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Sea Level Rise in the Twenty First Century: A Review

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REPORT SUMMARY

The sea level of the world's oceans has risen over the last century, and its rate of increase is projected to grow during the 21st century with potential adverse consequences. This report, which is based on the recent journal publications and other reports and the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4), provides background on the causes of sea level rise and outlines the observed and projected changes in sea level both globally and regionally, with an emphasis on the potential impacts to coastal areas of the United States.

Background

Sea level rise can be expected to have important direct and indirect impacts on electric utilities. The infrastructure of utilities in coastal regions may be subject to temporary flooding or permanent inundations, and inundation and erosion may indirectly impact the electric industry by damaging roads, rails, ports, bridges, and waste landfills. The landward migration of saline marine water can also have a deleterious effect on the corrosion rate of various components of a power plant.

Objectives

- To briefly explain the causes of global sea level rise
- To summarize the state of knowledge about observed and projected changes in sea level (combined with land changes) both globally and regionally, with a focus on the coasts of the United States.

Approach

The project team drew on the AR4 and more recent journal publications and other reports to review what is known about global and regional sea level change and different estimates of projected future sea level rise. The team also examined the specific vulnerabilities of coastal areas of the United States.

Results

While the underlying explanation of why the sea level has been rising is global warming, the major causes of sea level rise are the thermal expansion due to warming ocean waters and melting of large glaciers and ice sheets/icecaps, especially the Greenland and Antarctic ice sheets. Tide gauge records and satellite altimetry data indicate that in the twentieth century the average increase of sea level was 1.7 ± 0.5 mm/yr. The rate of sea level rise has accelerated in the last several years. From 1993 to 2007, the mean sea level increase is an estimated 3.36±0.41 mm/yr. Every climate scenario modeled by the AR4 predicts that the sea level will increase between the present and the end of this century, although the extent of increase varies from scenario to scenario. The projected median sea level rise in the AR4 is at a maximum of 0.26-0.59 m by 2100 in the case of a world of very rapid economic growth that continues to rely on the intensive use of fossil fuels and at minimum of 0.18-0.38 m by 2100 in the case of a world with the same population but with more rapid transition toward a service and information economy. Thermal expansion is the major contributor (70-75%) to these estimates of sea level rise.

It is important to recognize that the AR4 projections do not take into account future rapid dynamical changes in ice flow, which the IPCC itself suggests are likely to increase the sea level rise by 0.10 to 0.59 m. Several recent studies using different methodologies and assumptions suggest that the increase in sea level is likely to substantially exceed the projections made by the AR4, and much larger changes are possible as the perturbation of the climate system progresses. These studies also point out that sea level is likely to continue rising for centuries even if global temperatures stabilize.

Because of a number of climatic and geological reasons, sea level does not rise evenly from region to region; and the variability of sea level change has important planning implications—the North Atlantic and the East Indian Ocean are experiencing a higher than average rate of sea level increase, for example, which increases the vulnerability of adjacent coastlands in Indonesia, Thailand, Bangladesh. The eastern and southeastern states of the United States are more vulnerable than other areas of the country. This increased vulnerability not only includes direct inundation but also land loss through submergence and erosion of coastal lands, increased storm surges, wetland losses, and increased salinity in estuaries and coastal freshwater sources as well as in groundwater. These impacts, which can be expected to have a cumulative effect, have important implications for the electric power industry.

EPRI Perspective

As of 1990, 1.2 billion of the world's population lived close to the coasts at densities that were three times higher than the global mean; and the continuing worldwide trend toward urbanization will put even more people at risk in the future. Given the presence of densely populated coastal lands, local changes of sea level are of increasing importance to both coast-dwelling communities and industries. Understanding the likelihood and scale of future sea level change is of paramount importance for utility planning purposes, and EPRI will continue to track to emerging consensus on this critical consequence of climate change.

Keywords

Climate change
Sea level
Ice sheets
Storm surges
IPCC (Intergovernmental Panel on Climate Change)

EXECUTIVE SUMMARY

Introduction

The sea level of the world's oceans has risen over the last century, and its rate of increase is projected to grow during the 21st century. As of 1990, 1.2 billion of the world's population lived close to the coasts at densities that were three times higher than the global mean; and the continuing worldwide trend towards urbanization will put even more people at risk in the future. Given the presence of densely populated coastal lands, local changes of sea level are of increasing importance to both coast-dwelling communities and industries. The cost of adaptation to manage inundation is estimated to be in billions—raising the California Central Valley levees only 0.15 m, for example, will cost over $1 billion. Thus, for the sake of future planning, it is of paramount importance to gain more knowledge about future sea level changes.

Sea level rise can also have important direct and indirect impacts on electric utilities. The utilities infrastructure in coastal regions may be subject to temporary flooding or permanent inundations and erosion, which may indirectly impact the electric industry by damaging roads, rails, ports, bridges, and waste landfills. The landward migration of saline marine water can also have a deleterious effect on the corrosion rate of various power plant components.

This report, which summarizes recent journal publications and material from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4), provides some background on the causes of sea level rise and presents an overview of the state of knowledge of the observed and projected changes in global sea level rise. It also provides details on geographic variation in sea level rise based on regional factors and also examines consequences of sea level rise.

Causes of Sea Level Rise

Global sea level can rise due to global warming for three main reasons:

1. Higher water temperatures result in thermal expansion of the oceans; thermal expansion is currently the dominant contributor to the current increase in sea level. It is estimated to contribute up to 75% of the 0.18 to 0.59 m sea level rise by 2100 reported in AR4.
2. The melting of large Greenland and Antarctic ice sheets adds water to the oceans. Complete melting of these ice sheets can raise the global sea level by 64 m.
3. The melting of other glaciers and ice caps would produce an estimated additional sea level rise of 0.15 to 0.37 m by 2100.

Several other processes affect sea level. Increased water runoff from glacier and snow-fed rivers as well as increased precipitation in some regions can contribute to a rise in sea level. Sea level is also affected by vertical movements of land caused by geological processes such as the rising of the land that continues to occur in many areas in response to the recession of ice-age glaciers and the subsidence of land caused by groundwater or oil extraction. It should be noted, however, that sea level is not affected by the melting of sea ice because that ice is already floating on the surface and contributes to the present sea level.

While the global sea level is increasing, sea level changes vary from region to region. This variability needs to be taken into account in accessing the vulnerability of particular coastal areas. Regional temperature and salinity changes affect the local sea level by changing the density and volume of seawater, and changes in surface atmospheric pressure affect regional sea level to a considerable extent. Geological processes also affect local sea level both by raising or lowering coasts and through gravitational effects.

Global change in sea level

Sea level is measured both by satellite altimetry and by tide gauges. Satellite altimetry measures sea level with respect to the center of the Earth and hence is not affected by land movements. Tide gauges measure sea level with respect to the local land level and hence readings have to be corrected for local land movement. While satellite altimetry data have been available since the mid 20th century and provide global coverage, data from tide gauges are available from the late 19th century but with more sparse coverage.

According to the IPCC Fourth Assessment Report (AR4), the observed sea level has demonstrated an upward trend since mid-19th century. Tide gauge records and satellite altimetry data indicate that in the twentieth century the average increase of sea level was 1.7 ± 0.5 mm/yr. The rate of sea level rise has accelerated in the last several years. From 1993 to 2007, the mean sea level increase is an estimated 3.36±0.41 mm/yr. The recent increases in sea level have been largely attributed to losses of ice-masses from glaciers and ice sheets in Alaska, Greenland, and Antarctica.

Every climate scenario modeled by the AR4 predicts that the sea level will increase between the present and the end of this century, although the extent of increase varies from scenario to scenario. The projected median sea level rise is at a maximum of 0.26-0.59 m by 2100 in the case of a world of very rapid economic growth that continues to rely on the intensive use of fossil fuels and at minimum of 0.18-0.38 m by 2100 in the case of a world with the same population but with more rapid transition toward a lower-carbon service and information economy.

It is important to recognize that the AR4 projections do not take into account future rapid dynamical changes in ice flow, which the IPCC suggests will increase the seal level rise by 0.18 to 0.59 m. The AR4 did not include the acceleration due to melting of ice-sheets into its computed sea level projections due to limited understanding of these processes at the time. Much larger changes are possible as the perturbation of the climate system progresses.

As mentioned earlier, the major contributor to the sea level rise projected in the IPCC assessment is thermal expansion, which accounts for 70-75% of the rise for all scenarios. Other contributors are the melting of glaciers and ice sheets. Net contribution to sea level rise from melting of Antarctic ice sheets in this century is predicted to be negative due to concomitant increase in snowfall over the continent.

Are the IPCC projections too conservative?

Several recent studies using different methodologies and assumptions suggest that the increase in sea level is likely to substantially exceed AR4 projections. For example, the U.S. climate change science program (CCSP, 2008) points to recent rapid changes in observed accelerations of flow in Greenland and West Antarctica with the velocity of some glaciers increasing more than twofold. This acceleration is related to increased surface meltwater production that penetrates to the bottom and reduces resistance to flow, thus enhancing the motion of the glaciers.

Other recent studies project a higher magnitude of sea level rise because of positive feedback effects and system inertia or because of dynamical changes in ice flow. One study (Rahmstorf,

2007) suggested a sea level rise of as much of 0.5 to 1.4 m from the 1990 level in 2100 based on correlations between global sea level and global average near-surface air temperatures in the 20th century. Another study (Pfeffer, 2008) took into account the dynamical changes in ice flow and the glaciological conditions required for large sea level rise and estimated that the sea level can rise from 0.8 - 2 m by 2100. Most of the new studies suggest that the IPCC projections for sea level rise in the 21st century, which mostly include thermal expansion, may be too conservative.

Geographic variability

The extent of future sea level rise is expected to vary by geographic region because of changes in ocean circulation, wind and air pressure patterns, and ocean water density. Different models give different results, but there is some consensus. For example, a less than average rise in sea level is projected for the Southern Ocean and a larger than average rise is projected in the Arctic. The geographical pattern of long term sea level trends to date show an increase in the waters off east India, the eastern Pacific off California, and the North Atlantic off eastern states of the United States. The increasing trend in the East Indian Ocean can adversely affect the low lying areas of Indonesia, Thailand and Bangladesh.

