low-lying developed areas in the Gulf Coast, the South, and the mid-Atlantic regions are especially at risk from sea-level rise.
- The rapid growth of coastal areas in the last few decades has resulted in larger populations and more valuable coastal property being at risk from sea-level rise. This growth, which is expected to continue, brings with it a greater likelihood of increased property damage in coastal areas.
- The major physical impacts of a rise in sea level include erosion of beaches, inundation of deltas as well as flooding and loss of many marshes and wetlands. Increased salinity will likely become a problem in coastal aquifers and estuarine systems as a result of saltwater intrusion.
- Although there is some uncertainty about the effect of climate change on storms and hurricanes, increases in the intensity or frequency or changes in the paths of these storms could increase storm damage in coastal areas. Damage to and loss of coastal areas would jeopardize the economic and ecological amenities provided by coastal wetlands and marshes, including flood control, critical ecological habitat, and water purification.

Damages and economic losses could be reduced if local decision-makers understand the potential impacts of sea-level rise and use this information for planning.

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Executive Summary

Climate change is likely to accelerate the historical rise in sea level through warming of oceans and melting of ice, which in turn will affect coastal development, wetland resources, and recreation along the U.S. coast. The impacts of sea-level rise will occur in coastal areas that are continually evolving and already face a wide range of natural and human-induced stresses, including erosion, storms, land subsidence, wetland loss, and environmental degradation from recreation and development pressures. Responses to sea-level rise at the national, state, and local level must therefore reflect an understanding of the complex interactions of human and ecological systems in coastal areas. In this report, we review the state of understanding of the impacts of sea-level rise on U.S. coasts.

Impact assessment for sea-level rise requires careful assessment of local conditions, the magnitude and uncertainties of global sea-level rise, and the costs and feasibility of response options. Important local conditions include coastal topography, geology, and economic and demographic factors. The areas in the United States most vulnerable to sea-level rise are in the mid-Atlantic and south-Atlantic states (because of their low-lying topography, high economic value, and relatively high storm frequency) and along the Gulf Coast (because of low-lying topography and rapid land subsidence). Parts of New England are also at risk, particularly coastal islands in southern New England. The West Coast is generally at lower risk, with the exception of San Francisco Bay and Puget Sound.

Existing threats to coasts that may be increased by climate change include: gradual sea-level rise, catastrophic sea-level rise (i.e., Antarctic ice sheet melt), and changes in storm frequency or intensity. Impact assessments have focused on the first threat, with some consideration in recent studies of the effect of storms on development and redevelopment patterns in the coastal zone. Although evidence of Antarctic ice sheet melt exists in the geologic record, recent evaluations suggest the probability of this event occurring in the next century is very low. Research on the effects of climate change on storm frequency and intensity is active, but currently inconclusive.

The Intergovernmental Panel on Climate Change (IPCC) concludes that increases in global temperatures over the next century could accelerate the historical rate of global mean sea-level rise from 1 to 2.5 millimeters per year to about 5 mm/yr (50 cm/century), with an uncertainty range of 2 to 9 mm/yr (IPCC, 1996a). More recent work using new greenhouse gas emissions scenarios shows a slightly higher rate of sea-level rise (Wigley, 1999).

The impacts of sea-level rise will vary by location and depend on a range of biophysical characteristics and socioeconomic factors, including human response. The primary impacts of sea-level rise are physical changes to the environment. These changes, in turn, affect human uses of the coast such as tourism, settlement, shipping, commercial and recreational fishing, agriculture, and wildlife viewing. The most serious physical impacts of gradual sea-level rise on coastal lowlands are (1) inundation and displacement of wetlands and lowlands; (2) coastal erosion; (3) increased vulnerability to coastal storm damage and flooding; and (4) salinization of surface water and groundwater.

National assessments suggest that a one-meter rise in global sea levels could have significant impacts, including the inundation of about 35,000 square kilometers (km^2) (13,000 square miles (mi^2)) of land, divided about equally between wetlands and upland. In addition, the 100-year coastal flood plain could increase by 38 percent, or at least 18,000 km^2 (7,000 mi^2). Estimates of land inundated if global sea levels rise 0.5 meter are closer to 24,000 km^2 (9,000 mi^2). Major coastal cities such as New Orleans, Miami, New York, and Washington, DC, will have to upgrade flood defenses and drainage systems or risk adverse consequences.

Three options have been proposed to respond to coastal threats: planned retreat, accommodation, and protection. Impact and adaptation assessments evaluate where these responses might be implemented and then calculate the costs of implementation and the damages to resources that are not protected. Generally, property losses or the costs to protect property dominate the existing impact estimates for the United States. The implications of lost wetlands, which are not reflected in most current impact estimates, could also be significant. Based on a review of the existing literature, estimates of the cumulative impacts of a 50-cm sea-level rise by 2100 on coastal property range from about \$20 billion to about \$150 billion. Estimates at the low end of the range reflect modeling of the most economically efficient adaptation to sea-level rise. Those estimates at the high end reflect assessments of vulnerability or protection costs, and assume that all currently developed vulnerable areas will be protected, regardless of costs.

Although these cumulative costs are a relatively small percentage of total property values in the coastal zone, these aggregate estimates do not reflect the potentially large effects on coastal wetlands and, perhaps more important, provide no information on the distribution of impacts. Depending on the policy options chosen to respond to sea-level rise, the impact of rising seas could fall disproportionately on a small number of people or communities in the most vulnerable areas.

In many cases, the impacts of sea-level rise could be mitigated by forward-looking state or local land-use policies. The major challenges of future impact assessments include improving their comprehensiveness and accuracy and making their results more accessible and useful to state and local decision-makers who are most able to prepare coastal areas to respond to the threat of sea-level rise.

I. Introduction

An increase in sea level due to climate change could significantly influence the world's coastal zone, adversely affecting ecologically and economically important coastal systems (IPCC, 1990, 1996b). In the United States, the dimensions of the coastal zone potentially at risk from sea-level rise are enormous. There are roughly 20,000 km (12,000 miles) of coastline and more than 32,000 km^2 (over 13,000 mi^2) of coastal wetlands (EPA, 1989). The land area of coastal counties comprises about 25 percent of the total land area of the United States, while accounting for 53 percent of the U.S. population (141 million people) in 1997. Recreational beach visits account for almost 200 million visitor days a year. By one estimate, the total annual value of these recreational visits is over $3 billion (Loomis and Crespi, 1999).

Not surprisingly, knowledge of the potential impact of this sea-level rise has influenced land use and development policies in the coastal zone. At the local level, however, more immediate concerns about risks to property and recreation tend to dominate the agenda. For example, coastal property owners, local and state governments, and the insurance industry have long worried about the effects of beach erosion, land subsidence, and hurricanes, separate from any concerns about climate change and associated sea-level rise. With some notable exceptions, local decision-makers are only beginning to understand the ways in which the long-term influence of sea-level rise could influence their plans for responding to more immediate concerns.

The existing literature on the impacts of sea-level rise suggests three key conclusions:

- The potential effects of climate change in the coastal zone may be substantial.
- Forward-looking risk communication, land use, and development management measures taken today, particularly at the local level, can greatly reduce potential damages.
- The long-term and complex nature of effects are likely to continue to make forecasts of impacts highly uncertain; these concerns are magnified as one moves from coarser to finer resolutions, from global to national to local levels.

One of the important challenges for sea-level rise research is to put the results of climate change impact assessment into a context that is understandable and useful to local decision-makers. If this goal is accomplished, it is more likely that short-term measures that enhance the adaptive capacity of coastal areas to respond to sea-level rise can be implemented at the local level.

This report reviews the state of understanding of the impacts of future climate-induced sea-level rise on U.S. coasts. This report also emphasizes the importance of human activities in increasing the vulnerability of the coastal zone to sea-level rise, and measures to reduce that vulnerability. Section II reviews key geographic variables that may influence vulnerability to coastal impacts as well as major trends in development of the coastal zone. Section III reviews the basic science of sea-level rise assessment, including historic trends and projections of future rise, and Section IV reviews the authors' understanding of the major physical impacts of sea-level rise; these two sections assess the threat to coastal areas posed by sea-level rise and other risks posed by climate change. Section V summarizes a few of the potential responses to sea-level rise that researchers have explored. Section VI reviews the economic impact studies that combine data on vulnerability, sea-level rise threats, and costs of alternative responses to generate economic estimates of sea-level rise impacts. Section VII presents the authors' conclusions and discusses policy options that might improve the ability of U.S. decision-makers to respond and adapt to sea-level rise.

II. Review of Factors Affecting the Vulnerability of the U.S. Coastal Zone

The major coastal regions of the United States differ in their vulnerability to the risks of sea-level rise. Important local and regional factors that affect vulnerability include variations in the physical characteristics of the coastal area (e.g., the slope and elevation of coastal lowlands), rates of projected population growth and investment, and management policies and practices. These differences will in turn influence the extent of impacts of sea-level rise on coastal areas. Major physical impacts of sea-level rise include the following:

- erosion of beaches, bay shores, and tidally influenced river deltas;
- permanent inundation or wetland colonization of low-lying uplands;
- increased flooding and erosion of marshes, wetlands and tidal flats, potentially resulting in net degradation and losses as a result of normal tidal inundation and episodic storm surges;
- increased flooding and storm damage in low-lying coastal areas as episodic storm surges and destructive waves penetrate further inland; and
- increased salinity in estuaries, marshes, coastal rivers, and coastal aquifers (Leatherman, 1989; Kana et al., 1984).

