CHAPTER 16

POTENTIAL CONSEQUENCES OF CLIMATE VARIABILITY AND CHANGE ON COASTAL AREAS AND MARINE RESOURCES

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CHAPTER SUMMARY

Context

The US has over 95,000 miles of coastline and approximately 3.4 million square miles of ocean within its territorial sea,all of which provide a wide range of essential goods and services to human systems. Coastal and marine ecosystems support diverse and important fisheries throughout the nation's waters,hold vast storehouses of biological diversity, and provide unparalleled recreational opportunities. Some 53% of the total US population lives on the 17% of land in the coastal zone,and these areas become more crowded every year. Demands on coastal and marine resources are rapidly increasing,and as coastal areas become more developed,the vulnerability of human settlements to hurricanes,storm surges,and flooding events also increases. Coastal and marine environments are intrinsically linked to climate in many ways. The ocean is an important distributor of the planet's heat,and this distribution could be strongly influenced by changes in global climate. Sea-level rise is projected to accelerate in the 21st century, with dramatic impacts in those regions where subsidence and erosion problems already exist.

Climate of the Past Century

- Sea level has risen by 4 to 8 inches (10-20 cm) in the past century.
- Ocean temperatures have risen over the last 55 years,and there has been a recent increase in the frequency of extreme ocean warming events in many tropical seas.
- Sea ice over large areas of the Arctic basin has thinned by 3 to 6 feet (1 to 2 meters),losing 40% of its total thickness since the 1960s;it continues to thin by about 4 inches (10 cm) per year.
- Marine populations and ecosystems have been highly responsive to climate variability.

Climate of the Coming Century

- Sea level is projected to rise an additional 19 inches (48 cm) by 2100 (with a possible range of 5 to 37 inches [13 cm to 95 cm]) along most of the US coastline.
- Ocean temperatures will continue to rise,but the rate of increase is likely to lag behind temperature changes observed on land.
- The extent and thickness of Arctic sea ice is expected to continue to decline. All climate models project large continued losses of sea ice, with year-round ice disappearing completely in the Canadian model by 2100.
- Increased temperature or decreased salinity could trigger abrupt changes in thermohaline ocean circulation.

Key Findings

- Climate change will increase the stresses already occurring to coastal and marine resources as a result of increasing coastal populations, development pressure and habitat loss, overfishing, excess nutrient enrichment, pollution, and invasive species.
- Marine biodiversity will be further threatened by the myriad of impacts to all marine ecosystems, from tropical coral reefs to polar ecosystems.
- Coral reefs are already under severe stress from human activities, and have experienced unprecedented increases in the extent of coral bleaching, emergent coral diseases, and widespread die-offs.
- The direct impact of increasing atmospheric carbon dioxide on ocean chemistry will possibly severely inhibit the ability of coral reefs to grow and persist in the future.
- Globally averaged sea level will continue to rise, and the developed nature of many coastlines makes both human settlements and ecosystems more vulnerable to flooding and inundation.
- Barrier islands are especially vulnerable to the combined effects of sea-level rise and uncontrolled development that hinders or prevents natural migration.
- Ultimately, choices will have to be made between the protection of human settlements and the protection of coastal ecosystems such as beaches, barrier islands, and coastal wetlands.
- Human development and habitat alteration will limit the ability of coastal wetlands to migrate inland as sea levels rise, however, if sediment supplies are adequate, many wetlands may survive through vertical adjustments.
- Increases in precipitation and runoff are likely to intensify stresses on estuaries in some regions by intensifying the transport of nutrients and contaminants to coastal ecosystems.
- As rivers and streams also deliver sediments, which provide material for soil in wetlands and sand in beaches and shorelines, dramatic declines in streamflows could have negative effects on these systems.
- Changes in ocean temperatures, currents, and productivity will affect the distribution, abundance, and productivity of marine populations, with unpredictable consequences to marine ecosystems and fisheries.
- Increasing carbon dioxide levels could trigger abrupt changes in thermohaline ocean circulation, with massive and severe consequences for the oceans and for global climate.
- Extreme and ongoing declines in the thickness and extent of Arctic sea ice will have enormous consequences for Arctic populations, ecosystems, and coastal evolution.