Regional change of sea level in United States

Regional differences in the mean sea level result from the combined effects of changes in local sea level and local vertical land motion. Many of the regional effects of sea level are attributed to geologic processes and land use practices. The sinking of a broad region of the mid-Atlantic coastline is influenced by uplift in the Hudson Bay area, and the rapid shrinking of the Mississippi delta region in Louisiana is due to the loading of the lithosphere (outer solid layer of earth) and compaction of the sediments deposited by the Mississippi River. The sinking of the Texas coastline is influenced in addition by oil and gas extraction in this region. Parts of the coast of northern California, Oregon, and Washington are rising due to the subduction of a tectonic plate beneath the North American continent, and the sea-level trends in southeastern Alaska are influenced by glacial rebound (uplift of land after centuries under the oppressive weight of a glacier). Sea level changes vary widely, from a rise of 9.85 mm/yr at Grand Isle, Louisiana, due to subsidence of land, to a drop of 16.68 mm/yr in Skagway in southeast Alaska. Recent reports conclude from sea level data that the sea levels have been rising along most of the Atlantic and the Gulf coasts at the rate of 0.2 to 0.3 cm per decade. In the Atlantic coast, the highest rate of sea level rise is in the mid-Atlantic regions between New Jersey and southern Virginia; and lowest rates are along New England and from Georgia to northern Florida, where the rates are close to the global rate.

The tidal wetlands associated with Mississippi River delta in Louisiana and the Blackwater River marshes in Maryland are already experiencing submergence due to increase in relative sea level. Such wetlands are not likely to survive an acceleration of sea level rise by 7mm/yr (CCSP, 2009), and their loss can have important consequences for coastal populations since wetlands provide natural flood control and protect water quality.

Consequences of sea level rise

More than one-third of the population of the United States lives in coastal counties with 14 of 20 major U.S. urban centers located along the coasts. It is virtually certain that future sea level rise will inundate some areas of dry land in the United States and make many other areas vulnerable to storm surges. A rise in global sea level of 0.5 m would inundate an estimated 9,000 square miles. Under these conditions, most coastal cities in the east and gulf region face the risk of significant inundation.

Inundation is one of the most obvious and direct effects of rise in sea level. Although there are many other effects of sea level rise, most assessments have chosen to focus on the risk of inundation, which is the most important component of coastal changes especially in low-lying regions such as North Carolina. The extent of inundation is dependent on the slope of the land, with greater inundation resulting in regions with gentler gradients. Maps developed to show regions that face the risk of inundation for U.S. Atlantic and gulf coasts in the case of 1.5 m rise in sea level indicate that Louisiana, Florida, Texas, and North Carolina account for more than 80% of land at risk in the U.S.

Coastal vulnerability

The effect of sea level rise on the coastal areas is more complex than simple inundation. Apart from inundation, sea level rise can exacerbate erosion and accretion processes depending on the nature of the coastal landforms. It is virtually certain, for example, that the heads, spits, and barrier islands of the mid-Atlantic coasts will erode faster than other parts. An assessment of coastal vulnerability to sea level rise that takes into account tidal range, wave height, coastal slope, shoreline change, geomorphology, and historical rate of relative sea level rise showed high vulnerability in New Jersey, Delaware, Maryland, Virginia, North and South Carolina, and Florida, with moderate vulnerability for Long Island. Some highly populated regions of the Pacific coast, including San Francisco, Monterey Bay, and parts of Southern California from San Luis Obispo to San Diego, are also highly vulnerable. Studies developing higher resolution maps (under an EPA initiative) are revealing the impact of sea level rise on specific densely populated regions such as New York City where flooding by major storms could inundate many low-lying neighborhoods and adversely affect the transportation system with much greater frequency as local sea levels rise.

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1
INTRODUCTION

One of the key changes the global ocean has experienced over the last century is a rise in mean sea level (IPCC, 2007). The rate of increase of sea level is projected to increase in the 21st century. As of 1990, 1.2 billion of world's population lived close to the coasts at densities that were three times higher than the global mean and the increasing trend towards urbanization will increase these proportions(Nicholls and Small, 2002; Small and Nicholls, 2003). Given the presence of densely populated coastal lands, local changes of sea level are of increasing importance to both coast-dwelling communities and industries. The cost of adaptation to manage inundation is estimated to be in billions (Titus, 1991)—raising California Central Valley levees only 0.15 m, for example, will cost over $1 billion (Mount et al., 2005). Thus, for the sake of future planning, it is of paramount importance to gain more knowledge about future changes in sea level.

Locally, the changes in sea level can directly impact the infrastructure of electric utilities lying close to coastal regions and river deltas due to permanent inundation or temporary flooding due to increased storm surges. Other direct effects of increase in sea level are coastal erosion, shoreline inundation owing to higher than normal tide levels and increased temporary surge levels during storms (CCSP, 2009 and references therein). Inundation and erosion caused by an increase in sea level can have indirect effect on the electric industry by impacting infrastructure such as roads, rails, ports, bridges, and waste landfills (CCSP, 2008; CCSP, 2009). Increase in sea level can also lead to increase in saline intrusion of seawater into coastal aquifers, estuarine systems, and groundwater (Shrivastava, 2001). The landward migration of saline marine water can have deleterious effects on corrosion rate of various components of a power plant.

This report provides some background on the causes of sea level rise in Section 2 and presents an overview of the state of knowledge of the observed and projected changes in global sea level rise in Section 3. Section 4 provides details on geographic variation in sea level rise based on regional factors. Section 5 discusses consequences of sea level rise and Section 6 summarizes the report. The report relies on the Fourth Assessment of the Intergovernmental Panel on Climate Change (IPCC) as well as on some more recent journal publications that were not included in the IPCC report.

2
CAUSES OF SEA LEVEL RISE

The changes in global sea level occur due to three main reasons:

1. Thermal expansion: a process by which ocean water expands due to heat. Changes in the density of water with temperature cause the sea level to rise when the ocean warms. The change in global sea level depends on the three-dimensional distribution of heat because of the unequal expansion of water at different temperature and pressure conditions: warmer water expands more compared to colder water for the same heat input. Also, unlike other liquids, water expands more under higher pressure than under lower pressure. Currently, thermal expansion is the dominant contributor to increases in sea level rise.
2. Contribution due to melting of large Greenland and Antarctic ice sheets that is determined from the difference between snowfall and surface ablation (melting plus sublimation). The ice sheets contain vast expanses of slow moving ice that lead to ice shelves, ice tongues, or directly on to the ocean via local glaciers and ice streams. Water from melting of these large ice sheets contributes by addition to the total ocean mass and volume. It is estimated that melting of all the ice in the Greenland and Antarctic ice sheets would result in raising the sea level by 64 m (Bamber et al. 2001, Lythe et al, 2001).
3. Contribution from other glaciers and ice caps as computed from observed data of global mean temperature and mass loss: These glaciers are not immediately adjacent to the large ice sheets mentioned above. As in the case of ice sheets, waters from the melting of the glaciers contribute to sea level rise due to increase in ocean water mass and volume. Melting of all this glacial ice would contribute an estimated 0.15 to 0.37 m to sea level rise (Alley et al., 2007 in IPCC, 2007).

These processes are compounded by increased runoff from water due to discharge in many glaciers and snow fed rivers as well as increased precipitation in some regions such as the Arctic.

Vertical land movement, though not the cause of sea level rise, can influence the net results. The most influential vertical movement is ‘glacial isostatic adjustment’ (GIA), the rising of landmasses in response to the recession of ice sheets and glaciers that existed during the glacial age in most of North America, Asia, and Europe. The immense weight of these glaciers and ice sheets, whose thickness was of the order of few kilometers, depressed the underlying land and affected the subsurface mantle. These subsurface lands and mantle take thousands of years to rebound back after the glaciers and ice sheets have receded, and GIA continues to occur even in the present day. Finally, GIA not only affects the sea level by deformation of earth but also has gravitational effects that affect regional sea level by influencing the flow of the viscous mantle (material underneath the earth’s crust).

Other vertical movements of land that affect the sea level are land subsidence, tectonics, and sedimentation. Land subsidence is the process by which the surface of the Earth sinks due to subsurface movement caused by groundwater or oil extraction. Tectonic movement occurs due to movement of the earth’s crust that can lead either to uplifting or sinking of the earth’s surface.

Sedimentation leads to elevation of land compared to sea level as the sedimentary layers build up. On the other hand, the sea level is not affected by the melting of sea ice in the Arctic or elsewhere, because sea ice is already floating on the surface and already contributes to the present sea level.

The variability in sea level rise also arises from several other factors: regional thermal and salinity changes the density and hence the volume of seawater, affecting the local sea level. At the same time ocean circulation changes driven by changes in density also influence the sea level. Surface atmospheric pressure changes also affect regional sea level to a considerable extent: for each 1 hPa increase in sea level pressure, the ocean is depressed by approximately 10 mm thus causing the underlying water mass to shift to other regions.

Some of examples of local and regional effects of sea level are shown in Section 4 (see Figure 4-3). For example, the sinking of a broad region in the mid Atlantic coastline is influenced by the GIA that has uplifted the Hudson Bay region since the last glacial age. The rapid shrinking of the Mississippi delta region in Louisiana is due to the loading of the lithosphere (outer solid layer of earth) and compaction of the sediments deposited by the Mississippi River. The sinking of the Texas coastline is influenced in addition by oil and gas extraction in this region. On the other hand the lowering of sea level in some areas of northern California, Oregon, and Washington results from a slow rise of the shore due to the tectonic effects of subduction beneath the North American continent. The sea level trends in southeastern Alaska are dominated by glacial rebound (uplift of land after centuries under the oppressive weight of a glacier).

3
STATE OF KNOWLEDGE

Sea level is measured both by satellite altimetry and by tide gauges. Satellite altimetry measures the features of the ocean surface including height. Tide gauges are used to measure tides and quantify the size of tsunamis, and the mean sea level can be derived from those measurements. While satellite altimetry data have been available since the mid 20th century and has global coverage, data from tide gauges are available from late 19th century with more sparse coverage. Readings of tide gauges are obtained with respect to the local land level and hence have to be corrected for local land movement. On the other hand, satellite altimetry data are obtained with respect to the center of the Earth and hence are not affected by land movements.

3.1 Observed Sea Level Changes

The IPCC Fourth Assessment Report (AR4) states that the observed sea level has demonstrated an upward trend since mid-19th century (see Figure 3-1). This report concluded from tide gauge records and from satellite altimetry data that in the twentieth century the average increase of sea level was 1.7 ± 0.5 mm/yr (Bindoff et al., 2007).