These primary impacts will trigger other impacts such as damage to buildings and other coastal infrastructure, including ports, ship channels, and bridges. Where hazardous waste landfills are affected, pollutants in the landfills may migrate because of flooding and water-table changes. As sea-level rise accelerates, these impacts may become more severe, depending on individual site characteristics and protection strategies.

In addition, climate change may result in changing patterns of storm damage in coastal areas, although this effect is not a result of sea-level rise. Climate change could result in more northerly storm tracks, for example, or changes in the frequency or intensity of tropical storms and hurricanes.[1]

A. Geographic Characteristics

From a physical standpoint, the East and Gulf coasts are more vulnerable to sea-level rise than the West Coast because the former have extensive low-lying coastal plains, while much of the latter is composed of cliffs (National Research Council, 1987). Overall, the coastal zones of the Northeast and West are least susceptible to sea-level rise impacts because of steeper average coastal profiles, geologic substrates composed of less erodible rock or glacial and riverine till, and lower rates of natural land subsidence. Coastal barrier islands and spits in the Northeast (e.g., outer Cape Cod, Massachusetts) and low-lying salt marshes are exceptions in these regions; these areas are especially susceptible to erosion from storm surges associated with accelerated sea-level rise.

The most susceptible regions in the United States include the Gulf Coast (see Box 1), because of its relatively low-lying coastal topography and high existing rate of land subsidence, and the mid-Atlantic and south Atlantic areas, where low-lying coastal topography allows marine influence and hence sea-level rise to penetrate large distances inland. Extensive coastal lowlands that would be affected by

Box 1

Louisiana: Case Study in Coastal Vulnerability and Potential Sea-Level Rise Impacts

The deltaic coast of Louisiana exhibits the greatest vulnerability to sea-level rise of the entire U.S. coast. In this area, relatively high rates of vertical marsh accretion cannot offset high rates of natural and human-induced land subsidence. Extensive losses of wetlands are expected in the future as salt marshes convert to open or sheltered water (perhaps 1,800 km^2 over the next 50 years by one estimate, Louisiana Legislative Study Group, 1999), although many of these losses would occur even in the absence of accelerated sea-level rise (DeLaune et al., 1992). If there are extensive wetlands losses as sea level rises, concomitant economic impacts could be significant. Louisiana contains approximately 40 percent of the coastal wetlands in the continental United States. These wetlands and their associated estuarine ecosystems support natural resources with an estimated value of more than $1 billion annually (Stone and McBride, 1998).

Studies of various sites in coastal Louisiana show that annual rates of accretion of organic matter and mineral sediment to coastal marshes are insufficient to keep pace with increasing sea-level rise and submergence. A study of the Barataria Bay ecosystem, for example, found that widespread conversion of marshes to open water cannot be forestalled unless sediment from the Mississippi River system is reintroduced to counteract the effects of coastal submergence (Baumann et al., 1984).

The state has adopted several measures to restore wetlands, but they cannot keep up with current pressures, let alone the increased land loss expected with accelerated sea-level rise. By one estimate, the combined effects of all restoration projects currently being implemented will slow the rate of land loss by only about 23 percent. Nonetheless, the state is actively considering more aggressive land restoration efforts, utilizing freshwater and sediment diversions from the massive Mississippi and Atchafalaya Rivers in a strategic manner (Louisiana Legislative Study Group, 1999).

sea-level rise are found in Louisiana and south Florida as well as eastern Texas, North Carolina, and the Chesapeake Bay of Maryland and Virginia. These coastal areas are fragmented by human use, such as urban settlements, resort towns, agriculture, and national seashores, which interact with physical effects to lead to a range of impacts.

B. Development, Demographic, and Storm Damage Trends

Physical factors may determine whether an area is susceptible to flooding or storm damage, but the overall magnitude of vulnerability in economic terms also depends on population patterns and economic investment. At the national level, more than half of the U.S. population currently lives in counties located along the 20,000 km (12,000 miles) of coastline (Miller and Auyong, 1991). Projections of growth of the coastal population suggest that by 2010 the coastal population will have grown by 60 percent from 1960 levels (Culliton et al., 1990; Miller and Auyong, 1991). Florida is experiencing unprecedented population shifts as baby boomers enter retirement age and depart northern population centers for the southwest coast and the Miami-Ft. Lauderdale metropolitan region. Similarly, coastal resort communities such as Hilton Head and Myrtle Beach, South Carolina; the Outer Banks of North Carolina; and various communities in Georgia and along the Gulf of Mexico in Mississippi and Alabama are experiencing dramatic population growth. From 1950 to 1985, the coastal population of Texas increased 250 percent (Landsea, 1993); Southern California's population is expected to increase by 5.6 million people (almost 20 percent) over the next 20 years (NOAA, 1999).

Not surprisingly, the increase in coastal population has spurred a concomitant increase in population density, infrastructure, and property values that also contribute to the vulnerability to sea-level rise. Each week, about 8,700 new single-family homes are constructed along the U.S. coast (NOAA, 1999). Moreover, use of coastal public lands and recreational resources has risen in step with population growth. In the decade from 1979 to 1989, recreational visits to coastal national parks, seashores, and monuments increased at a faster rate than coastal population itself (Reid and Trexler, 1991).

Rates of population and property value growth in some coastal regions exceeded these national trends. Table 1 summarizes three of the important historical trends affecting the vulnerability of U.S. coastal regions to sea-level rise: (1) size of coastal populations, (2) value of insured coastal property, and (3) amount of coastal wetlands. Portions of the Gulf and Atlantic coasts, for example, have experienced the greatest proportional growth in numbers of people living close to the shoreline. Florida's population alone nearly tripled from 1960 to 1995 (from 5 million to 14 million), with much of that growth occurring since 1980 (Pielke and Landsea, 1998). From 1988 to 1993, the total value of insured property in coastal counties from Maine to Texas increased 69 percent, from $1.9 trillion to $3.15 trillion, while the value of all insured U.S. properties, coastal and otherwise, increased about 65 percent (Pielke and Landsea, 1998).[2]

Table 1

Key Regional Trends in the U.S. Coastal Zone Affecting Vulnerability to Sea-Level Rise

Coastal Region	Change in Coastal Population (millions of people)/Percent Change, 1980-1993[a]	Change in Value of Insured Coastal Property (billions of 1993 dollars)/Percent Change, 1988-1993[b]	Coastal Wetlands, 1985 (in thousands of acres)/Projected Percent Change to 2100[c,d]
Northeast (ME, NH, MA, RI)	0.4/ +8%	$211/+74%	121/ -3%
Mid-Atlantic (CT, NY, NJ, DE, MD, VA)	1.0/ +7%	$591/+79%	733/-13%
South Atlantic (NC, SC, GA)	0.3/+23%	$62/+88%	1,377/ +4%
Florida	2.8/+37%	$306/+54%	736/+29%
Gulf Coast (MS, AL, LA, TX)[e]	0.1/ +3%	$145/+62%	3,885/-62%
West Coast[f]	n/a	n/a	89/-40%

Notes: a) Includes population in coastal counties only. b) Includes insured commercial and residential property in coastal counties only. c) Baseline wetlands estimates based on a 1986 estimate by NOAA. d) Projected changes in wetlands acreage based on estimates by Armentano et al. (1988), assuming a 57-cm rise in sea level due to climate change. e) Louisiana accounts for the majority of wetlands in this region, as well as the majority of potential wetlands losses under a 57-cm rise in sea level. f) Does not include Hawaii or Alaska.

Sources: Socioeconomic data from Insurance Institute for Property Loss Reduction and Insurance Research Council (1995); wetlands loss estimates from Armentano et al. (1988)

Assessment of sea-level rise impacts should include assessment of vulnerability to storm damage. Coastal areas might be affected by climate change both through increased vulnerability to flooding (i.e., storm surges) and through effects on the intensity or frequency of storms (discussed further in Section IV.C). Recent tropical storms and hurricanes provide powerful evidence of the vulnerability of people and properties in U.S. coastal areas. Total damages from Hurricane Andrew in 1992, for instance, equaled about $30 billion, making it the most costly hurricane in U.S. history.

One reason for increased vulnerability to storms may be the interaction of the natural variability in storm intensity and its link to trends in coastal development. In the two or three decades prior to 1990, the eastern United States experienced a period of relatively mild hurricane activity. Perceptions of the risk of storms to property during this period may therefore have been underestimated. In the 1990s, as hurricane frequency and intensity increased to the higher end of the normal range, 20 to 30 years of relatively aggressive coastal development had left coastal regions much more vulnerable to storm damage. Analysis of landfalling hurricanes since 1925 indicates that seven hurricane seasons similar to the seasons experienced between 1940 and 1969 would have resulted in damages of $10 billion or more if they had occurred with 1995 patterns of coastal development (Pielke and Landsea, 1998). Future hurricane damages, projected from past storms, could average $5 billion per year (Pielke and Landsea, 1998). If climate change results in more frequent or more powerful storm events, damages could conceivably be even higher.