POTENTIAL CONSEQUENCES OF CLIMATE VARIABILITY AND CHANGE ON COASTAL AREAS AND MARINE RESOURCES

INTRODUCTION

Human caused alterations and impacts to coastal and marine environments must be considered in the context of evaluating the health and viability of these resources. In many instances,it is difficult to assess the effects of climate variability and changes because human activities are often responsible for the greatest impacts on coastal and marine environments. Such disturbances often reduce the capacity of systems to adapt to climate variations and climate stress,and often mask the physical and biological responses of many systems to climate forces. For example,naturally functioning estuarine and coastal wetland environments would typically be expected to migrate inland in response to relative sea-level rise,as they have responded to sea-level variations throughout time. When this natural migration is blocked by coastal development,such habitat is gradually lost by "coastal squeeze" as rising sea levels push the remaining habitat against developed or otherwise altered landscapes. Similarly, estuaries already degraded by excess nutrients could recover more slowly from droughts or floods.

Population Distribution across the US

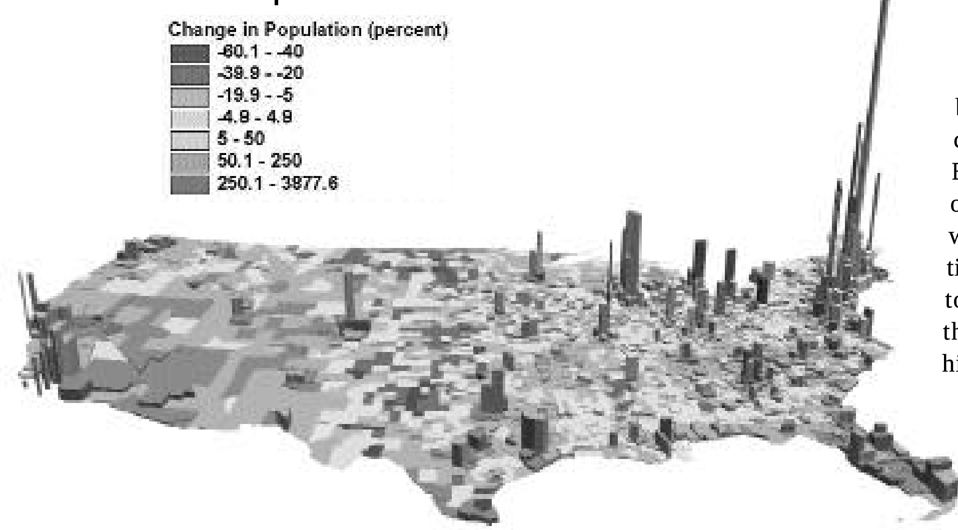

Figure 1: Over the next 25 years, population gains of some 18 million people are projected to occur in the coastal states of Florida, California, Texas, and Washington (NPA, 1999). See color figure appendix.

CONTEXT

The US has over 95,000 miles of coastline and approximately 3.4 million square miles of ocean within its territorial sea,all of which provide a wide range of essential goods and services to society. These include overlapping and often competing uses,including but not limited to tourism,coastal development,commercial and recreational fisheries, aquaculture,biodiversity, marine biotechnology, navigation,and mineral resources.

The coastal population of the US is currently growing faster than the nation's population as a whole, a trend that is projected to continue. Currently some 53% of the total population of the US live in 17% of the land area considered coastal (Culliton,1998). Over the next 25 years,population gains of approximately 18 million people are projected to occur in the coastal states of Florida,California,Texas,and Washington alone (Figure 1) (NPA,1999). With this growth,as well as increased wealth and affluence,there are rapidly increasing demands on coastal and marine resources for both aesthetic enjoyment and economic benefits.

This large and growing population pressure in coastal areas is responsible for many of the current stresses to coastal resources. For example,the EPA (1996) estimated that nearly 40% of the nation's surveyed estuaries were impaired by some form of pollution or habitat degradation. Some 30 to 40% of shellfish-growing waters in the nation's estuaries are harvest prohibited or restricted each year, primarily due to bacterial contamination from urban and agricultural runoff and septic systems (Alexander, 1998). Additionally, over 3,500 beach advisories and beach closings occurred in the United States in 1995,primarily due to storm-water runoff and sewage overflows (NOAA,1998).