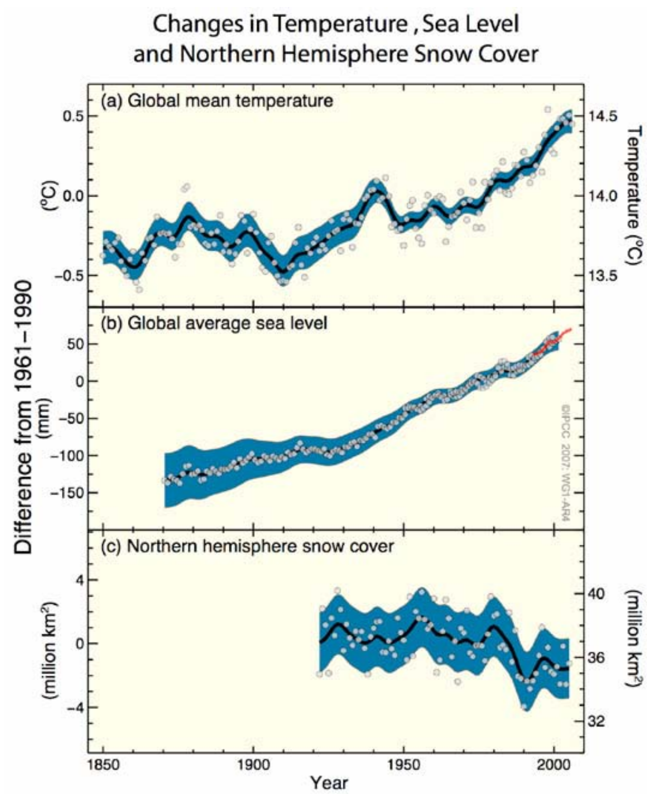

Figure 3-1
Rate of observed change in temperature, sea level and northern level snow cover

Source: IPCC, 2007

In the years from 1993 to 2007, the mean sea level has been estimated to have increased by 3.36±0.41 mm/yr based on most recent satellite altimetry data with an improved orbit computation and tide gauge-based drift correction (Beckley, 2007). These estimates have been carried out by recomputing global mean sea level trends from recent satellite data using updated gravity fields and an updated terrestrial field. These reported rates are higher than some of the previous studies that considered shorter spans of time. While during the 1993-2000 period the mean sea level increased at the rate of 2.53±0.46 mm/yr, the rate of increase was 3.39±0.47 mm/yr during the period 2000-2007 (Beckley, 2007). This increase in sea level in the latter period (2000-2007) has been attributed to relatively recent losses of ice masses from the glaciers in Alaska and from Greenland and Antarctica.

To determine changes in sea level rise resulting from the melting of glaciers in Alaska, Arendt et al. (2002) used airborne laser altimetry study to observe the largest glaciological contribution to rising sea level measured at the time. They reported that during mid-1990s to 2000-2001, the Alaska glaciers contributed 0.27 ± 0.10 mm/yr. The annual volume losses of Alaska glaciers were nearly double the estimated annual loss from the entire Greenland Ice Sheet during the same time period. More recently, Tamisiea et al. (2005) concluded that the accelerated melting that began in the late 1990s continues unabated. Using data from Gravity Recovery and Climate Experiment (GRACE) and forward modeling, this study inferred an average contribution to sea level rise of 0.31 ± 0.09 mm/yr from Alaska glaciers for the period during which data were available (2002-2004).

A mass loss of 101 ± 16 Gton/yr has been observed from the Greenland ice sheet during the period 2003-2005 using data from the GRACE mission (Luthcke et al, 2006). This loss was equivalent to a global sea level rise of 0.28 ±0.04 mm/yr during this period. Melting of glaciers in Greenland was also observed to accelerate in recent years. Rignot and Kanagaratnam (2006), using satellite data, detected widespread glacier acceleration below 66° north between 1996 and 2000, which rapidly expanded to 70° north in 2005. Ekstrom et al (2006) also reported a doubling of frequency of glacial earthquakes in Greenland. These glacial earthquakes are indicators of movement of glaciers due to subsurface melting that leads to periodic lurching forward of some glaciers and ice streams.

Mass losses were also observed in the Antarctic ice sheets during 2002-2005, most of it in the West Antarctic. Velicogna and Wahr (2006) used measurements of time-variable gravity from the GRACE satellites data to infer significant decrease of ice sheet mass (152 ± 80 km^3/yr), equivalent to global sea level rise of 0.4 ± 0.2 mm/yr.

In summary, the rate of global sea level rise in the twentieth century was 1.7 ± 0.5 mm/yr, but that rate had almost doubled by end of the century. Some studies have tried to estimate the contribution of recent losses of ice masses from the glaciers in Alaska, Greenland and Antarctica to the rise in sea level. The contribution from melting of glaciers in these regions is estimated to be quite similar; ranging from 0.3 to 0.4 mm/yr each in recent years.

3.2 Projected Sea Level Changes

According to the AR4, sea level is projected to increase between the present (1980–1999) and the end of this century (2090–2099) in every future climate scenario (Meehl, 2007). The projections for the increase in global sea level vary with different IPCC scenarios. The scenarios are defined below:

A1: a world of very rapid economic growth, a global population that peaks in mid-century, and rapid introduction of new and more efficient technologies.

A1F1: fossil intensive

A1T: non-fossil energy resources

A1B: A balance across all sources.

B1: a world with the same global population as A1, but with more rapid changes in economic structures toward a service and information economy.

B2: a world with intermediate population and economic growth, and with local solutions to economic, social, and environmental problems.

A2: a very heterogeneous world with high population growth, slow economic development, and slow technological change.

Table 3-1
Projected Sea Level Change for different IPCC Scenarios

Scenario	Sea level change (m at 2090-2099 relatively to 1980-1999)
B1	0.18 – 0.38
A1T	0.20 – 0.45
B2	0.20 – 0.43
A1B	0.21 – 0.48
A2	0.23 – 0.51
A1F1	0.26 – 0.59

Source: IPCC 2007

According to IPCC estimates, the median sea level rise is a maximum of 0.26-0.59 m in the case of A1F1 and lowest in the case of B1 at 0.18-0.38 m. The IPCC projection did not take into account the future rapid dynamical changes in ice flow—processes that affect the movement of ice such as basal melting and the effect of gravity. However, the AR4 does state that taking ice flow dynamics into consideration will increase the sea level rise by 0.10-0.59 m as these dynamics increase the vulnerability of ice sheets to warming. Although current model results suggest that abrupt changes such as collapse of west Antarctic ice sheet are unlikely in the 21st century, occurrence of such changes becomes more likely as the perturbation of the climate system progresses (AR4, chapter 10). Recent acceleration of glaciers feeding to Larsen B Ice Shelf after its collapse has renewed these concerns (Scambos et al., 2000).

The major contributor to the sea level rise projected in this assessment of IPCC is thermal expansion (Meehl, 2007), constituting 70-75% of the central estimate in these projections for all scenarios. Other contributors are melting of glaciers, icecaps, and Greenland ice sheets. Further acceleration of the melting of the ice sheets, such as that already observed in the Greenland, is expected to increase the sea level to balance out the negative contribution of the Antarctic. The AR4 did not include the acceleration due to melting of ice sheets into its computed sea level projections due to limited understanding of these processes at the time of its publication.

The US climate change science program recently reported (CCSP, 2008) that the increase in sea level is likely to substantially exceed the projections made in IPCC fourth assessment (IPCC, 2007). This conclusion comes from recent rapid changes in observed accelerations of flow and thinning at the edges of Greenland and West Antarctic ice sheets where the velocity of some glaciers has increased more than twofold. This acceleration is related to increased surface meltwater production that penetrates to the bottom and reduces resistance to flow, thus enhancing the motion of the glaciers.

Meier et al. *(2007)* extrapolated the current acceleration to estimate a total contribution to sea level of 240±128 mm by 2100 due to acceleration from all glacial inventories, assuming that the current acceleration of loss continues. However, if the loss continues at its current rate of 400 Gt a^{-1}, the total contribution is 104±25 mm. The authors of the study caution that these estimates should be accounted as underestimates because dynamically forced losses of sea ice are not included in all calculations where these loses remain unknown. In the current cryosphere (land with frozen water), contribution from glaciers to sea level (104±25 mm) outweigh those from other ice sheets (Greenland ice sheet: 47±8 mm, West Antarctic Ice sheet: 30±4 mm, East Antarctic ice sheet: -56±40 mm).

These changes to glaciers and ice sheets were not included in sea level projections of the last IPCC report due to limitations in the models used in estimating losses of sea ice due to dynamic processes. Thus current global modeling studies project that the Antarctic ice sheet will remain too cold for widespread surface melting and will even gain mass due to increased snowfall (IPCC, 2007), but these models do not take into account the dynamical processes. Net loss of ice mass could occur if dynamical ice discharge dominates the ice sheet mass balance A one-meter thinning of all Antarctic ice shelves would involve the melting of 1600 km^3 of ice, equivalent to a 4 mm rise in sea level (Titus and Richman, 2001).

Other recent studies have also projected a higher magnitude of rise in sea level than what was projected in the IPCC estimate. Hansen (2007) reported that the feedbacks unaccounted for in the IPCC estimate could quickly cause several meters of rapid sea level rise because the response to an increase in temperature is nonlinear due to positive feedbacks and system inertias. Warming of oceans will continue even if the CO_2 is constrained at the present level, because temperature at ocean depth is out of equilibrium with present environmental conditions.

More recently, Pfeffer (2008) took into account the dynamical changes in ice flow that had been ignored by IPCC reports and the glaciological conditions required for large sea level rise to occur by 2100. This study suggested that the sea level can rise from 0.8 - 2 m by 2100, with 2 m being the absolute upper limit. The study gave particular attention to the Greenland ice sheets because of recent accelerations of ice motions, melt-water related feedbacks, and the vulnerability of the ice sheets to ongoing Arctic warming.

Based on a strong correlation of a global sea level and global average near-surface air-temperature in the 20th century, another study (Rahmstorf, 2007) suggested a sea level rise of as much as 0.5 to 1.4 m from the 1990 level in 2100. This study calculated sea level rise from observed variables without going deeply into the complicated mechanisms that determine changes in global sea level. The analysis was tested for robustness by examining how correlations between key variables in the historical data held up at various levels of data smoothing.

Examining a scenario in the geological past to predict the future, Carlson et al. (2008) reported that the melting of the Laurentide ice sheet raised the sea levels by 0.7 to 1.3 m in the early Holocene epoch. Taking a cue from the past, this study suggests that the sea level could rise by 50 to 80 cm by end of the century, drowning large areas of coastal region. This study reveals a prehistoric precedent for changes in mass balance of the Greenland ice sheets and their consequences.

These studies also point out that rise in sea level is likely to continue for centuries even if the global temperature stabilizes. Church (2001) reports that after 500 years sea level rise would only reach half of the eventual rise caused by CO_2 levels of twice the pre-industrial value. Meehl et al. (2005) estimates from two different global circulation models that even if the concentrations of greenhouse gases in the atmosphere had been stabilized at the concentration of the year 2000, the planet would be committed to an increase in global temperature of about another half degree and an additional 320% sea level rise (equivalent to 10 to 15 cm) from the present level due to thermal expansion alone by the end of the 21st century.