C. Ecological Services and Diversity

The myriad of cultural and aesthetic amenities as well as numerous valuable ecological services provided by coastal areas, although not traded in economic markets, also influence vulnerability. Seventeen million hectares (42 million acres) of coastal marshes and wetlands in the United States remain today. Key ecosystem functions of these wetlands include: providing vital habitat and nursery grounds for various species of fish, shrimp, birds, and fur-bearing mammals; protecting uplands from saltwater intrusion and storm surges; and improving water quality through natural filtration of nutrients and toxic substances (Turner et al., 1996; Titus, 1988; Mitsch and Gosselink, 1986).

Coastal zones are also among the most biologically diverse areas in the United States. An evaluation of the viability of species in the coastal fringe by The Nature Conservancy shows the negative impacts of human development, pollution, and habitat fragmentation on coastal ecosystems. The Nature Conservancy found that 80 species and subspecies that exist only below the ten-foot contour of the U.S. coast are considered rare, imperiled, or critically imperiled. An additional 40 to 50 species that use coastal habitats extensively are similarly threatened, including the peregrine falcon, Belding’s savannah sparrow, and the San Francisco garter snake (Reid and Trexler, 1991). Growing populations and increased development in these regions are likely to increase stresses on coastal zones over time.

III. Summary of Key Concepts in the Science of Sea-Level Rise Assessment

Climate change could trigger a global rise in sea level by increasing the volume of water contained in the oceans' basins through thermal expansion of ocean water and the melting of polar ice and mountain glaciers. Thermal expansion would occur as higher global atmospheric temperatures over the next century warm the world's oceans, causing ocean water to expand. In addition, although the oceans contain most of the world's water, if all the ice on the earth's surface were to melt, global sea level would increase by about 100 meters. While 90 percent of the earth's frozen water is stored in the comparatively stable Antarctic ice sheet, other ice deposits (e.g., the Greenland ice sheet and high-latitude and mountain glaciers) are more susceptible to melting as a result of global warming (IPCC, 1996a).

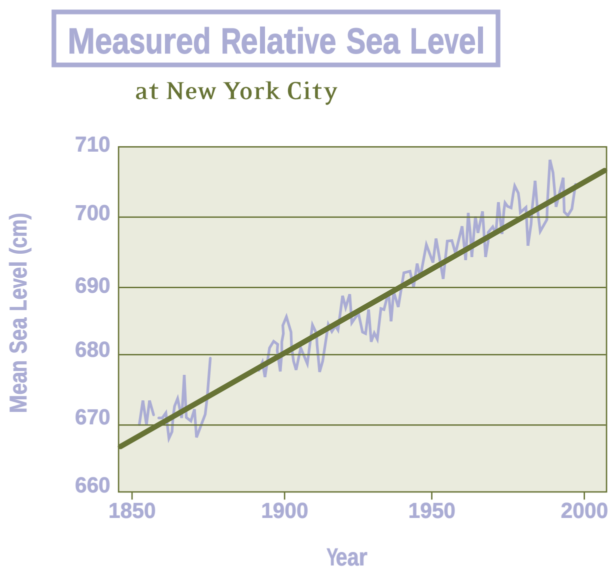
Assessments of future changes in sea level require construction and implementation of a complex modeling framework, projections of future scenarios of major factors affecting climate change, and a clear characterization of the uncertainty these analyses introduce. Using such a modeling framework, the Intergovernmental Panel on Climate Change concludes that increases in global temperatures over the next century could accelerate this rate of sea-level rise to an average of 5 millimeters per year (50 cm/century), with a range of uncertainty of 2 to 9 mm/yr (1996a). The contribution of melting of Greenland ice to global sea levels is projected to be relatively small, while the Antarctic ice sheet is projected to increase in size with global warming because snowfall there will increase more than the ice will melt, lessening the overall sea-level rise.

In addition, because of the many local factors that affect land elevation, a rise in global sea level associated with increased global temperatures would not result in an equal increase for all coastal areas. Impacts in the coastal zone depend not only on the climatic influence on increases in the oceans' volume (defined as the eustatic sea-level rise), but also on the relative effect of rising seas and changes in land elevation. Relative sea level is a measure that accounts not only for changes in ocean volume, but also for changes in land elevation (i.e., a fall in land level produces a relative rise in sea level and vice versa). No location on the earth's surface can be considered stable: regional- and local-scale vertical land movements are attributed to tectonic causes (e.g., plate movements), neotectonic causes (e.g., post-glacial rebound caused by the crust adjusting to the melting of the land-based ice caps about 10,000 years ago), and anthropogenic causes (e.g., groundwater and petroleum extraction) (Emery and Aubrey, 1991). Subsidence of land associated with the compaction of loose soils, which is often found in river delta areas, also affects land elevation. Relative sea-level rise (or fall) comprises the cumulative effect of all these local, regional, and global components, regardless of their cause.

A. Historical Rates of Relative Sea-Level Rise in the United States

While mean sea level rises and falls from year to year, and even from decade to decade, there is a clear long-term rising trend along most of the U.S. coast. IPCC (1996a) concludes that there has been a global mean rise in sea level of between 10 and 25 cm over the last 100 years, representing the combined effect of an increase in ocean volume due to thermal expansion and the observed retreat of small ice caps and glaciers. Tide gauges have recorded relative sea levels in the United States for much of the 20th century. In a few locations, such as San Francisco, Key West, and New York, the data go back well into the 19th century. Data for New York City are shown in Figure 1.

Figure 1



Source: Nicholls and Leatherman (1996).

The combined effect of the global trend in sea-level rise and the contribution of geological processes that affect land elevation is illustrated in Figure 2. Relative sea level has been rising everywhere along the East and Gulf coasts at a rate of about 0.2 meter per century. The most rapid rise is in the Mississippi delta in Louisiana and the Chenier plain in east Texas, where relative sea levels are rising at up to 1 meter per century. The Mississippi delta and Chenier plain are composed of geologically young sediments that are still consolidating. This consolidation produces natural land subsidence rates that largely explain the observed high rates of relative sea-level rise.

Figure 2

Historical **Relative Sea-Level Rise** on the U.S. Coast

Source: Nicholls and Leatherman (1996).

The mid-Atlantic region is also seeing relatively rapid rises in sea level with rates of 0.3 to 0.4 meter per century at several stations. From Wilmington, North Carolina, to southern New Jersey, geophysical models suggest that post-glacial rebound, which causes land that was not formerly glaciated to sink once glaciers retreat, is contributing 0.1 to 0.2 meter per century to relative sea-level rise, approximately doubling the effect of global sea-level rise.[3] On the West Coast, data are more scarce, but available evidence indicates both rising and falling trends. Specifically, the West Coast is on a geological plate boundary, and in some areas there is a tendency for uplift to occur as one plate pushes up another, counteracting global sea-level rise. La Jolla, San Diego, and Seattle show relative sea-level rises of about 0.2 meter per century, similar to the East Coast. From northern California to Washington, relative sea level is falling at 0.05 to 0.16 meter per century. (During major earthquakes, rapid subsidence will occur, but the time interval between events is typically hundreds of years.)

Regional or local land subsidence also occurs. In some areas, groundwater or oil withdrawal has enhanced subsidence. Around Houston, Texas, 13,500 km^2 has subsided more than 30 cm in the 20^{th} century. Around Galveston Bay, this subsidence necessitated coastal abandonment or increased coastal protection. In Long Beach, California, oil extraction produced land subsidence up to 9 meters (National Research Council, 1987).