Population pressures from further inland can also have detrimental impacts on coastal resources. Effluent discharges as well as agricultural runoff have caused significant nutrient over-enrichment in many coastal areas. Sewage and siltation are significant contributors to coral reef degradation in Hawaii,Florida,and US-affiliated islands of the Pacific and Caribbean. Dams,irrigation projects,and other water management activities have further impacted coastal ecosystems and shorelines by diverting or otherwise altering the timing and flow of water, sediments,and nutrients.

As population and development in coastal areas increase,many of these stresses can be expected to increase as well,further decreasing the resilience of coastal systems. This,in turn,increases the vulnerability of coastal communities and economies which depend upon healthy, functioning ecosystems. The interaction of these ongoing stresses with the expected impacts imposed by future climate change is likely to greatly accentuate the detrimental impacts to coastal ecosystems and communities (Reid and Trexler, 1992,Mathews-Amos and Bernston,1999).

Despite these ongoing stresses to coastal environments,the oceans and coastal margins provide unparalleled economic opportunities and revenues. One estimate suggests that as many as one out of every six jobs in the US is marine-related,and nearly one-third of the gross domestic product (GDP) is produced in coastal areas (NOAA,1998;NRC,1997). In 1996,approximately $590 billion worth of goods passed through US ports, over 40% of the total value of US trade and a much larger percentage by volume. The US is also the world's fifth largest fishing nation and the third largest seafood exporter;total landings of marine stocks have averaged about 4.5 million metric tons over the last decade. Ex-vessel value (the amount that fishermen are paid for their catch) of commercial fisheries alone was estimated at approximately $3.5 billion in 1997,and the total (direct and indirect) economic contribution of recreational and commercial fishing has been estimated at over $40 billion per year (NRC,1999). The growing field of marine biotechnology has also generated substantial opportunities; for example recent research has yielded five drugs originating from marine organisms with a cumulative total potential market value of over $2 billion annually (NOAA, 1998).

Coastal tourism also generates enormous revenues. Travel and tourism are multi-billion dollar industries in the US, representing the second largest employer in the nation (after health care) and employing some 6 million people (NOAA,1998). It has been estimated that the US receives over 45% of the developed world's travel and tourism revenues,and oceans,bays,and beaches are among the most popular tourist destinations in the nation (Houston, 1996). As many as 180 million people visit the coast each year for recreational purposes in all regions of the country, and many regions depend upon tourism as a key economic activity. For example one study estimated that in the San Francisco Bay area alone tourism has been estimated to generate over $4 billion a year (EPA,1997). Clean water, healthy ecosystems,and access to coastal areas are critical to maintaining tourism industries;ironically, however, these industries themselves often pose additional impacts to coastal environments and local communities (Miller and Auyong,1991).

As coastal populations increase,the vulnerability of developed coastal areas to natural hazards is simultaneously expanding. Disaster losses are currently estimated at about $50 billion annually in the US, compared to just under $4.5 billion in 1970. As much as 80% of these disasters were meteorologically related storms,hurricanes,and tornadoes (as opposed to geologically related disasters such as earthquakes and volcanoes) and many of these had their greatest impacts on coastal communities. The potential increase in such events related to climate change will pose an even greater threat to coastal population centers and development in the future. However, the ongoing trends of population growth and development in coastal areas alone will ensure that losses due to hurricanes,storms,and other disasters in coastal areas will continue to increase.

In addition to direct economic benefits,coastal and marine ecosystems,like all ecosystems,have characteristic properties or processes which directly or indirectly benefit human populations. Costanza et al.(1997) have attempted to estimate the economic value of sixteen biomes,or ecosystem types,and seventeen of their key goods and services,including nutrient cycling,disturbance regulation, waste treatment, food production, raw materials, refugia for commercially and recreationally important species, genetic resources,and opportunities for recreational and cultural activities. For example,the societal value per hectare of estuaries,tidal marshes,coral reefs,and coastal oceans were estimated at $22,832, $9,990,$6,075,and $4,052 per hectare, respectively. On a global basis,the authors suggested that these environments were of a disproportionately higher