In summary, IPCC in its AR4 provides projections of sea level rise in the 21st century that range from 0.18 m to 0.59 m depending on the future scenario being studied. The AR4 also stated that there will be additional sea level rise of 0.1 to 0.59 m if ice flow dynamics were taken into consideration. More recent studies that have also taken dynamic changes in ice flow into consideration have estimated sea level rise in the 21st century ranging from 0.5 m to 2 m. It is difficult to draw any firm conclusions from these numbers, but there seems to be a growing consensus among the later studies that the IPCC projections for sea level rise in the 21st century may be too conservative.

4
GEOGRAPHIC VARIATIONS OF SEA LEVEL RISE

4.1 Global Sea Levels

Substantial geographic variability is projected in the sea level rise. Regional scale variability is caused by changes in ocean circulation, ocean-water density, and wind and sea level pressure patterns (Gregory, 1993). Although the patterns for all regions are not the same in all the models, there are some commonalities. These include a projection of less than average rise in sea level in the Southern Ocean and a larger than average rise in the Arctic. Pronounced increase in sea level is also projected in a narrow band stretching across the southern Atlantic and Indian Oceans (AR4, Chapter10). The higher than global average increase in the Arctic Ocean (Church, 2001) is most likely due to increase in river runoff as well as precipitation over the ocean (Bryan, 1996; Miller and Russell, 2000).

Long-term changes in sea level from 1955-2003 are depicted on the right side of Figure 4-1. The top map on the right side shows net sea level rise; the bottom map shows the amount of sea level rise attributable to thermal expansion. The difference in the geographical pattern of sea level from what is shown on the short-term maps on the left side of Figure 4-1 is attributed to thermal expansion (AR4WG1- see section 5.5.3 for more references). The geographical pattern of long-term sea level trends indicates an increase in the eastern Pacific off California, on the East Indian Ocean, and in the North Atlantic. The increasing trend in the East Indian Ocean can adversely affect the low lying areas of Indonesia, Thailand and Bangladesh.

Figure 4-1 illustrates the non-uniformity of sea level rise in the global oceans. The global average sea level rise during the 1993-2003 period was estimated to be 3.1±0.7 mm/yr (Cazenave and Nerem, 2004), with a major contribution from the Southern Hemisphere (Cabanes et. al., 2001). Figure 4-1 also illustrates that there was an increasing trend in the last decade in the sea level in the Eastern Indian and Western Pacific and a decreasing trend of the same in the Western Indian and Eastern Pacific. These decadal variations are due to effects of El Nino, which are most apparent in these two oceans.

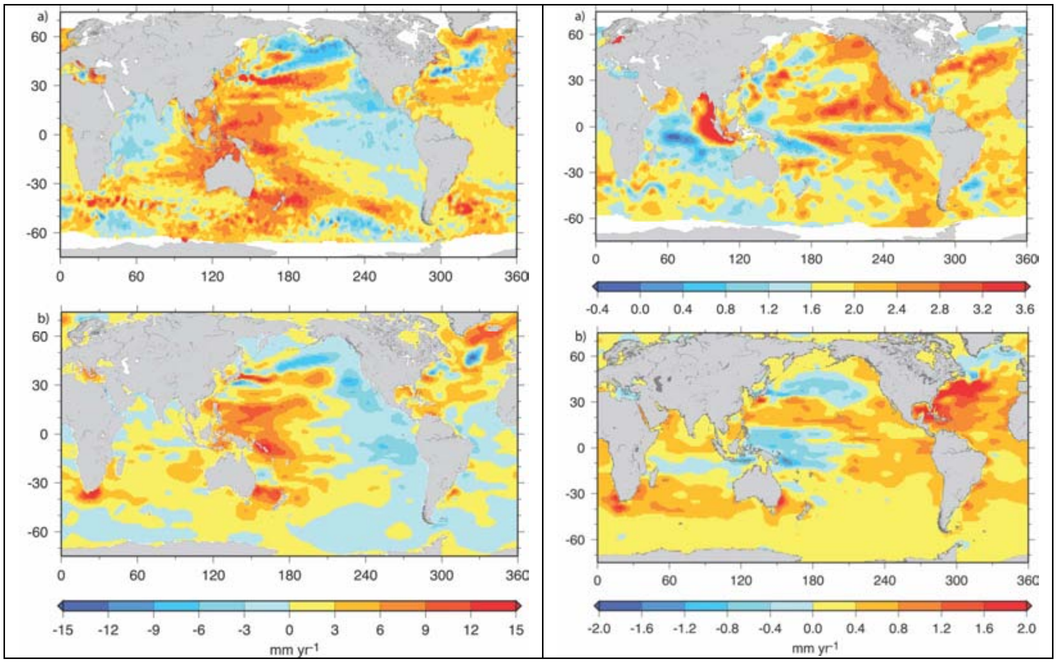

Figure 4-1
Short term and long term changes in sea level changes.

Left panels: Geographic distribution of short-term linear trends in mean sea level (mm/yr) for 1993 to 2003 based on TOPEX/Poseidon satellite altimetry. Right panels: Geographic distribution of long-term linear trends in mean sea level (mm/yr) for 1955 to 2003 based on the past sea level reconstruction with tide gauges and altimetry data. The top panel of each side shows net sea level rise. The bottom panel shows the amount of sea level rise attributable to thermal expansion.

Source: IPCC (2007)

4.2 US Sea Levels

There is significant geographic variability in sea level rise in the U.S. too. The most recent reports (CCSP, 2009 and references therein) as well as some of the older reports (National Research Council, 1987) have concluded that regions most vulnerable to increased sea level are the East and Gulf coasts in the United States. This greater risk is due to the extensive low-lying coasts in these regions compared to the higher altitude stretches that predominate on the west coast. More recent reports (CCSP, 2008; CCSP, 2009) concluded from sea level data that sea levels have been rising along most of the Atlantic and the Gulf coasts at the rate of 0.2 to 0.3 cm per decade. This rate of sea level rise varied from a few inches per decade along the Louisiana coasts caused by sinking of land, to a rise of few inches per decade in Alaskan coasts because of rising land due to tectonic and other processes.

The sea level trend in Figure 4-2 illustrates the upward trend in the 20th century in all but one city. The overall sea level trend in the United States is depicted in Figure 4-3. The difference in the mean sea level shown in Figures 4-2 and 4-4 is due to the combined effect of changes in local sea level and local vertical land motion. The tide-gauge observations in the mid-Atlantic region from New York to North Carolina indicate that the relative sea level rise rates of these regions are higher than the global mean sea level over the twentieth century (CCSP, 2008).

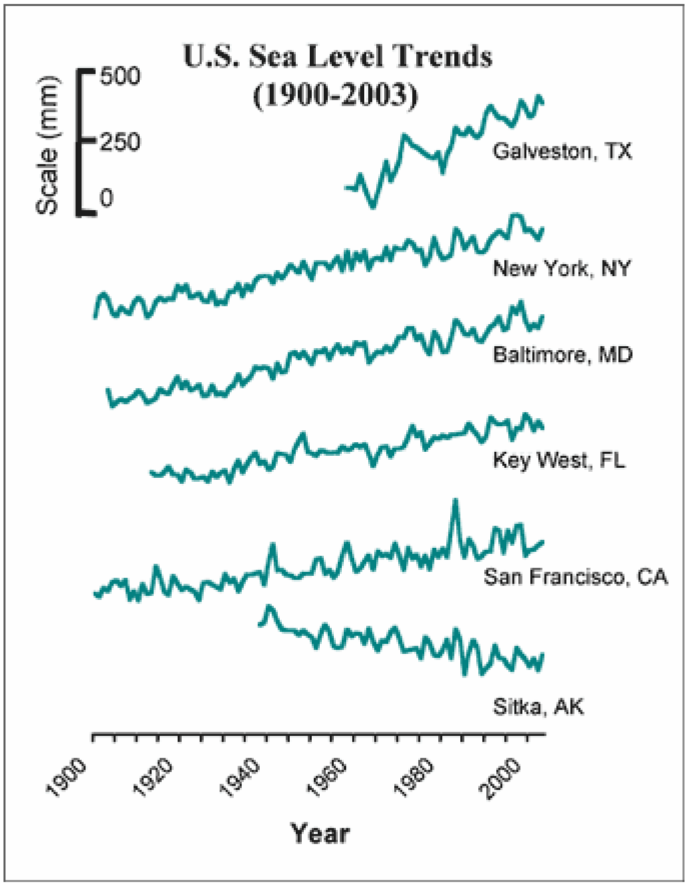

Figure 4-2
Change in sea level in some of the coastal cities of USA (US EPA, Permanent Service for Mean Sea Level). All cities shown here, but one (Sitka, AK) has been experiencing a secular increase in mean sea level.

Source: US EPA, and Permanent Service for Mean Sea Level (PSMSL)

The green color in Figure 4-3 represents areas experiencing little-to-no change in mean sea level, including stations consistent with average global sea level rise rate. These stations are not experiencing significant vertical land motion. Stations with warmer colors (yellow to red) are experiencing a relative rise in sea level due both to global sea level rise and lowering or sinking of the local land. The stations illustrated with negative trends (blue-to-brown) are experiencing global sea level rise but the greater vertical rise in the local land causes a decrease in relative sea level. These rates of relative sea level rise reflect actual observations and must be accounted for in any coastal planning or engineering applications.

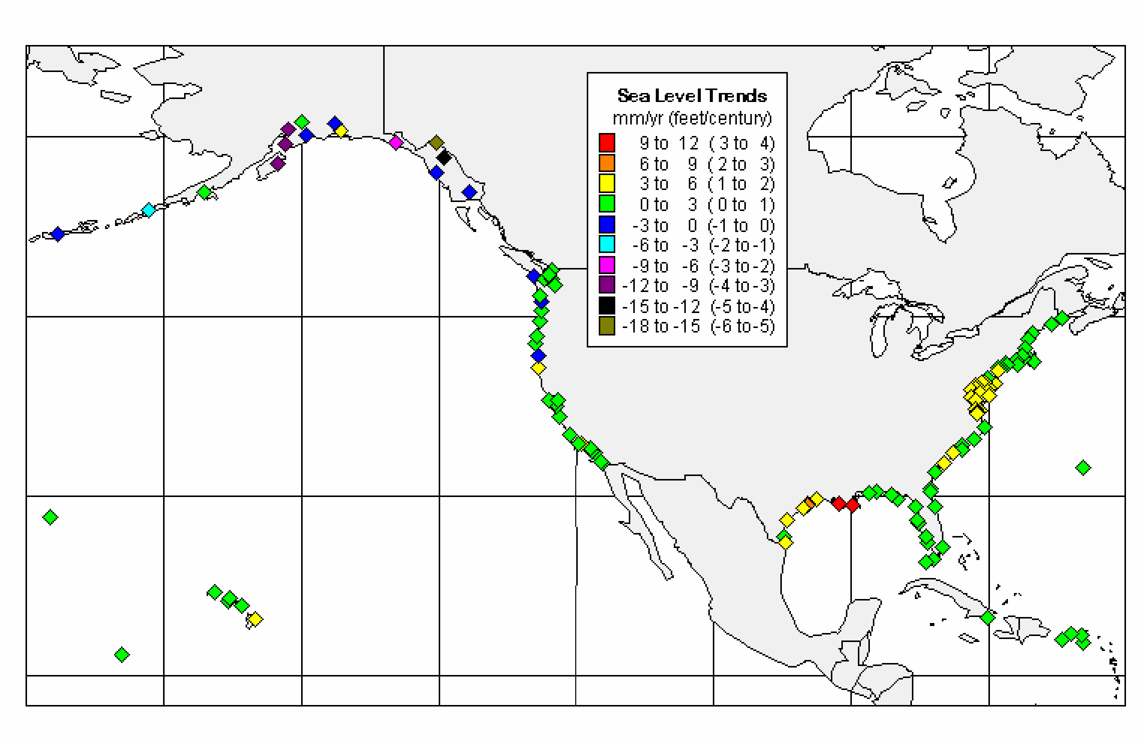

Figure 4-3
This map developed by NOAA shows the regional trends of mean seal level in the US coasts, based on data that is at least 30 years old

Source: NOAA (http://tidesandcurrents.noaa.gov/sltrends/sltrends.html)

The twentieth century annual relative sea level rise rates are illustrated in Figure 4-4 (from CCSP, 2009).