B. Projections of Global Sea-Level Rise over the Next Century

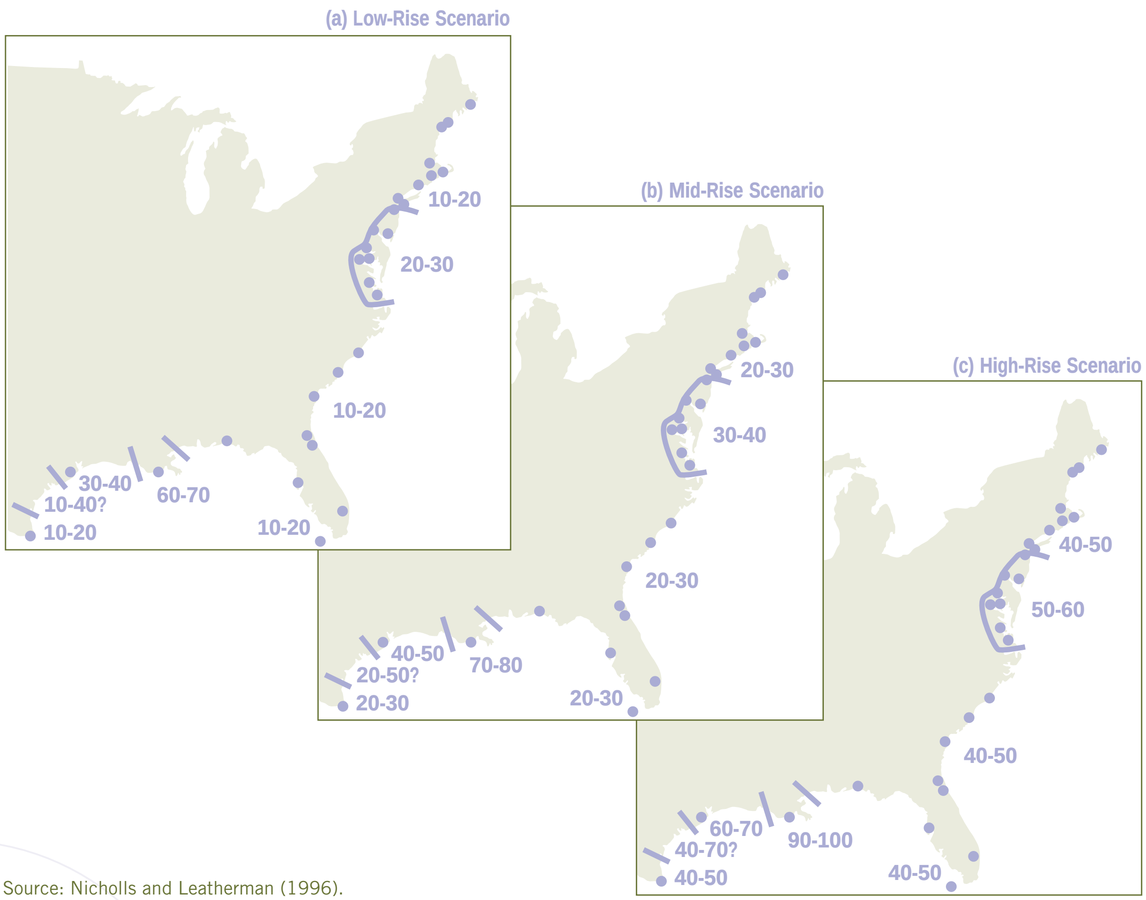
Climate-induced increases in sea level from 1990 are projected to be 23 cm by 2050 (with a range of 9 to 42 cm) and 55 cm by 2100 (with a range of 23 to 96 cm) (IPCC, 1996a).[4] More recent work using new greenhouse gas emissions scenarios to model the effect of a warmer climate on global mean sea level shows a slightly higher rate of sea-level rise (Wigley, 1999). IPCC estimates of global rises in sea level suggest a broad continuation of present trends up to a four- to ten-fold acceleration in rates of global sea-level rise by the end of the century, with a mid-range estimate of two- to five-fold acceleration. Titus and Narayanan (1995), on the other hand, conducted a probability-based analysis of global sea-level rise, based on a survey of the opinions of climate modelers. Their median estimate is that global sea levels would rise 34 cm from 1990 to 2100 (or 21 cm less than the mid-range IPCC estimate), with a 99 percent confidence interval falling between a decrease of 1 cm and a rise of 104 cm. (The unlikely case of a decrease in global sea level is produced if the growth of Antarctica more than offsets the other terms contributing to global sea-level change).

Gregory (1993) and IPCC (1996a) noted a further complication: on a regional scale there will be departures from the global rise due to factors such as changes in ocean circulation, wind and pressure patterns, and ocean-water density. These factors will produce a regionally variable rise in the ocean surface around the global mean rise already discussed, and are additional factors to consider when constructing sea-level rise scenarios for impact assessment. However, this effect is still being quantified in modeling experiments and there are no widely-accepted scenarios available at present for impact analysis or coastal planning purposes.

Low, medium, and high relative sea-level rise scenarios over a long-term planning horizon (1990 to 2050) are shown in Figure 3 for the East and Gulf coasts, combining the global sea-level rise estimates from IPCC (1996a) with expected land elevation changes. These estimates correspond to a continuation of present historical trends (i.e., an 11-cm global rise), a 20-cm global rise, and a 40-cm global rise. The "hot-spots" of coastal Louisiana/east Texas and the mid-Atlantic region are apparent, with relative

Figure 3

Future Projections of Relative Sea-Level Rise (cm) on the U.S. Coast; 1990-2050



Source: Nicholls and Leatherman (1996).

sea-level rises up to 100 cm in the first region and 60 cm in the latter region. Elsewhere, the rise could be up to 50 cm, with a higher uncertainty in the area between Galveston and Port Isabel, Texas, owing to uncertainties in the rate of subsidence. Note that even the low-rise scenario (i.e., continuation of the historical trend) produces significant rises in sea level.

These data indicate that large uncertainties exist about future global and regional sea levels. This uncertainty is unlikely to be substantially reduced in the near future. When estimating possible impacts, uncertainty can be handled by scenario-based vulnerability assessment (e.g., Yohe, 1990; Titus et al., 1991). The range of estimates that emerges from this approach reflects the outcome of alternative model inputs. An alternative approach is to consider the probabilistic long-term sea-level rise scenarios for coastal planning, for example, those provided by Titus and Narayanan (1995). However, assigning probabilities to alternative outcomes given the current state of knowledge is subjective. Considering all the uncertainties outlined above, different researchers could estimate significantly different probabilities.

IV. Physical Impacts of Climate Change on Coastal Resources

A. Assessing Impacts of Relative Sea-Level Rise

The physical impacts of relative sea-level rise will vary by location and depend on a range of physical and socioeconomic factors, including human response (Turner et al., 1996). There are already widespread problems on the East and Gulf coasts linked by varying degrees to observed sea-level rise in the 20th century and often exacerbated by poor management. Most beaches are eroding and extensive tidal wetland losses are occurring, particularly in Louisiana and around the Chesapeake Bay. Recent hurricanes such as Hugo and Andrew have caused multi-billion-dollar losses, and freshwater supplies in the lower reaches of rivers can be adversely affected during periods of low flow. In the Mississippi delta, roughly 40 km^2 (15 mi^2) of wetlands are lost every year (see Box 1). While relative sea-level rise is a major cause of these changes, attempts to maintain navigation channels and other human management of the delta have removed the sediment supplies that help the wetlands maintain elevation and keep pace with sea-level rise, as well as severely altering their hydrology (Boesch et al., 1994). On the open coast, poor management of beach sand and its movement along shorelines has contributed to substantial erosion (National Research Council, 1990). Beach erosion will increase and the tourist industry will face the dilemma of maintaining beaches through the costly process of replacing sand (i.e., beach nourishment) or staging a planned retreat. The availability of sufficient sand and the question of who pays for beach nourishment will be key issues to be assessed (Davison et al., 1992). Accelerating sea-level rise would intensify all of these problems.

National assessments suggest that a one-meter rise in global sea levels could have significant impacts, including the inundation of about 35,000 km^2 (13,000 mi^2) of land divided almost equally between wetlands and upland (Smith and Tirpak, 1989; Titus et al., 1991). The 100-year coastal flood plain (i.e., the area subject to flooding during a storm that occurs on average once every 100 years) also could increase by 38 percent, or at least 18,000 km^2 (7,000 mi^2) (FEMA, 1991). Estimates of land inundated by a 0.5-meter global sea-level rise are about 24,000 km^2 (9,000 mi^2), which is still two-thirds the inundation estimated under a one-meter rise because of the distribution of coastal elevation

(Smith and Tirpak, 1989). Major cities such as New Orleans, Tampa, Miami, Baltimore, Philadelphia, New York, Boston and Washington, DC, will have to upgrade flood defenses and drainage systems or face adverse consequences. New Orleans is particularly threatened by the loss of the surrounding wetlands in the Mississippi delta, which currently reduce the flood risk to the city from hurricane storm surges.

The extent and geographic distribution of wetlands losses depends on physical and human factors as well. The location of coastal wetlands is linked to present sea level; changes in sea level can cause wetlands to migrate landward. Wetlands with limited sediment supplies and low tidal range (i.e., a small elevation difference between low and high tide) appear to be most threatened by sea-level rise (IPCC, 1996c). The availability of low-lying upland areas landward of the wetlands is also critical for wetland survival. If the uplands are protected by coastal defenses, landward migration is not possible. Titus et al. (1991) estimate that a one-meter rise in sea level would cause the loss of about 16,000 km^2 (6,000 mi^2) of wetlands, and if no wetland migration were possible, this loss would rise to 22,000 km^2 (8,500 mi^2). Loss estimates under a 0.5-meter rise are about two-thirds those under the one-meter scenario. Global analyses identify the Atlantic coast of North America as one of the more sensitive regions to wetland losses from sea-level rise (Hoozemans et al., 1993; Nicholls et al., 1999). Where wetlands support commercial fisheries, that resource could be dramatically affected. For example, a model by Browder et al. (1989) suggests that the present catch rate in the Louisiana fishery is unsustainable if Louisiana's wetland losses continue, and the fishery could dramatically decline in the next century.

B. Effects of Catastrophic Melting

In addition to the gradual sea-level rise described above, the threat of rapid, abrupt rises in sea level associated with massive glacier and ice shelf melting has been raised in the scientific literature. If the West Antarctic ice shelf were destabilized by global warming and slid into the ocean, there would be a 5 to 7-meter rise in global sea levels (Mercer, 1978). There is geological evidence that this scenario occurred about 100,000 years ago.