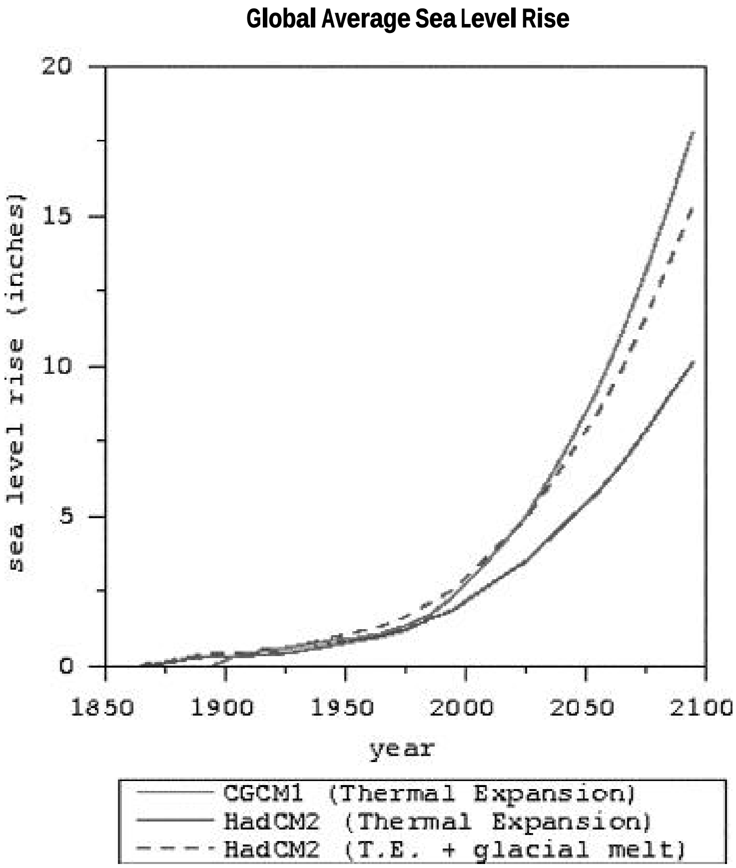

Figure 2 : Projected rise in global average sea level based on the Hadley and Canadian General Circulation Model (GCM) scenarios. See color figure appendix.

value, covering only some 6.3% of the world's surface area but responsible for some 43% of the estimated value of the world's ecosystem services. These results suggest that the oceans and coastal areas contribute the equivalent of some $21 trillion per year to human activities globally (Costanza, 1999). The approach of Costanza et al. (1997) to valuation is not universally accepted, and the authors themselves agree that ecosystem valuation is difficult and fraught with uncertainties. However, the magnitude of their estimates, and the degree to which coastal and marine ecosystems rank as amongst the most valuable to society, serve to place the importance of the services and functions of these ecosystems in an economic context.

CLIMATE AND COASTAL ENVIRONMENTS

Sea-level Change

Global sea levels have been rising since the conclusion of the last ice age approximately 15,000 years ago. During the last 100 years, globally averaged sea level has risen approximately 4 to 8 inches (10-20 cm, or about 1 to 2 millimeters per year). This represents "eustatic" sea-level change, the change in elevation of the Earth's oceans that has been determined from tidal stations around the globe. Most of