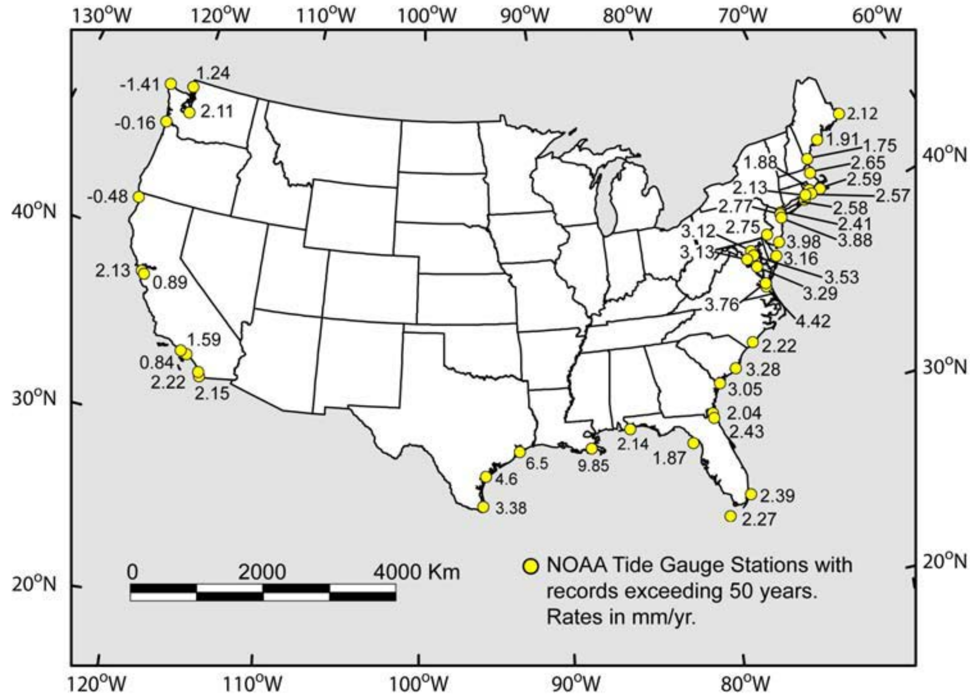

Figure 4-4
Map of twentieth century annual relative sea level rise rates around the U.S. coast. The higher rates for Louisiana (9.85 millimeters [mm] per year) and the mid-Atlantic region (1.75 to 4.42 mm per year) are due to land subsidence. Sea level is stable or dropping relative to the land in the Pacific Northwest, as indicated by the negative values, where the land is tectonically active or rebounding upward in response to the melting of ice sheets since the last Ice Age.

Source: CCSP (2009)

The large variation in sea level rise ranges widely: from a rise of 9.85 mm/yr at Grand Isle, Louisiana, due to subsidence of land, to a drop of 16.68 mm/yr in Skagway in southeast Alaska due to uplifting of land caused by tectonic processes and GIA. In the Atlantic coast, the highest rate of sea level rise is in the mid-Atlantic regions between New Jersey and southern Virginia; and lowest rates are along New England and from Georgia to northern Florida, where the rates are close to the global rate.

5
CONSEQUENCES OF SEA LEVEL RISE

Increases in sea level can have widespread consequences depending on the level of rise discussed in previous sections. One of the major consequences of sea level rise is the inundation of coastal areas, but the effect on the coastal areas is more complex than simple inundation (CCSP, 2009). Apart from inundation, sea level rise can exacerbate erosion and accretion processes. Based on the 2000 census data, more than one-third of the US population resides in the coastal counties (Crossett et al., 2004; Crowell et al., 2007). Moreover, out of 20 largest US urban centers, 14 are located along the coasts (CCSP, 2009).

The fact-sheet of CCSP (2008) summary report states that it is virtually certain that future sea level rise will cause some areas of dry land in the United States to become inundated as well as to become increasingly vulnerable to storm surges. It also cautions that potential accelerations in ice flow of the kind recently observed in some Greenland outlet glaciers and West Antarctic ice streams could substantially increase the contribution from the ice sheets to sea level in future, thus exacerbating these risks. A rise of one-meter in global sea levels would cause an inundation estimated at about 35,000 km^2 (13,000 mi^2) of land, divided about equally between wetlands and upland (Smith and Tirpak, 1989).

In the case of the increase in global sea levels rise of 0.5 meter, estimated inundated area would be about 24,000 km2 (9,000 mi^2) (Smith and Tirpak, 1989). Under these conditions, most coastal cities in the east and gulf region face the risk of inundation.

The nature of the coastal landforms (e.g. barrier islands, cliffs) and physical processes will determine the rate and manner of changes due to erosion and accretion. Figure 5-1 (CCSP, 2009) shows that in the sandy shore environments that comprise most of the mid-Atlantic coasts, it is virtually certain that headlands spits and barrier islands will erode faster in response to future sea level rise.

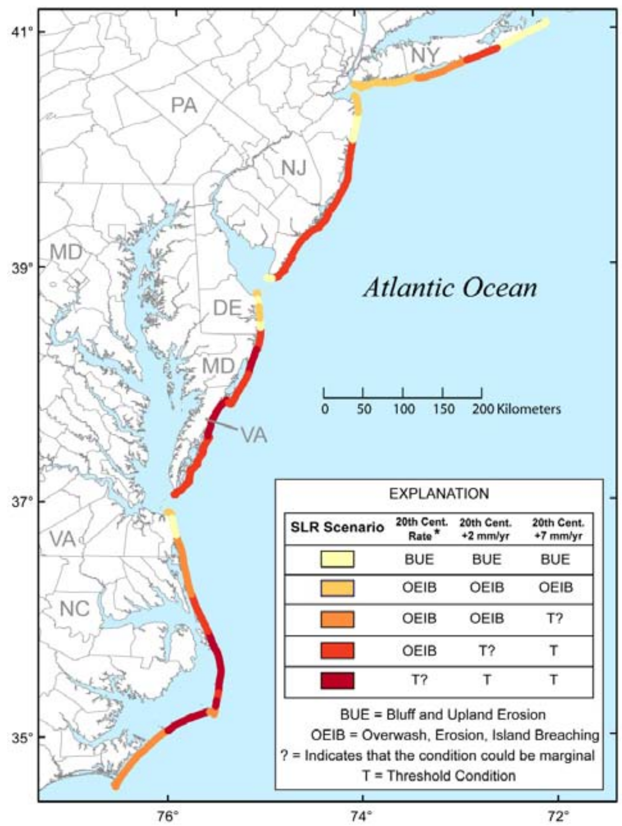

Figure 5-1:
Potential mid-Atlantic coastal landform responses to three sea level rise scenarios. Most coastal areas are currently experiencing erosion, which is expected to increase with future sea level rise. In addition to undergoing erosion, coastal segments denoted with a "T" may also cross a threshold where rapid barrier island migration or segmentation will occur.

Source: CCSP (2009)

The regions that are already experiencing submergence due to increase in relative sea level are the tidal wetlands associated with Mississippi River delta in Louisiana and Blackwater River marshes in Maryland as described in CCSP, 2009. The same report also states that it is likely that such wetlands will not survive an acceleration of sea level rise by 7mm/yr (Figure 5-2). The loss of associated wetland ecosystem functions such as providing natural flood control, acting as natural storm surge buffers, and protecting water quality can have important consequences for populations living near coasts. These consequences include an increase in storm surges associated with hurricanes. The danger from storm surges increases because a higher sea level provides an elevated platform for a storm surge to build upon and also reduces the rate of drainage from the low-lying areas, thus increasing the risk of flooding (CCSP, 2009). Increase in erosion also increases the risk by eroding protective dunes, beaches, and wetlands. Although serious storms occur episodically, their impact is long-term.

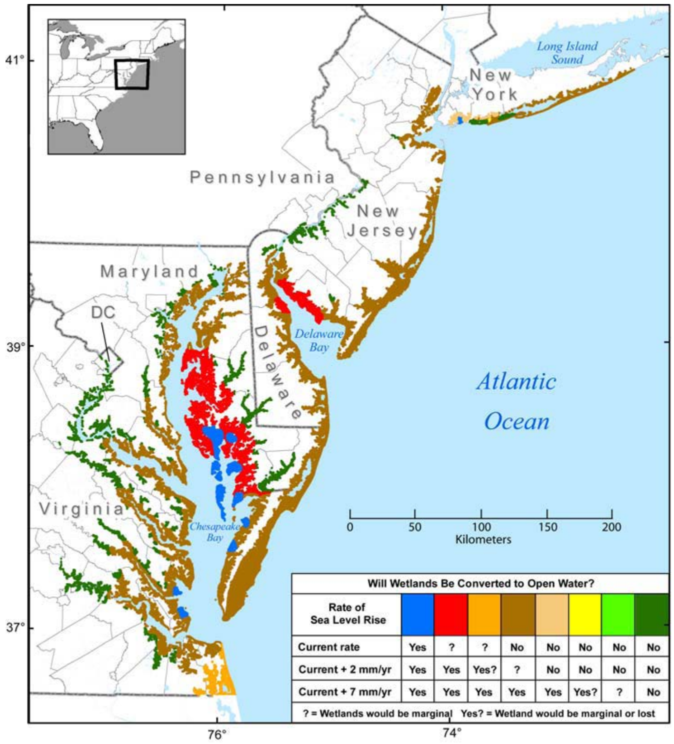

Figure 5-2
Areas where wetlands would be marginal or lost (converted to open water) under three rates of sea level rise

Source: CCSP (2009)

Changes in shoreline and coastal erosion are influenced by the following factors (CCSP, 2009): 1) physical processes and natural factors such as storms, waves, and currents; 2) human activity such as dredging, dams, and coastal engineering; and 3) the geologic character of the coast. Figure 5-3 illustrates the erosion rates of coasts around United States.