While IPCC (1990; 1996a) reviewed the available evidence and concluded that such an event is unlikely in the 21st century, the impacts of catastrophic melting of ice sheets could be enormous. Large parts of the East and Gulf coasts, particularly in Louisiana and Florida, are beneath a 5 to 7-meter elevation. While the risk of this type of event is extremely low (and would take considerable time to manifest in any case) it would be prudent to continue research to better understand the likelihood of such changes, and consider the needs of appropriate monitoring systems for Antarctica.[5]

C. Potential Changes in Storm Intensity, Frequency, and Track

The number, track, rainfall quantity, and intensity of storms and hurricanes might also change with global warming, although future patterns of storms and hurricanes are uncertain (IPCC, 1996c; Knutson et al., 1998; Wigley, 1999). Generally, climate-forecasting tools used in climate studies do not have fine enough spatial resolution to be able to simulate individual tropical storms. There is some empirical evidence that the frequency of Atlantic hurricanes might increase as sea surface temperatures increase because of the positive correlation between these temperatures and hurricane frequency (Raper, 1993). In addition, with warmer sea surface temperatures, hurricanes might reach higher latitudes more often. Storms may also be accompanied by larger rainfall amounts (Wigley, 1999). Increases in hurricane intensity predicted by the models, however, fall within the range of natural interannual variability and of uncertainties of current studies (Wigley, 1999; Henderson-Sellers et al., 1998).

Based on present understanding, IPCC (1996b) has concluded that future patterns of storm frequency, track, and intensity are uncertain. Both increases and decreases in storminess are possible, and changes are likely to differ among regions around the world. Given present variability in the occurrence and strength of storms, it might be difficult to observe long-term trends. Based on an analysis summarized in Pielke and Landsea (1995), 11 major hurricanes (Category 3 or stronger) hit the East Coast, including the Florida Peninsula, from 1941 to 1965. From 1965 to 1990, when the populations of Florida and other southern states grew enormously, only two major hurricanes (Gloria and Hugo) struck the East Coast and none struck Florida. In the 1990s, hurricane frequency returned to more typical levels, and the risk to coastal property is more present in the public mind. As discussed in Section II, future hurricane damages, if projected based on past storms, could average $5 billion per year. If climate change results in more frequent, more powerful, or wetter storm events, or, if it substantially changes the track of future hurricanes toward more northerly locations, damages could increase (Pielke and Landsea, 1998). Even if climate change has no major long-term effects on the occurrence of storm effects, the variability in storm and hurricane occurrence discussed above will interact with sea-level rise. Therefore, understanding and predicting this variability is also an important topic for further research.

V. Human Response and Adaptation to Coastal Threats

Three options are available to decision-makers who contemplate responding to coastal threats, each implying tradeoffs in the distribution of costs and benefits: protection, accommodation, and planned retreat (IPCC, 1996b). Protection seeks to exclude the hazard, accommodation allows human activities and the hazard to coexist, while planned retreat removes human activity from the hazardous zone. Protection options include hard structure responses (such as building dikes and sea walls) and "soft" engineering responses that utilize sediment (particularly beach nourishment, or replenishment of sand resources). These strategies could protect some of the resources vulnerable to sea-level rise (e.g., coastal property), but might sacrifice other resources in the process (e.g., natural wetlands or beaches). Building hard structures, for example, would limit the ability of beach and wetland resources to migrate inland as sea-level rises. These losses are often termed "coastal squeeze" (IPCC, 1996c). Accommodation might include elevation of buildings, modification of drainage systems, or land-use changes. Planned retreat could involve such strategies as coastal development restrictions. In both cases, coastal squeeze is avoided.

In the United States, most decisions that involve a structural response are made at the local level, sometimes on the basis of cost-benefit analysis. State and national institutions can also play a role, particularly by providing appropriate guidance and incentives. In all cases, the distribution of costs and benefits is a critical factor. Costs of protection are typically borne collectively, while potential damages threaten individuals or their immediate communities. The interests of individuals with property at risk can play a disproportionate role in the framing of policy and its implementation. Overall, the particular strategy adopted in response to perceived threats from sea-level rise depends on many factors. These factors include the value of the land or infrastructure under threat, the financial and economic resources that can be brought to bear, the local landscape of coastal management policy, and the ability to understand and implement adaptation options.

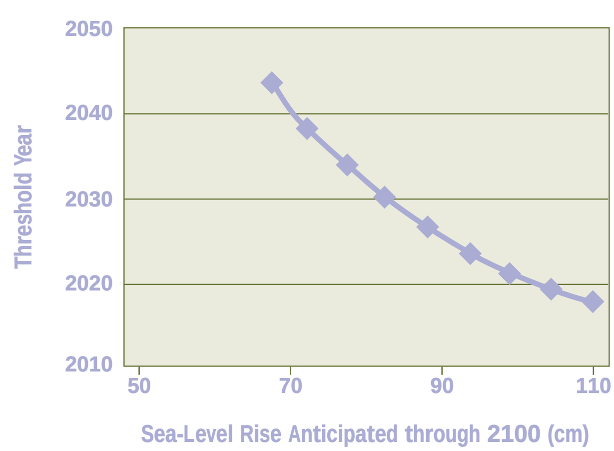
A. Hard Structure Protection

Hard structures are perhaps most sensibly applied in developed and urban areas. Seven published studies have offered specific cost estimates for various protective structures.[6] Estimates of their fixed construction costs for dikes or levees built to protect against a one-meter rise in sea level range from $150 to $800 per linear foot (1990 dollars). Corresponding cost estimates for sea wall and bulkhead construction range from $150 to $4,000 per linear foot (1990 dollars). The range in costs reflects location-specific factors such as the amount of site and foundation preparation work necessary, drainage requirements, and differences in materials and labor costs. Much of the sea-level rise impacts literature uses the median estimate of $750 per linear foot (1990 dollars) drawn from Gleick and Maurer (1990).

Hard structures do not have to be constructed until they are needed. Ideally, hard structures would be built just in advance of the threat of inundation. Because the pace of greenhouse induced sea-level rise is unknown, some anticipation and monitoring is required to implement appropriate pre-emptive responses. Yohe and Neumann (1997) assessed the timing decision and developed the notion of a warning threshold that relates anticipated sea-level rise through 2100 to the year of potential need for hard structure protection. Figure 4 displays a threshold calculation for downtown Charleston, South Carolina. Given the local subsidence in this area (estimated to be 2.2 cm per decade), the threat of inundation appears when relative sea-level rises 62 cm. Combining this warning threshold with linear sea-level rise trajectories produced results for a range of high sea-level rise scenarios. In this example, 2017 is the earliest date of concern, and then only if sea-level rise of 110 cm (i.e., the extreme high-end of expected sea-level rise)[7] is expected through 2100.

Figure 4

Results of Warning Threshold Calculation for Charleston, South Carolina



Source: Yohe and Neumann (1997).

B. Soft Protection

Since hard protection in response to an erosion problem does not solve the fundamental problem of a diminishing sediment resource, an alternative approach is artificial addition of sediment and/or improved sediment management, or soft protection, to increase the size of the beach or wetland (Davison et al., 1992; Boesch et al., 1994). The added sediment is generally sacrificed as the erosive processes continue; therefore repeated additions of sediment are required.

Beach nourishment (i.e., the placement of sand usually dredged from offshore) is a popular and cost-effective option in highly developed areas with popular beaches and valuable beachfront real estate, especially during the early onset of erosion (American Society of Coastal Engineers, 1992). Florida and New Jersey, for example, have established funds for a variety of beach nourishment projects (Yohe and Neumann, 1997). However, the long-term effectiveness of beach nourishment remains uncertain due to an incomplete understanding of coastal processes and how they will be influenced by sea-level rise and climate change. Adequate monitoring of beach nourishment projects is essential to understanding technical issues concerning their longevity and effectiveness. The question of who pays and who benefits from nourishment is another issue of concern.

While many experts agree that beach nourishment with regular renourishment cycles is an appropriate response to sea-level rise, it remains unclear when nourishment would cease to be cost-effective and another response strategy would be required. This strategy is a site-specific function of the rate of sea-level rise, the unit cost of sand, and the length of beach being nourished. As sea levels rise more rapidly, and the cheaper sand resources are exhausted, nourishment is likely to cease to be cost-effective in some coastal locations. A move to hard protection will eventually degrade the beach, as the sand is scoured away by wave action, and hence may imply loss of recreational and ecological resources.

As nourishment has become more popular, it has shown the value of coastal sediment. Therefore, in addition to nourishment, the importance of bypassing sand at inlets and beneficial uses of dredge spoil have received greater priority. Sea-level rise reinforces this trend and suggests that soft defenses should be placed in a broader context of sediment management. This approach would comprise a regional understanding of sediment fluxes, including human interventions. Efforts in other countries towards improving shoreline management based on coastal cells may be instructive (see Leafe et al., 1998). Soft protection strategies therefore raise a number of important trade-offs which require urgent attention.

C. Accommodation and Planned Retreat

The primary tools for accommodation and planned retreat are land use and development planning. Setback measures, a zoning mechanism for planned retreat employed by states, require that new structures be set back from the shore, usually by some multiple of the average annual rate of erosion (e.g., 20 to 60 times). Nine states require new construction to be set back by a distance equivalent to the extent of erosion expected over the next 30 to 60 years (Klarin and Hershman, 1990; Titus, 1990; Yohe and Neumann, 1997). Maine's Dune Rules reference setbacks explicitly to sea-level rise by requiring demolition of large structures if the sea level rises by one meter or more (Titus, 1990). These types of measures can be controversial and legally contentious, but once implemented they are an effective means of communicating and enforcing a planned retreat strategy.