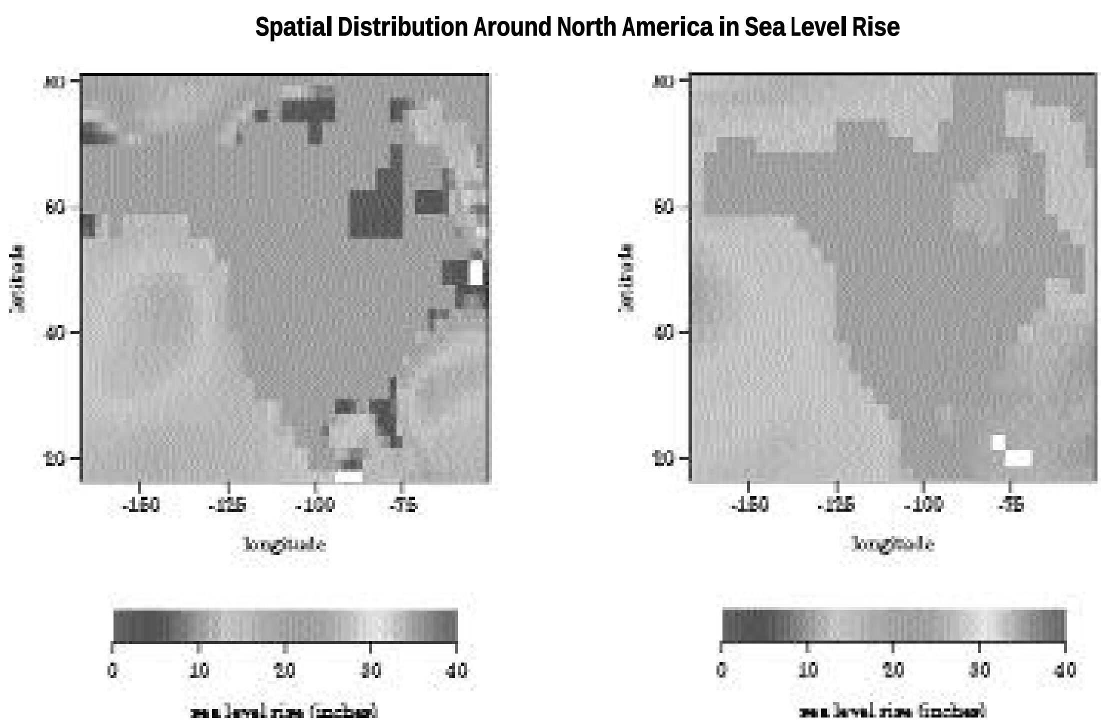

Figure 3 : Projections of the regional pattern of global sea level rise by the year 2100 based on the Canadian (left) and Hadley (right) scenarios. These estimates do not include contributions to sea-level change due to vertical movement of coastal lands. See color figure appendix.

the observed global sea-level change is accounted for by two major variables:the thermal expansion of seawater in the oceans with rising ocean temperatures and changes in the amount of the Earth's water that is locked up in glaciers and ice sheets. The vast majority of landlocked water, enough to raise global sea levels by some 80 meters,is found in the Greenland and Antarctic Ice sheets. Of these, there has been considerable concern regarding the stability of the West Antarctic Ice Sheet (WAIS). Oppenheimer (1998) suggested that the probability of mass wasting (melting) of this ice sheet over the next 100 years is relatively low, but the probability of wasting after 2100 will be considerably greater. Over the next 100 years,most studies predict that the majority of observed sea-level change is expected to come as a result of thermal expansion of the oceans (Gornitz,1995).

In addition to global changes in mean sea level, there are large regional variations in sea level as measured at the shoreline due to changes in coastal land masses such as subsidence (sinking),isostatic (glacial) rebound and tectonic uplift. The combined effects of eustatic and land mass factors contribute to relative sea-level change in each locality. For example,within the US,portions of the Gulf Coast are experiencing a relative sea-level rise of nearly half an inch (approximately 10 mm) per year due to subsidence. Concurrently, some portions of the southeastern Alaska coastline are experiencing uplift associated with tectonic activity, causing a local relative sea-level fall of slightly less than one half inch (approximately 8 mm) per year.

Finally, there are also regional changes in mean sea level that result from dynamic changes to the ocean geoid,or the "topography"of the sea surface. These result from changes in ocean circulation,wind and pressure patterns,and ocean-water density (IPCC, 1996). The result is that sea-level rise will affect various coastal regions differently, independent of the land motion that contributes to sea-level change. Figures 2 and 3 show the results of Hadley and Canadian General Circulation Model (GCM) projections for regional changes in sea level,independent of land movement. In general,the Hadley model predicts a greater sea-level rise for the Pacific coast than for the Atlantic and Gulf coasts as a result of current and wind patterns. By contrast,the Canadian model predicts a more complex pattern of sea-level rise but with increases relatively similar along all US coasts.