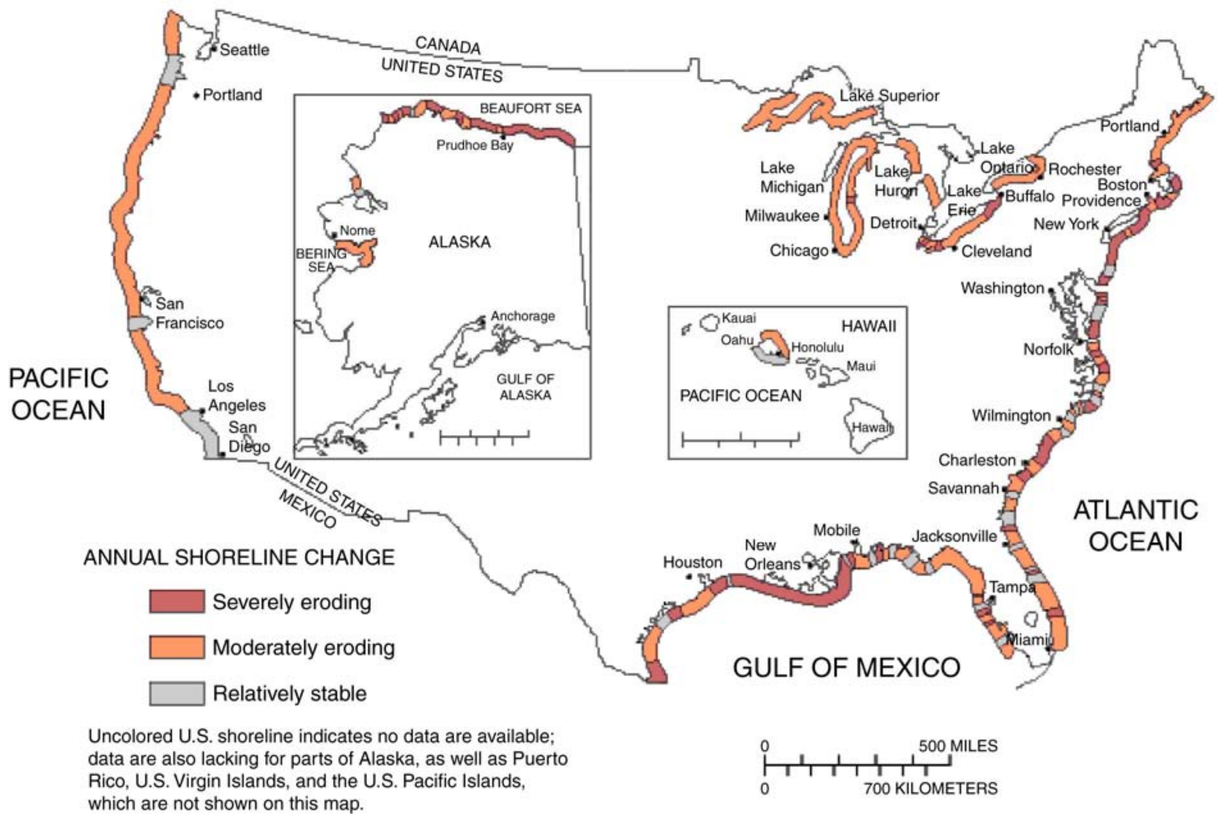

Figure 5-3
Shoreline change around the United States based on surveys over the past century. All 30 coastal states are experiencing overall erosion at highly variable rates due to natural processes such as storms and sea level rise and human activity

Source: CCSP, 2009

Inundation is one of the most obvious and direct effects of rise in sea level. Although there are other effects of sea level rise, most assessments have chosen to focus on the risk of inundation, due to lack of clear alternatives. Inundation is the most important component of coastal changes (Leatherman, 2001) especially in low-lying regions such as North Carolina.

The elevation of coastal areas plays a crucial part in determining the risk of inundation. The extent of inundation is dependent on the slope of the land, with greater inundation in regions with gentler gradients (CCSP, 2009). The available elevation data are coarser in resolution than what is required for local planning and decision making. However, with the advent of higher quality elevation data from LIDAR (Light Detecting and Ranging), higher resolution maps would be relatively easier to develop.

5.1 Risk of Inundation Maps

Some state level maps have been developed by United States EPA (Titus and Richman, 2001) to show regions that face the risk of inundation for the U.S. Atlantic and the gulf coasts in case of a 1.5 m rise in sea level. Some of the regions are shown in Figures 5-4 through 5-7. Maps of other regions

can be found at:
http://yosemite.epa.gov/oar/GlobalWarming.nsf/content/ResourceCenterPublicationsSLRMaps.html

A contour of 1.5 m was chosen for these maps because the digital elevation model from USGS that has been used in this study has a lowest limit of 1.5 m, the highest resolution available to date. The 1.5 m contour roughly represents the area that would be inundated during spring high water with a 70 cm rise in sea level—a mean spring high tide is typically 60 cm above mean sea level.

These maps are the first step towards determining which regions are at risk for inundation due to increase in sea level and which are not. Of the States that were studied, Louisiana, Florida, Texas, and North Carolina accounted for more than 80% of the low land. Apart from these states, the most vulnerable regions are the Eastern Shore of Chesapeake Bay that stretches from Dorchester County, Maryland to Accomac County, Virginia. These maps illustrate the elevation of lands close to sea level and do not depict future shorelines. Table 5-1 illustrates the areas of lands in these states that have an elevation between 0 to 1.5 m and hence can potentially be affected by sea level within this range. According to this study, the first six states that have highest percentage of land area within the 0-1.5 m elevation in their coastlines are Louisiana, Florida, Delaware, Maryland, New Jersey and North Carolina. The maps corresponding to the elevation study of these regions are provided in Figures 5-4 to 5-7.

Table 5-1
Area of land between the elevations of 0-1.5 (modified from Titus and Richman, 2001 to include % land area affected)

State	Area between elevation 0 and 1.5 meters (Km2)	% of state land
Louisiana	24725	21.9
Florida	12251	8.8
Delaware	388	7.7
Maryland	1547	6.1
New Jersey	1083	5.6
North Carolina	5836	4.6
Rhode Island	122	4.5
South Carolina	2334	3.0
Massachusetts	365	1.8
Georgia	1743	1.2
District of Columbia	2	1.0
Virginia	969	0.9
Texas	5178	0.8
Connecticut	63	0.50

Table 5-1:
Area of land between the elevations of 0-1.5 (modified from Titus and Richman, 2001 to include % land area affected) (continued)

State	Area between elevation 0 and 1.5 meters (Km2)	% of state land
Maine	383	0.5
New York	240	0.2
New Hampshire	42	0.2
Alabama	195	0.2
Mississippi	173	0.1