Post-disaster reconstruction plans are a second type of mechanism for planned retreat. Post-disaster plans limit or prohibit reconstruction of coastal property severely damaged by hurricanes, storms, or other episodic flooding. An example is the federal National Flood Insurance Program (NFIP), which provides subsidized insurance for damage to coastal structures due to flooding or coastal erosion. NFIP requires elevation of structures damaged more than 50 percent of pre-storm value above the 100-year flood level plus wave heights. Another example is South Carolina's Beachfront Management Act of 1988, which states that structures incurring damages of more than two-thirds of pre-storm value cannot be reconstructed (Yohe and Neumann, 1997).

In practice, in those states with coastal management policies that feature setback rules, there has been considerable public resistance to their implementation even for existing erosion problems. Planning for sea-level rise implies larger setbacks might be required. In other instances, case law may dictate that setback rules represent an unconstitutional taking of property (Titus, 1990; Titus, 1998). Both of these issues may limit the effectiveness of these planned retreat policies. As evidence of the difficulty of implementing setbacks, owners of beachfront property in South Carolina were able to either circumvent the setbacks or showed a reluctance to consider the risks of sea-level rise when making decisions about whether to rebuild after Hurricane Hugo in 1989. Most owners repaired or rebuilt their homes despite extensive damage to their structures, and presumably with the full knowledge of the risks of proximity to the shoreline (Yohe and Neumann, 1997).

At the federal level, the Coastal Zone Management Act (CZMA) encourages better management and planning for nonfederal coastal resources by state and federal agencies. In response to the CZMA, most states have developed their own coastal zone management programs. In some cases, states have enacted legislation to explicitly address the potential for accelerated sea-level rise. The South Carolina Beachfront Management Act, for example, includes provisions for identifying critical erosion areas and for regulating construction along the coastline. Other federal programs that frame local land-use management and planning in local and state contexts are summarized in Table 2.[8]

Table 2

Federal Land-Use Policies for U.S. Coastal Zones

Agency	Policy	Major Provision	Concern
Federal Emergency Management Agency	National Flood Insurance Program	Subsidize insurance for communities that adopt land-use regulations and building standards	Creates incentives to develop flood-prone areas (Klarin and Hershman, 1990)
	Upton-Jones Amendment	Encourage removal of unstable structures and conduct long-term planning	Few claims have been made (Platt et al., 1992)
Department of Commerce	Coastal Zone Management Act	State coastal programs must plan to minimize loss of life and damage caused by the destruction of natural features	States have wide latitude (Edgerton, 1991)
Department of the Interior	Coastal Barrier Resource Act	Creates national system of protected areas and disallows federal subsidies of insurance and the location of infrastructure	States have wide latitude

One method of accommodating sea-level rise is to elevate structures. This option has been implemented by individual property owners in places such as the New Jersey and South Carolina shorefronts, and provides an effective means of responding to concerns about increased frequency of episodic flooding associated with sea-level rise. This strategy does nothing to preserve the beach, however. Raising land elevations can preserve beaches, where the cost of sediment placement is not prohibitive, and has been considered for highly valued coastal areas such as New Jersey's Long Beach Island (Titus, 1990; Yohe, 1989; Smith and Tirpak, 1989).

VI. Economic Impacts of Sea-Level Rise on Coastal Properties and Wetlands

IPCC (1996b) suggests impact assessments should reflect at least five categories of impacts: inundation and erosion of property, inundation of wetlands, effects on recreation, effects on drinking water quality and quantity, and effects on port infrastructure. The potential costs associated with all of these impacts are interrelated, although they are often assessed separately. Property losses dominate cost estimates in the United States, but the wetland acreage lost is comparable to upland acreage lost. The monetary value of wetland losses, currently not included in most impact assessments, may prove to be large. As a result, major estimation difficulties must be overcome. Likewise, national assessments of the effects of sea-level rise on recreation, water, and ports have not been conducted. Some portion of these effects may be captured, however, in more careful studies using property value changes to measure economic impact. For example, coastal property values may reflect opportunities for nearby coastal recreation. While these five categories of impact are likely to be the most important for impact assessments in the U.S. context, studies in other countries may consider a broader range of effects. Box 2 provides more information on impact assessment in countries other than the United States.

A. The Economic Cost to Developed Property

The magnitude of developed property impact estimates reflects two key factors: the sea-level rise scenario and the modeling of responses. Some of the earliest results, such as those produced by Schneider and Chen (1980), reflected extreme sea-level rise scenarios, 450 to 750 cm by 2100, that are irrelevant by current standards. The first systematic national study of more moderate sea-level rise scenarios was the U.S. Environmental Protection Agency's 1989 Report to Congress (EPA, 1989). Results from this and other studies are summarized in Table 3 and discussed in this section.

Box 2

International Impacts of Sea-Level Rise

The effects on tourism, subsistence fishing, agriculture, human settlements, and freshwater supplies may be of much greater relative importance in developing coastal countries than in the United States. Globally, the impacts of flooding from sea-level rise are expected to be most serious in Africa and South and South-East Asia (Nicholls et al., 1999). Delta areas of Bangladesh, Vietnam, and Myanmar, for example, support significant agricultural production in areas that would be threatened by sea-level rise. Small coral atolls and reef islands in the Pacific and Indian Oceans face a significantly greater risk of loss of freshwater supplies to saltwater intrusion than the United States. Inundation of some small island nations, whose economies may be largely or almost entirely dependent on coastal activities, may cause economic and social collapse. Although the contribution of these threatened countries to the global economy may be small, the loss of unique cultures and ecosystems would be significant (IPCC, 1996b).

In addition, the capacity to adapt to accelerated sea-level changes is likely to be more limited in developing countries than in the United States. The costs of protection or adaptation to sea-level rise may represent a much larger percentage of the total economy of a developing nation. One estimate for the Marshall Islands indicates that the costs of a one-meter sea-level rise could exceed 7 percent of gross national product (GNP) (Holthus et al., 1992). In the Maldives, costs could approach one-third of GNP (IPCC, 1996b). Considering impacts of this magnitude may require new frameworks of analysis. For example, a recent study of Fiji found that traditional impact assessment methods could undervalue economic and cultural assets of the coast and might overstate the resilience of the economy to sea-level rise (Yamada et al., 1995).

Table 3

The Potential Cost of Sea-Level Rise Along the Developed Coastline of the United States (billions of 1990 dollars)

Global Sea-Level Rise (source)	Measurement	Annualized Estimate	Cumulative Estimate	Annual Estimate in 2065
100 cm (Yohe, 1989)	Property at risk of inundation	n/a	321	1.37
100 cm (EPA, 1989)	Protection	n/a	73-111	n/a
100 cm (Nordhaus, 1991)	Protection	4.9	n/a	n/a
100 cm (Fankhauser, 1994)	Protection	1.0	62.6	n/a
100 cm (Yohe et al., 1996)	Protection and abandonment	0.16	36.1	0.33
50 cm (Yohe, 1989)	Property at risk of inundation	n/a	138	n/a
50 cm (Fankhauser, 1994)	Protection	0.57	35.6	n/a
50 cm (Yohe et al., 1996)	Protection and abandonment	0.06	20.4	0.07
50 cm (Yohe and Schlesinger, 1998)	Expected protection and abandonment	0.11	n/a	0.12
100 cm (Yohe and Schlesinger, 1998)	Expected protection abandonment	0.38	n/a	0.40
41 cm (mean) (Yohe and Schlesinger, 1998)	Protection and abandonment	0.09	n/a	0.10
10 cm (10th percentile) (Yohe and Schlesinger, 1998)	Protection and abandonment	0.01	n/a	0.01
81 cm (90th percentile) (Yohe and Schlesinger, 1998)	Protection and abandonment	0.23	n/a	0.31

Note: All of the cumulative estimates but Fankhauser's are undiscounted; his estimates are discounted effectively by the annual rate of growth of per capita GNP (expected to average approximately 1.6% for the United States through 2100). The annual estimate in 2065 is available for the one study that estimates costs along the transient (i.e., estimates for each individual year); this estimate is undiscounted.

For the EPA study, Yohe (1989) estimated the costs of allowing sea level to inundate low-lying property along the much more reasonable global sea-level rise scenarios of 50 cm and 100 cm through 2100. Yohe's results indicate the value of property that could be inundated at $138 billion for a 50-cm rise and $321 billion for a 100-cm rise (1990 dollars).

As part of the same EPA study, Titus estimated the cumulative cost of protecting all developed property along the U.S. coastline resulting from a 100-cm rise at $73 billion to $111 billion (1990 dollars). Nordhaus (1991) used the EPA report to estimate an annual cost of protection of $4.9 billion (1990 dollars) and an annual cost of lost land of $2.4 billion (1990 dollars), consistent with a scenario of seas rising roughly one meter by 2100.[9] However, both the Yohe and Titus estimates reflected simple decision rules for the response — either protect or abandon all developed property. Neither estimate reflected the fact that for highly valued areas protection is the least cost response, while for lesser valued areas abandonment is less costly.