The Hadley climate model projects that sea level will rise between 8 and 12 inches (20 to 30 centimeters) by 2100 for the Atlantic and Gulf Coasts, and 13 to 16 inches (33 cm to 41 cm) for the Pacific Coast (Figure 3). The Canadian model projects a significantly greater estimate of 20 to 24 inches (51 cm to 61 cm) along parts of the US coast (Figure 3). These results are very similar to those found by the Intergovernmental Panel on Climate Change (IPCC, 1996),which estimated that sea levels would most likely increase by approximately 19 inches (48 cm) by 2100,with a range of 5 to 37 inches (13 to 95 cm). Most additional studies conducted since then yield similar estimates, generally projecting increases of about one foot above current trends over the 21st century, for a total sea-level rise of approximately 18 to 20 inches (45 to 52 cm) above their current level by the year 2100 (Titus and Narayanan,1996; Wigley, 1999). In addition,sea-level rise will continue to occur, even accelerate,beyond 2100 as a result of the long time frame necessary for oceans and ice sheets to approach equilibrium under the long-term perturbations anticipated with climate change.

Hurricanes and Non-Tropical Storms

Storm flooding, wave forces,and coastal erosion are natural processes that pose hazards only when they affect people,homes,and infrastructure that are concentrated in coastal areas. During the 20th century, loss of life and threats to human health during hurricanes has decreased substantially because of improved tracking and early warning systems;however, property losses have increased greatly (Herbert et al.,1996). Yet even if storm intensity and frequency remain the same in the future,continued acceleration in property losses is likely as the increased concentration of people and infrastructure along the coasts continues. This acceleration in property losses will be amplified should global climate change increase storm activity, although the current relationship between climate change and hurricane frequency and intensity is not clear.

Historical records of hurricanes suggest strong annual to decadal variability. For example,the number of hurricanes occurring per year can vary by a factor of three or more for consecutive years,and during El Niño years,hurricanes are less prevalent in the Atlantic Basin (Pielke and Landsea,1999). Furthermore,during the 25-year period from 1941 to 1965,there were seventeen Category 3 hurricanes landfalling on the US East Coast or peninsular Florida, yet between 1966 and 1990 there were only two (Figure 4). The mid-1990s have seen a recurrence of large numbers of hurricanes in the North Atlantic,perhaps suggesting a return to an active regime,although the long term implications are not yet clear (Landsea et al.,1996). Globally, the historical record shows “no discernible trends in tropical cyclone number, intensity, or location”(Henderson-Sellers et al.,1998). However, regional variability, such as observed in the North Atlantic,can be large.

While interdecadal and interannual variability of hurricane frequency and strength is likely to dominate changes in hurricanes for at least the first half of the next century, increases in hurricane wind strength could result from future elevated sea surface temperatures over the next 50 to 100 years. A recent model investigation shows that increases in hurricane wind strength of 5 to 10% are possible with a sea surface warming of 4˚F (2.2˚C) (Knutson et al., 1998). Other research supports the possibility that tropical cyclones could become more intense (Kerr, 1999). For a moderate hurricane,such an increase in wind strength would translate into approximately a 25% increase in the destructive power of the winds; thus the resulting increase in wave action and storm surge would be greater than the percentage increase in wind speed. Similarly, wave height and storm surge would have a greater percentage increase than wind speed, potentially yielding increased impacts to coasts.

However, it should be noted that recent global climate model investigations have shown that El Niño/Southern Oscillation (ENSO) extremes could become more frequent with increasing greenhouse gas concentrations. For example, work by Timmermann et al. (1999), using a GCM with sufficient resolution,suggests that the tropical Pacific is likely to change to a state similar to present-day El Niño conditions. Since fewer hurricanes occur in the Atlantic during El Niño years,their results suggest that Atlantic hurricanes will likely decrease in frequency in the future. Interestingly, during severe El Niño events such as those in 1982-83 and 1997-98, the jet stream over the North Pacific brought winter storms farther south causing extensive coastal erosion and flooding in California. Hence, a prolonged El Niño state should decrease the occurrence of hurricanes in the Atlantic but lead to an increase in coastal impacts by winter storms on the West Coast. On the other hand, the results of Timmermann et al. (1999) also suggest stronger interannual variability, with relatively strong cold (La Niña) events becoming more frequent. Although these La Niña events would be superimposed upon a higher mean temperature, this could suggest more interannual variability in Atlantic hurricanes with more intense activity during the stronger cold events.