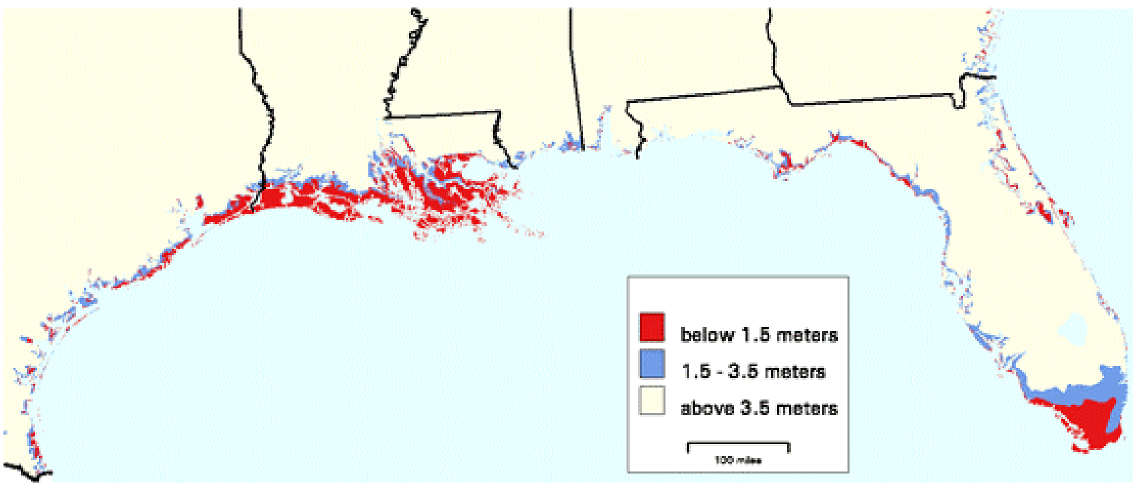

Figure 5-4
Land close to Sea level: U.S. Gulf Coast

Source: US EPA

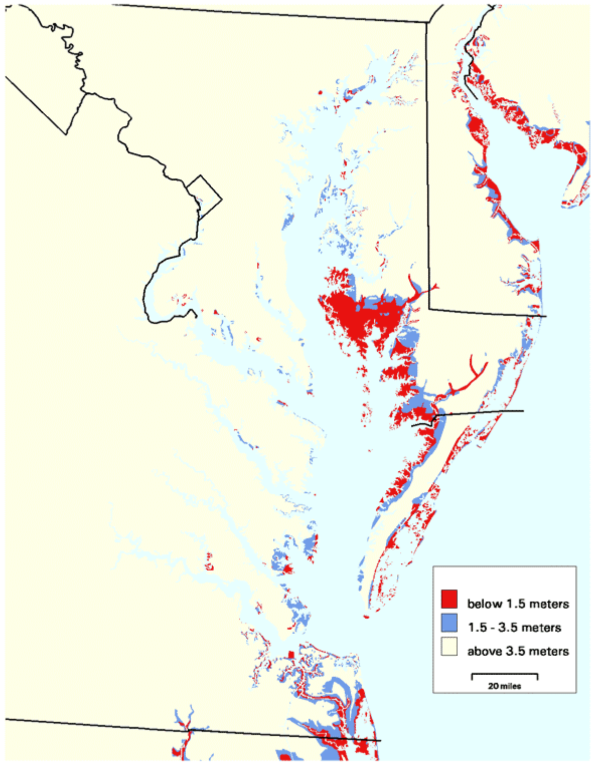

Figure 5-5
Land close to Sea level: Chesapeake and Delaware Bays

Source: US EPA

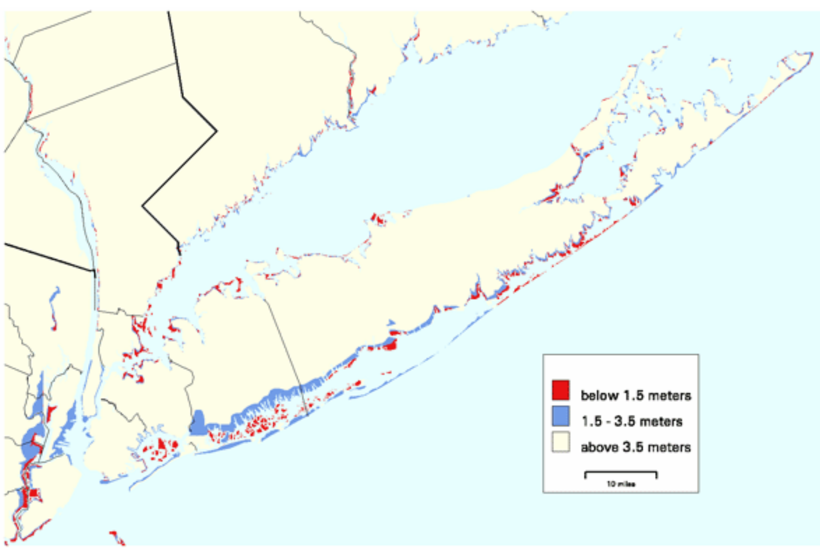

Figure 5-6
Land close to Sea level: Long Island, New York

Source: US EPA

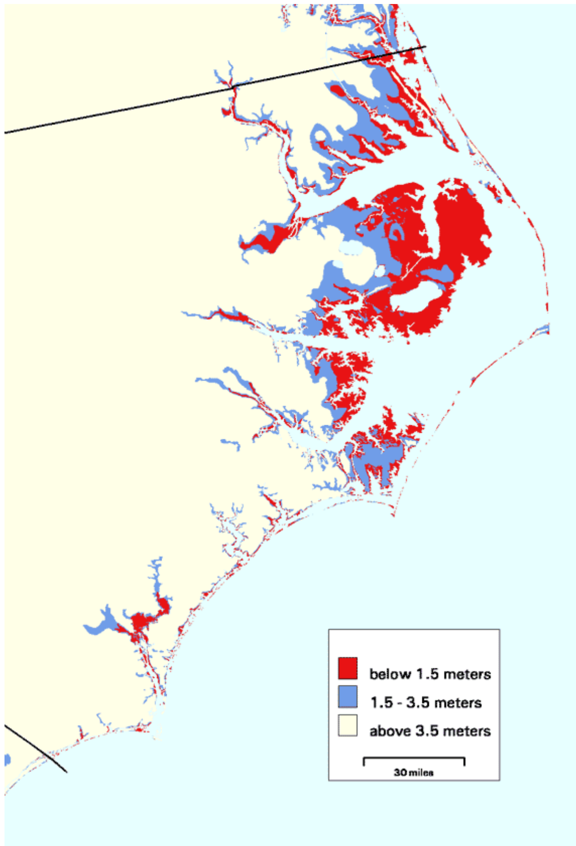

Figure 5-7
Land close to Sea level: North Carolina

Source: US EPA

The only other study that estimated the land areas of the United States at risk of inundation with sea level rise was EPA's report to Congress (1989). That study had larger uncertainties compared to Titus and Richman (2001), owing to an indirect elevation model, low sample size, and extrapolation. The two studies are compared below:

Table 5-2
Comparison of U.S. Land Areas (km^2) with elevation less than 1.5 Meters, at Risk of Inundation from Two Different Studies

Region	Titus and Richman, 2001	Report to Congress Estimate (1991)	Report to Congress Standard Deviation
Northeast	974	839	490
Mid-Atlantic	4227	4685	1274
South Atlantic	12339	9433	3313
S & SW Florida	8744	4605	2168
Louisiana	24724	14856	4416
Other Gulf	6625	5879	4312

An EPA initiative is underway to develop higher resolution local maps. Here is the status of those maps:

Complete and Under Review: Delaware, Rhode Island, and North Carolina
In Progress: Maryland, Virginia, New Jersey, South Carolina, Georgia, Southwest Florida
Planned for later in 2009: New York, Massachusetts, Texas, Alabama, Mississippi, South Florida

5.2 Coastal Vulnerability Assessment Analysis

USGS (http://woodshole.er.usgs.gov/project-pages/cvi/) assessed coastal vulnerability to sea level rise based on the criterion of tidal range, wave height, coastal slope, shoreline change, geomorphology, and historical rate of relative sea level rise. This approach took into account the susceptibility of the coastal regions to change, including the natural ability of land to adapt to changing environmental conditions. This assessment was codified into maps as shown in Figures 5-8 through 5-10 depicting the Map of the Coastal Vulnerability Index (CVI) for the U.S. coast (Thieler and Hammar-Klose, 1999, 2000). The CVI shows the relative vulnerability of the coast to changes due to future rise in sea level. Areas along the coast are assigned a ranking from low to high risk, based on the analysis of physical variables that contribute to coastal change. This is a valuable tool for evaluating the potential for coastal changes in a given area.

This study showed high CVI in New Jersey, Delaware, Maryland, Virginia, North and South Carolina, and Florida. Long Island demonstrated a moderate CVI whereas coastline of northern New England and particularly Maine had a low CVI. There are numerous areas of very high vulnerability along the coast, particularly along the mid-Atlantic coast (Maryland to North Carolina) and northern Florida. The regions with high CVI are typically high-energy coastlines where the regional coastal slope is low and where the major landform type is a barrier island. A significant exception is the regions in the lower Chesapeake Bay where the low coastal slope, vulnerable landform type such as salt marsh, and high rate of relative sea level rise combine for a high CVI value.

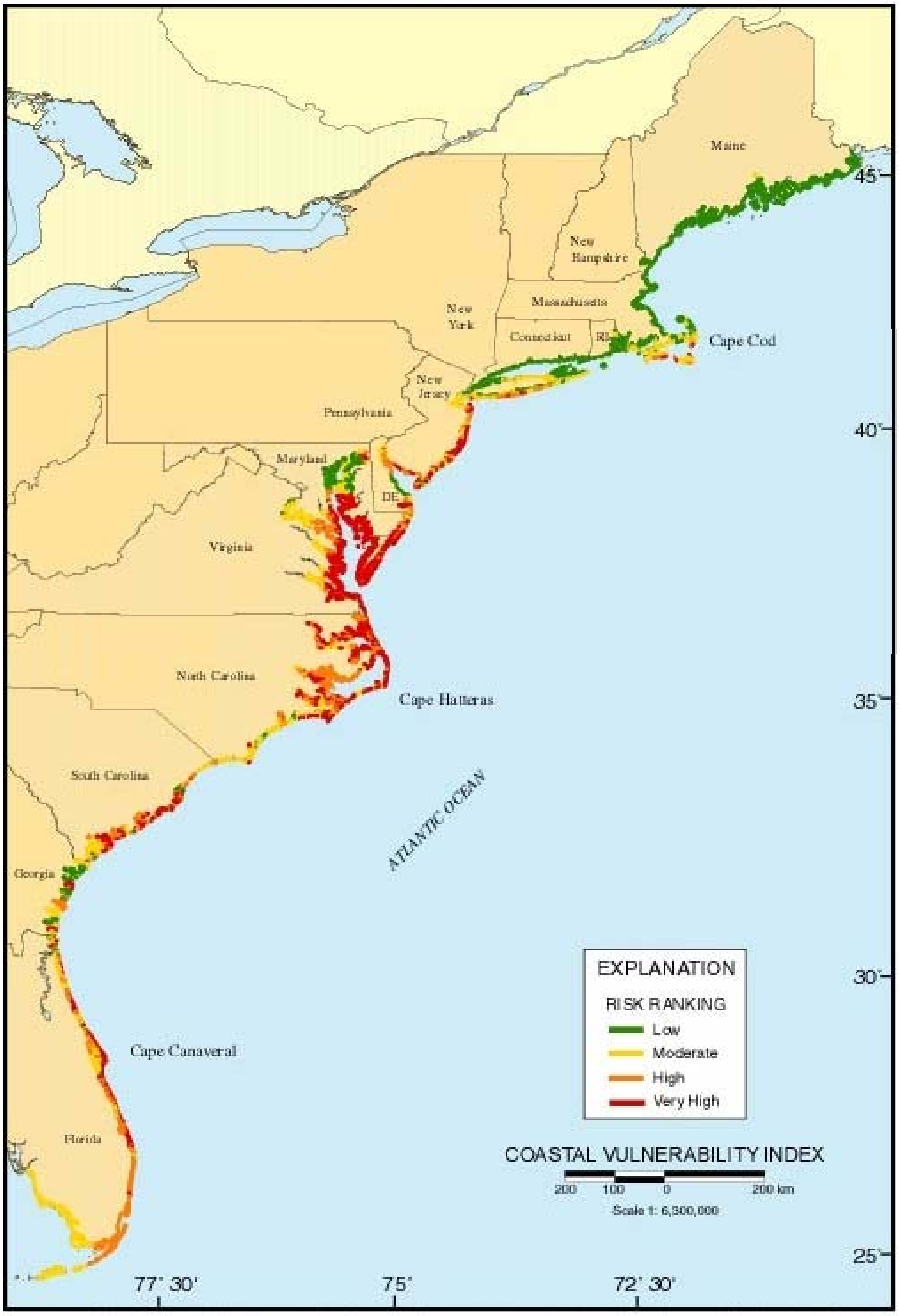

Figure 5-8
Coastal Vulnerability Index in the Atlantic Coasts

Source: USGS

Figure 5-9
Coastal Vulnerability Index in the Gulf Coasts

Source: USGS

In the Gulf Coast (Fig 6b), the CVI values show large areas of very high vulnerability, particularly along the Louisiana coast, the Texas coast north of Corpus Christi and in the southwest Florida coast, similar what was reported in the NOAA and EPA study mentioned earlier. These high indexes arise from geomorphology, coastal slope, and rate of relative sea level rise.