Other authors also reported impact estimates in the early 1990s, but as is the case with Nordhaus' study, estimates through 1993 were based on then current property values. These estimates assumed, at least implicitly, that current property values represented the discounted value of property services that should be expected into the indefinite future. As a result, this approach did not consider the dynamics that might define the actual rate of change of a coastline or other adaptations that coastal communities might undertake as property values change over time. These estimates also did not consider the effect of individuals and local governments processing information about sea-level rise over time and timing the implementation of response actions to minimize costs.

Later studies suggest that taking adaptation into account could matter significantly. Specifically, in a global study, Fankhauser (1994) addressed a key issue about whether protecting individual segments of coastal property reflected local conditions and consideration of the relative costs and benefits of protection. Fankhauser assumed gradual inundation patterns and reported amortized and cumulative protection costs of $570 million for a 50-cm rise and $1 billion for a 100-cm rise by 2100 (in 1990 dollars). Thus, including adaptation for a 100-cm rise resulted in an estimate one-fifth that of Nordhaus' estimate, which did not include adaptation.

Yohe et al. (1996) followed with a micro-level assessment of a sample of U.S. coastal sites that reflected the variability in local topography and baseline land use. This assessment modeled adaptation decisions to protect or abandon property assuming a cost-benefit decision framework at a relatively high resolution (500 meter by 500 meter cells) within a sample of U.S. coastline. The sums of protection costs and the contemporaneous values of lost property were reported for each year though 2100. Table 3 reports representative results as annual and cumulative estimates (for 2065) for two reference scenarios (i.e., $0.07 billion for a 50-cm rise and $0.33 billion for a 100-cm rise). The annual estimates for this study are between one-tenth and one-fifth of the Fankhauser (1994) estimates, although property losses were added to protection costs. These lower costs result from incorporating a local decision-making framework for determining the response. Specifically, at the scale of the Yohe et al. (1996) study, some property is not vulnerable to rising seas because of abrupt contours, while other property is not very valuable because it is already susceptible to tidal flooding. By accommodating both of these effects, the cost estimates of Yohe et al. were much lower than Fankhauser's (1994) even though they were based on property values designed to change over time in line with anticipated increases in future per capita income and population growth.

Yohe and Schlesinger (1998) used the Yohe et al. (1996) methodology to produce a representation of transient protection costs and property losses as a function of sea-level rise and greenhouse gas emissions trajectories. Their work incorporated three different assumptions about future sulfate emissions (as sulfates have a net cooling effect), seven probabilistically weighted carbon and associated gas emissions trajectories, three different climate sensitivities to greenhouse gas concentrations, and three different forcing coefficients for sulfates to produce a probabilistically weighted range of "not-implausible" sea-level rise trajectories. The two lines in Table 3 that indicate expected protection and abandonment costs were computed across this range, using the conservative assumption that property owners will respond to sea-level rise only as it happens, without the benefit of foresight.

The Yohe and Schlesinger (1998) results are 30 percent higher than comparable expected values computed under the assumption of perfect foresight — a difference that Nordhaus (1999) has recently offered as a first representation of the extra cost of climate surprise. Nordhaus' point is that adjustment to moderate sea-level rise will not be terribly expensive to market economies if the change is foreseen. On the other hand, sudden, surprising changes could be costly. Comparison of the foresight and no-foresight estimates in the series of studies conducted since 1996 provides some insight into the magnitude of costs associated with surprise.

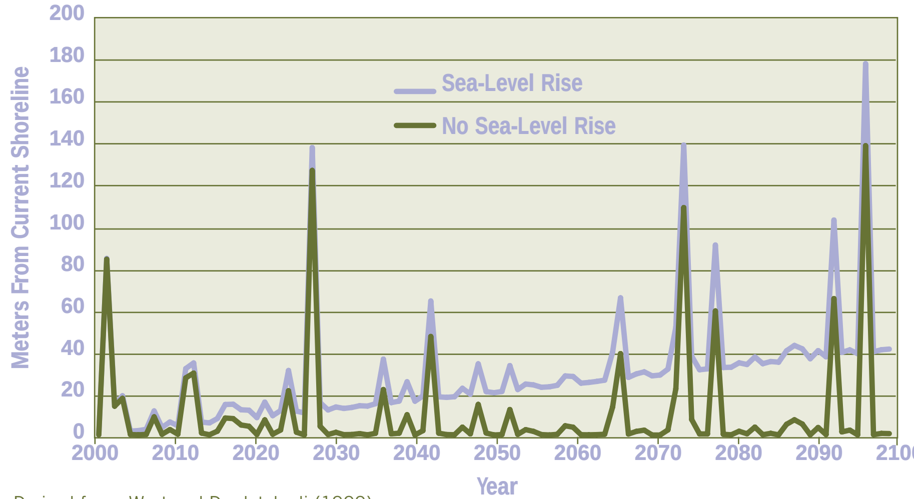
The Yohe and Schlesinger (1998) results also illustrate the range of economic impact results that are possible using alternative sea-level rise scenarios. Table 3 reports protection and abandonment costs without foresight along the mean sea-rise trajectory (i.e., 41 cm sea-level rise) through 2100 and the 10th and 90th percentile scenarios. The results indicate that economic impacts to developed property are not proportional to anticipated sea-level rise. Specifically, the most moderate scenarios yield much smaller than expected results, implying that the impacts of sea-level rise at the low end of current estimates could be as small as $10 million per year in 2065.

As illustrated by recent work (Nordhaus, 1999), Yohe's series of estimates relying on a cost-benefit decision model provide valuable insights for policy-makers. However, these studies have been criticized for being too optimistic about the potential for adaptation and optimal decision-making at the local level. There are two main classes of criticism. First, long-term costs and benefits over the life of a project are difficult to estimate at the local level, so the cost-benefit framework may not be a practical model of local decision-making. For example, while the U.S. Army Corps of Engineers does adopt a cost-benefit criterion for their projects, there are many examples where local governments invest in coastal protection despite the limited likelihood that benefits will exceed costs. In these cases, other information besides costs and benefits may influence local decision-making.

Second, the cost-benefit decision model used does not incorporate the influence of storms on development patterns over time. In a local case study, West and Dowlatabadi (1999) modeled the effects of storms and erosion using a model of random storm intensity. The West and Dowlatabadi model incorporates market valuation and private investor decisions into an analysis of a hypothetical coastal community with and without sea-level rise. They begin with the methodology of Yohe et al. (1996) so that the incremental effect of storms and erosion can be measured directly. West and Dowlatabadi (1999) conclude that expected costs attributable to sea-level rise are small (i.e., less than 5 percent of total sea-level rise costs computed using the pre-Yohe methodologies that ignore adaptation potential). They also observe, though, that actual damages could become more significant under different assumptions about the geographical distribution of property values, accelerated dune erosion, or even unlucky sequencing of coastal storms, increasing total costs attributable to sea-level rise by almost 20 percent. Figure 5 shows the results of a sample run; the figure illustrates that the landward reach of inundation tends to be greater with sea-level rise, and that the pattern of storm damage (indicated by spikes on the graph) is an important influence on the timing of damages. The results suggest that the combined effects of inundation and increased storm vulnerability need to be more carefully reflected in future national assessments.

Figure 5

Simulated **Inundation From Coastal Storms** with and without Sea-Level Rise



Derived from: West and Dowlatabadi (1999).

The overall conclusion from this body of work is that as estimates of sea-level rise have moderated, and as the ability to model adaptation and incorporate local conditions has increased, estimates of the impact of sea-level rise on coastal property have moderated. However, attaining economically efficient adaptation will require a widespread understanding of sea-level rise that does not yet exist. While it is clear that a significant magnitude of investment in coastal structures is at risk from sea-level rise, uncertainty as to the ultimate response affects the magnitude of impacts. Estimates in Table 3 suggest that a 50 cm sea-level rise by 2100 could cause cumulative impacts to coastal property in the United States of $20 billion (assuming an economically efficient adaptation) to roughly $150 billion (if vulnerable areas are inundated). The large difference between estimates that reflect no adaptation (i.e., estimates prior to 1996), and the more recent studies that reflect economically efficient adaptation suggest that there should be major efforts to encourage understanding of strategies to more efficiently respond to sea-level rise.

In addition, some important research directions emerge. First, it is important to test the assumptions of rational economic decision-making at the local level to ensure that this model reflects a reasonable evaluation of local response options. Second, incorporating the impacts of storms on the profile of future response options, as well as the impact on future development patterns, ought to be a high priority for future national assessments.