Even if storm magnitudes and frequencies of occurrence remain the same,an important impact of future storms,whether tropical or extratropical,will be their superposition on a rising sea level. This has recently been demonstrated by examining historical storm surge magnitudes calculated from sea-level records (Zhang et al.,1997). These records included surges induced by both winter storms and hurricanes but were dominated by the more frequent winter storms. No significant long term trends were found in storm frequency or severity. When considering that the storms were

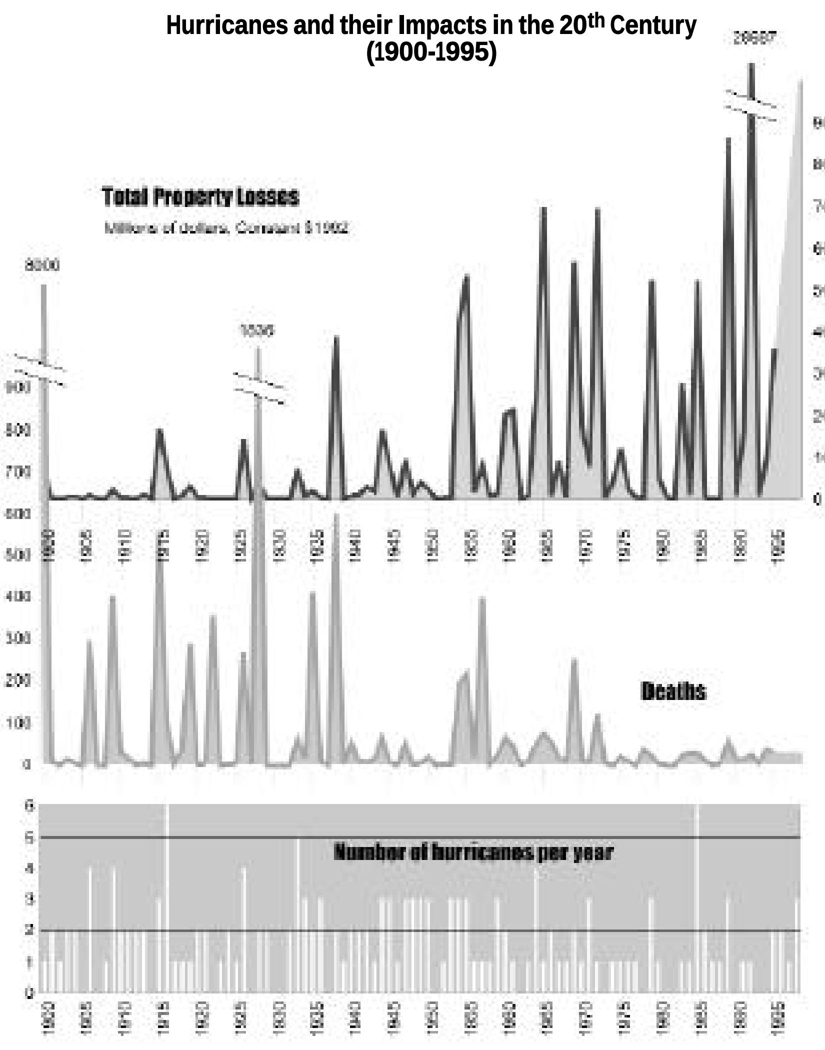

Figure 4: Loss of life and property from hurricanes making landfall in the continental U.S. over the past 20th century Source: National Hurricane Center: NOAA. See color figure appendix.

superimposed on a rising sea level (0.15 inch/year or 3.9 mm/year at Atlantic City),there is an inferred increase in storm impact over an 82-year record. For example,the number of hours of extreme water levels per year increased from less than 200 in the early 1900s to abnormally high values of up to 1200 hours (averaging typically 600 hours) in the 1990s. Thus sea-level rise will increase impacts to the coast by a storm of a given magnitude.

Freshwater Runoff

Hydrological cycles are fundamental components of climate,and climate change is likely to affect both water quality and water availability. In general,the consensus is that the hydrologic cycle will become more intense,with average precipitation increasing, especially at high latitudes. Extreme rainfall conditions,already demonstrated to have increased over the 20th century, are likely to become more common,as could droughts and floods (Karl et al., 1995a;Karl et al.,1995b). Changes in freshwater runoff will result both from climate-related factors and changes in population and land use patterns relating to supply and demand. While the reader is referred to the Water Sector chapter for further discussion of both climatic and human-induced changes in hydrological cycles,the close relationship between precipitation,streamflow, and coastal ecosystems is a topic of special interest to coastal researchers,managers,and planners.