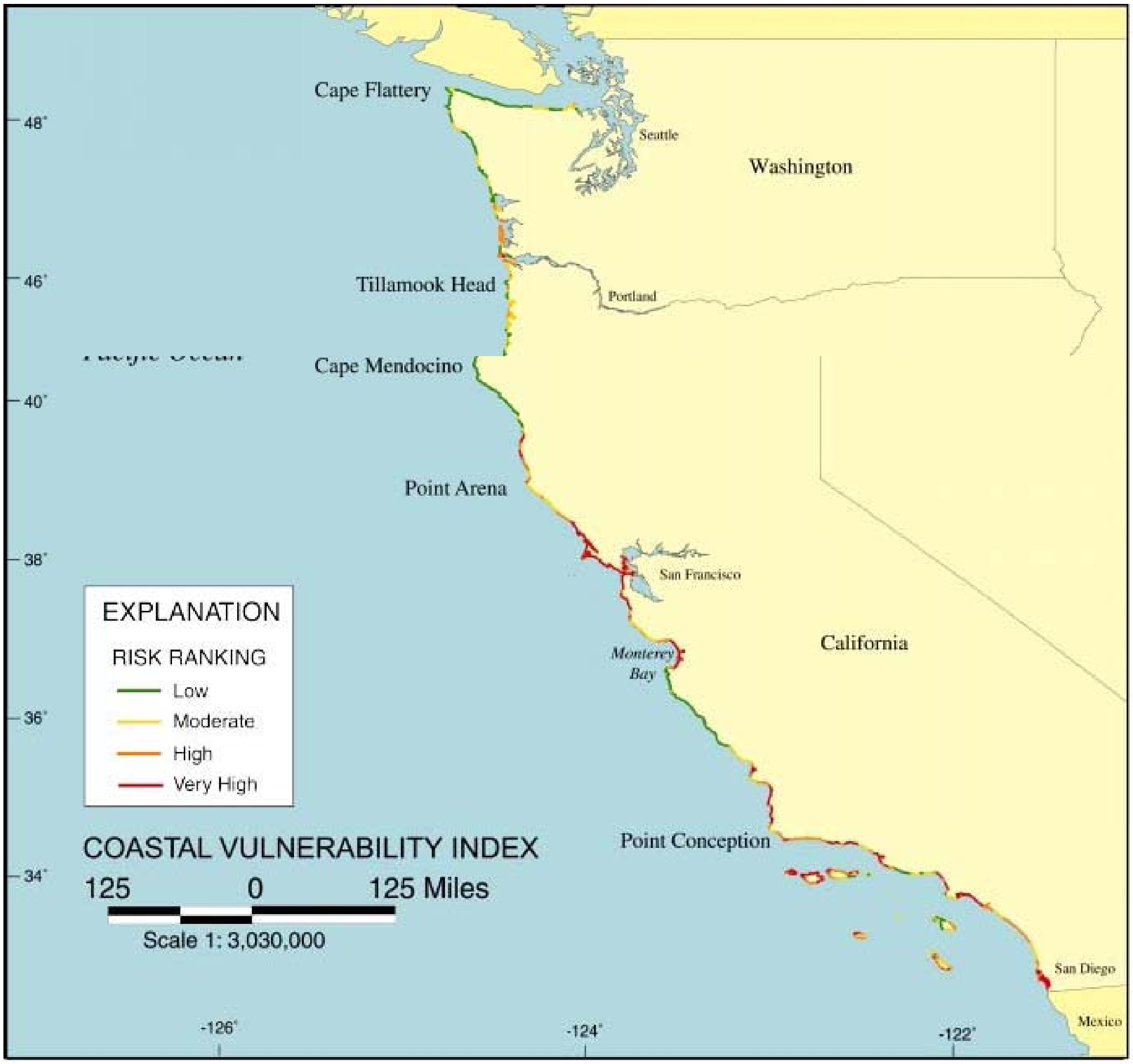

Figure 5-10
Coastal Vulnerability Index in the Pacific Coast

Source: USGS

In the Pacific coast (Figure 5-10), the CVI shows high vulnerability in some highly populated regions on the coast from San Francisco to Monterey Bay areas and in southern California from San Luis Obispo to San Diego. The susceptibility is mainly due to geomorphology and coastal slope. The regions with low CVI occur at rocky headlands along cliffed coasts where the coastal slope is steep, relative sea level is falling, tide range is large, and wave energy is lower. Examples of these areas are the northern coast of Washington; south of Monterey, California; and Cape Mendocino, California (Thieler and Hammar-Klose, 2000).

Higher resolution study has been conducted or is underway to investigate repercussions of sea level rise on densely populated regions such as New York. A Columbia University-NASA (Gornitz et al., 2006) study has shown that by the 2080s the sea level in New York could rise by 30-95.5 cm and regionally by 24-108 cm. Simulations of sea level rise for the metropolitan region using NASA Goddard Institute for Space Studies General Circulation Model (GCM) suggested increases of 0.25 to nearly 1 m by 2100. Estimates of sea level rise for New York City from three GCMs suggest increases of 17.5 to 27.0 cm by the 2050s.

As a result of increasing storm surge, it is estimated that flooding by major storms would inundate many low-lying neighborhoods and adversely affect the transportation system with much greater frequency (Gornitz et al., 2001). Figure 5-11 shows the risk of inundation with current and projected sea level rise for a Category 3 hurricane on a worst-case track slightly west of New York City.

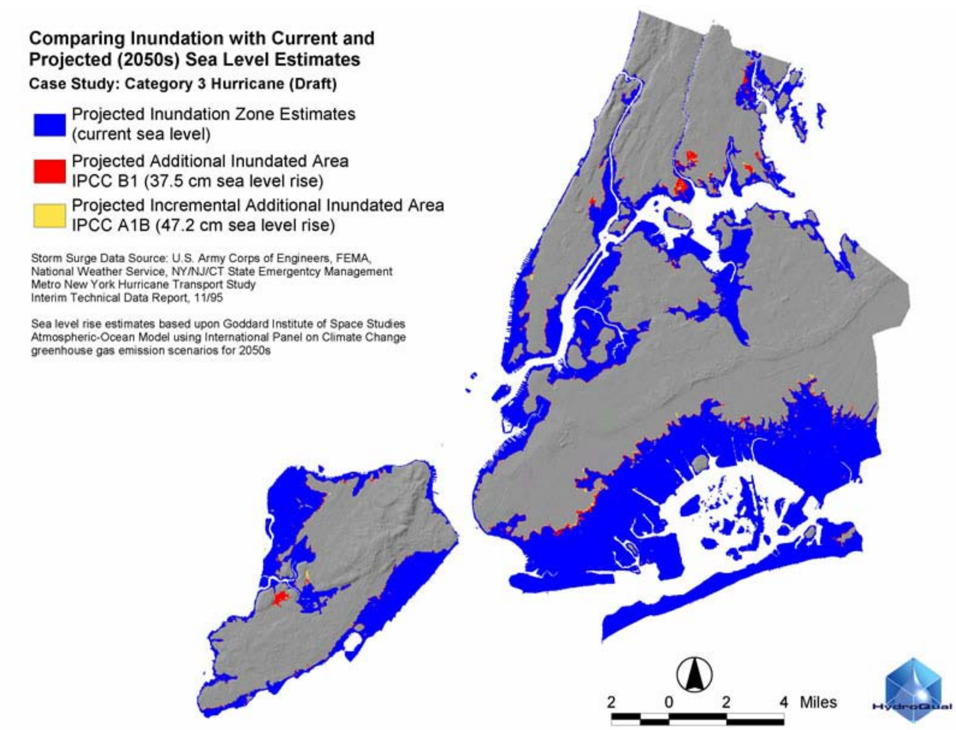

Figure 5-11
Risk of inundation in current and projected sea level estimates.

Source: NYCDEP CU SUNY/HydroQual; surge data from USACE/FEMA/NWS/NY/NJ/CT State Emergency Management

6
CONCLUSIONS

This report introduced the underlying causes of sea level rise, reported the current scientific knowledge of observed and projected sea level changes, and discussed the variability in global and regional sea level changes. It also highlighted recent reports that deal with consequences of sea level change on U.S. coasts.

Global sea level can rise due to global warming because of thermal expansion of the oceans, the melting of large Greenland and Antarctic ice sheets, and the melting of other glaciers and ice caps. Increased runoff from water from glacier and snow-fed rivers as well as increased precipitation in some regions can also contribute to a rise in sea level. Sea level is also affected by vertical movements of land caused by geological processes such as the rising of the land that continues to occur in many areas in response to the recession of ice-age glaciers and the subsidence of land caused by groundwater or oil extraction

According to the IPCC Fourth Assessment Report (AR4), the twentieth century experienced an average increase of sea level of 1.7 ± 0.5 mm/yr. The rate of sea level rise has accelerated in the last several years. From 1993 to 2007, the mean sea level increase is an estimated 3.36±0.41 mm/yr. These recent increases in sea level have been attributed to losses of ice-masses from glaciers and ice sheets in Alaska, Greenland, and Antarctica. Recent reports argue that the IPCC predictions of future sea level changes may be too conservative. These suggestions largely reflect recent observations of accelerated movements of glaciers and ice sheets that were not included in the IPCC models, because the complex nature of these dynamic processes has yet to be quantified for modeling purposes. These reports estimate a global sea level rise ranging from 0.5 m to 2 m in the 21^{st} century.

Apart from the global changes in sea level, there is also much variability at regional level. For example, a less than average rise in sea level is projected for the Southern Ocean and a larger than average rise is projected in the Arctic. Determining the relative sea level at any coastal point is complicated by local processes including the vertical movement of land. As a result of these local processes, the coastal states of United States have widely different sea level rise characteristics. It is widely believed that the eastern and south eastern states are more vulnerable due to a combination of sea level increase and land subsidence.

Inundation is one of the most obvious and direct effects of rise in sea level. Although there are many other effects of sea level rise, inundation is the most important component of coastal changes especially in low-lying regions such as North Carolina. The extent of inundation is dependent on the slope of the land, with greater inundation resulting in regions with gentler gradients. The risk of inundation for U.S. Atlantic and gulf coasts in the case of 1.5 m rise in sea level is quite large with projections that in Louisiana, Florida, Texas, and North Carolina more than 80% of land may be at risk. The increased vulnerability not only includes direct inundation but also land loss through submergence and erosion of coastal lands, increased storm surges, wetland losses, and increased salinity in estuaries and coastal freshwater sources as well as in groundwater. In most cases, these impacts have a cumulative effect.

Apart from inundation, sea level rise can exacerbate erosion and accretion processes depending on the nature of the coastal landforms. It is virtually certain, for example, that the heads, spits, and barrier islands of the mid-Atlantic coasts will erode faster than other parts. An assessment of coastal vulnerability to sea level rise showed high vulnerability in New Jersey, Delaware, Maryland, Virginia, North and South Carolina, and Florida, with moderate vulnerability for Long Island. Some highly populated regions of the Pacific coast, including San Francisco, Monterey Bay, and parts of Southern California from San Luis Obispo to San Diego, are also highly vulnerable. Studies developing higher resolution maps (under an EPA initiative) are revealing the impact of sea level rise on specific densely populated regions such as New York City where flooding by major storms could inundate many low-lying neighborhoods and adversely affect the transportation system with much greater frequency as local sea levels rise.

7
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