B. Wetlands Assessment

Existing assessments of lost wetland areas, while only first approximations, nonetheless point to the potentially large magnitude of damages that sea-level rise could cause to coastal wetland resources (Smith and Tirpak, 1989; Titus, 1992). As discussed in Sections II and IV, coastal wetlands provide a wide range of amenities that are economically and ecologically valuable. These amenities include flood control, habitat for ecologically important and endangered species as well as commercially important fish and shellfish species, and groundwater recharge.[10]

Current estimates of the impact of wetland losses suffer from two critical methodological and data gaps. First, it is difficult to model the dynamic processes of wetland accretion and migration (Reed, 1995). As evidenced by historical data in south San Francisco Bay, accretion and migration could mitigate wetland losses in some cases (Patrick and DeLaune, 1990). If these processes are constrained in these areas, however (for example, through natural barriers or the construction of hard protection on the landward edge of wetlands), wetland losses might increase due to coastal squeeze. Moreover, as suggested by historical rates of wetland loss in some areas, the beneficial accretion of sediment and biogenic material within wetlands may or may not keep pace with the rate of relative sea-level rise (Titus, 1988). If wetlands fail to keep pace with sea level by accretion and/or migration, they will be progressively degraded and ultimately destroyed and would no longer provide most of the services they currently provide. However, significant challenges remain in determining which wetlands will be inundated given different scenarios of sea-level rise and other changes, when the inundation will occur, the extent to which the built environment will affect these estimates, and whether wetlands that migrate can replace existing wetlands.

Second, there have been many efforts to assign a dollar value to wetland resources over the last two decades, but the overall economic value of wetlands (including aesthetic value) is not well-characterized by existing value estimation techniques. Currently, estimates of the total unit value of specific functions at specific wetlands exist, and can be used to develop a sense of the potential value of wetlands. However, critical gaps remain in our understanding of the marginal impact of wetland decline and loss. For example, it is almost certainly a vast oversimplification to assume that the first unit of wetland inundated has the same impact as the last unit inundated. Additionally, most wetland values are based either on nonmarket assessment techniques or on estimates of the replacement cost for services that could be provided in the market. Both types of assessments are subject to a great deal of uncertainty.

C. Impacts of Recreation Losses

Accelerated beach erosion caused by sea-level rise might lead to large losses in recreational value. Beaches may be able to migrate inland, mitigating losses, but may still lose value (e.g., a narrower strip of beach between dune and waterline, or a loss of the dune altogether). Another scenario would be the construction of hard structures to protect beachfront property, which might lead to the progressive loss of the beach. Some of these losses could be mitigated through beach nourishment. While there have already been numerous nourishment projects around the U.S. coast (Davison et al., 1992), the scale of nourishment required to hold the line for the next century could be vast, even if sea-level rise does not accelerate. In all instances, the costs of adapting to rising sea levels, which may be quite high in certain cases, must be considered. Therefore, while certain beaches, such as Miami Beach, are likely to be nourished irrespective of the sea-level rise scenario, less densely developed coastal areas may have to consider a managed retreat in the face of sea-level rise. Strategic assessments of potential demands for nourishment over the next century given a range of sea-level rise scenarios would be helpful. These assessments might be best accomplished at the state level.

At least a portion of the recreational impact should be reflected in the estimates of lost property value since the value of coastal recreation should be closely linked to the value of nearby structures. In other words, the value of coastal property includes a substantial premium that is associated with access to the coast's recreational amenities. An issue for future research is whether the methods for estimating losses in property value associated with sea-level rise also capture any reduction in the recreational amenity.

D. Implications for Future Assessments

Future assessments are faced with the daunting challenge of acknowledging the complexities of sea-level rise impacts as they attempt to characterize climate change impacts and recommend policy responses appropriate for the U.S. coast. The context of the impacts of sea-level rise is complex. The risks posed by sea-level rise to the coastal zone may sometimes be considered more straightforward to assess than other climate change impacts. Unlike these other impacts, sea-level rise occurs in one dimension with some confidence about the direction of change, if not always the magnitude. Yet, sea-level rise occurs within the already dynamic geology of the coastal zone. Responding to any rise will require balancing multiple and sometimes competing uses and values. It also will involve planning construction and protection of long-lived capital assets (i.e., land and structures). Responding to sea-level rise in the most economically efficient manner will challenge humans to learn and adapt over a long period of time.

There has been some progress in defining coastal management policies that can enhance the ability of coasts to adapt to sea-level rise. Nicholls and Branson (1998) describe research efforts focusing largely on long-term coastal planning not only for uncertain sea-level rise but also for weather events that can cause enormous damage. They introduce the concept of natural and human resilience to routine and extreme events. Klein et al. (1998) cast the issue clearly in their review of policies of the Netherlands, which has a law that forbids coastal erosion — an extreme manifestation of humans standing in the way of natural forces. Klein et al. criticize this static approach and advocate more flexibility, recognizing that coping with coastal dynamics could provide more safety at a lower cost. They argue that systems designed to handle only the gradual consequences of sea-level rise may be more vulnerable to the disastrous consequences of extreme events like storms. Enhancing coastal resilience can be an effective response to an uncertain future, including sea-level rise.

In addition, some efforts to improve impact assessments are underway. EPA has begun an effort to better understand the impact of state and local policies on protect and retreat decisions. Other efforts are being made to develop models of the process of local policy-making and, in particular, the process of learning in response to storm damage (Moser, 1999). These efforts build on the conclusions of West and Dowlatabadi (1999) regarding the importance of storms in determining development patterns. Such efforts may provide not only improved accuracy in impact assessment but also better ways to communicate their results to influence local decisions affecting the long-term capacity to adapt.

VII. Conclusions

1. Estimates of future sea-level rise attributed to climate change have moderated over the last several decades; the most recent IPCC (1996a) estimates indicate that a rise of 50 cm by 2100 remains likely. Available evidence implies that these estimates of climate change-induced global sea-level rise could inundate over 20,000 km^2 (8,000 mi^2) in the United States, and major coastal cities such as New Orleans, Miami, New York, and Washington, DC, will have to upgrade flood defenses and drainage systems or risk adverse consequences.

2. Significant investments in coastal areas are at risk from gradual sea-level rise. Current estimates suggest a 50 cm sea-level rise by 2100 could cause cumulative impacts to coastal property in the United States of $20 billion to $150 billion. Estimates at the low end of the range reflect modeling of the most economically efficient adaptation to sea-level rise. Those at the high end assume that all currently developed vulnerable areas will be protected, regardless of costs.

3. More extensive damage could result if climate change increases storm frequency and intensity or if climate change leads to catastrophic melting of ice sheets, though the likelihood of those impacts occurring is currently uncertain. An improved prediction capability for near-future storm climatology and better monitoring of changes to Antarctica would help to manage these risks.

4. Most existing sea-level rise impact assessments cannot take into account the economic value of lost wetlands; these missing values could be substantial. Leaving space for migration of wetlands may prove to be critical for their survival. Defining the areas of upland that might be converted to wetlands as sea levels rise would be useful, because these are the areas where there is likely to be conflict between coastal construction and allowance for wetland migration.

5. Economic impact estimates that assume a rational balancing of costs of protection with benefits of protection suggest impacts could be lower than previously thought. This assumption implies an understanding of the implications of sea-level rise at the local level that does not yet exist. As a result, while the Yohe et al. (1996) research and the efforts that have followed it provide important insights on the potential for adaptation to lessen losses, responses that are less than optimal are likely.

6. Impact assessments that keep better track of winners and losers as sea level rises are needed to provide local decision-makers with better information on the implications of alternative response strategies. There is a need to address both humans' capacity for learning as well as local governments' ability to respond to the threat of sea-level rise.

Endnotes

1. While the relationship between climate change and storms is quite uncertain, increases in coastal populations, infrastructure, and development (which have resulted in increasing damages from storms) suggest that even small growth in storm frequency or severity would create a disproportionate increase in damage (Pielke and Landsea, 1998).

2. Estimates in constant 1993 dollars, see Insurance Institute for Property Loss Reduction and Insurance Research Council (1995).

3. Note that post-glacial rebound contributes to uplift in formerly glaciated areas, but also contributes to subsidence on the fringes of glaciated areas.

4. Estimates based on business-as-usual scenario, with no reduction in the growth of greenhouse gas emissions and no increase in aerosol cooling.

5. Recent research suggests that the melting of clathrates, sea floor water ice crystals that contain methane, may explain sea-level drops during warm periods of the geologic record (Bratton, 1999). Catastrophic melting of clathrates, however, is probably a very low probability event (Harvey and Huang, 1995).

6. Sorenson et al. (1984); San Francisco BCDC (1986); Weggel (1989); Leatherman (1989); Gleick and Maurer (1990); URS Consultants (1991); and Leatherman (1994).

7. The analysis assumes that flooding risk increases proportionately with the risk of inundation. If the risk of flooding increases faster than the risk of inundation, protective structures might be needed sooner. In addition, the assumption of a linear trajectory reflects an assessment that gradual increases in sea level are considered more likely than abrupt, cataclysmic changes.

8. Structural shoreline protection falls to the U.S. Army Corps of Engineers, which also regulates navigation within coastal waterways and authorizes development within coastal wetlands; for many projects, the Corps is required to work with cost-benefit decision tools to decide when and whether to initiate protection projects with federal support.

9. Note that many of the impact assessments published in the late 1980s and early 1990s are based on sea-level rise estimates from several years prior to publication. As a result, many of those assessments focus on a scenario of 1-meter sea-level rise by 2100, even though contemporary scientific estimates may have already acknowledged that 1 meter was a “high” estimate.

10. A future Pew Center report will address impacts on aquatic ecosystems, including coastal wetlands.

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