The Canadian and Hadley climate models have been used in concert with hydrology models to estimate the changes in freshwater runoff for three portions of coastline:the Atlantic,the Gulf of Mexico,and the Pacific. In contrast to GCM scenarios of temperature changes under the influence of increased CO_2, the estimates of runoff vary widely. Wolock and McCabe (1999) determined that for some regions the Hadley and Canadian climate models produce opposite results. For the Atlantic coast,the Hadley model projects an increase of more than 60% by the 2090s,whereas the Canadian model projects a runoff decrease of about 80%. The large differences are attributed to the projected increases in precipitation in the Hadley model, versus small changes to significant decreases in precipitation in the Canadian model during the 21st century.

Freshwater runoff affects coastal ecosystems and communities in many ways. The delivery of sediment, nutrients,and contaminants is closely linked to both the strength and timing of freshwater runoff. Salinity gradients are driven by freshwater inputs into estuaries and coastal systems,and have strong effects on biotic distributions,life histories, and geochemistry. Coastal runoff also affects circulation in estuaries and continental shelf areas,and increases in runoff have the potential to increase the vertical stratification and decrease the rate of thermohaline circulation by adding more freshwater to the system.

In the event that increased river flows result from climate change,more suspended sediments could be transported into the coastal regions,increasing the upper layer turbidity and potentially reducing available light to both plankton and submerged aquatic vegetation. Changes in sediment transport could also alter the amount of sediment available for soil aggradation (accumulation) in wetlands and sands for littoral systems. Increased sediment transport will provide needed material for accretion to coastal wetlands threatened by sea-level rise,whereas a decrease in sediment transport will concurrently diminish the ability of some wetlands to respond to sea-level rise.

Increased river flows could also increase the flux of nutrients and contaminants into coastal systems, which influence eutrophication and the accumulation of toxins in marine sediments and living resources. Both increased temperatures and decreased densities in the upper layers might also reduce the vertical convection enough to prevent oxygenation of the bottom waters,further contributing to anoxic conditions in the near-bottom waters (Justić et al.,1996). Decreased freshwater inflows into coastal ecosystems would be likely have the reverse effect, reducing flushing in estuaries, increasing the salinity of brackish waters,and possibly increasing the susceptibility of shellfish to diseases and predators.

Ocean Temperatures

The oceans represent enormous reservoirs of heat; their heat capacity is such that the upper 16 to 33 feet (5 to 10 meters) of the water column generally contain as much heat as the entire column of air above it. The oceans work to distribute heat globally, and atmospheric and oceanic processes work together to control both pelagic and coastal ocean temperatures.

Strong evidence for ocean warming was recently published by Levitus et al.(2000),who evaluated some five million profiles of ocean temperature taken over the last 55 years. Their results indicate that the mean temperature of the oceans between 0 and 300 meters (0 and 984 feet) has increased by

0.31˚C (0.56˚F) over that same period, which corresponds to an increase in heat content of approximately 1 x 10^{23} Joules of energy. Furthermore, the warming signal was observable to depths of some 3000 meters (9843 feet), and the total heat content between 300 and 3000 meters increased by an additional 1 x 10^{23} Joules of energy (see Figure 5). Although Levitus et al.(2000) could not conclude that the signal was primarily one of climate change, as opposed to climate variability, they note that their results are in strong agreement with those projected by many general circulation models. Earlier work done by Cane et al.(1997) also suggest that observed patterns of change in ocean temperature are consistent with warming scenarios.

Understanding how future ocean temperatures will be affected by climate variability and change will depend on improved understanding of the coupling between atmospheric and oceanic processes, and predicting future variations in the forcing functions. The coupling between these processes is regionally or locally controlled, whereas the climate change models are usually more global. As these physical structures and processes, along with their natural modes of variability, have important implications for overall levels of biological productivity in the ocean, an accurate assessment of potential changes in ocean dynamics will necessarily be speculative until GCMs with finer resolution of ocean processes are developed.

Ocean Heat Content in the 0-3000 m Layer

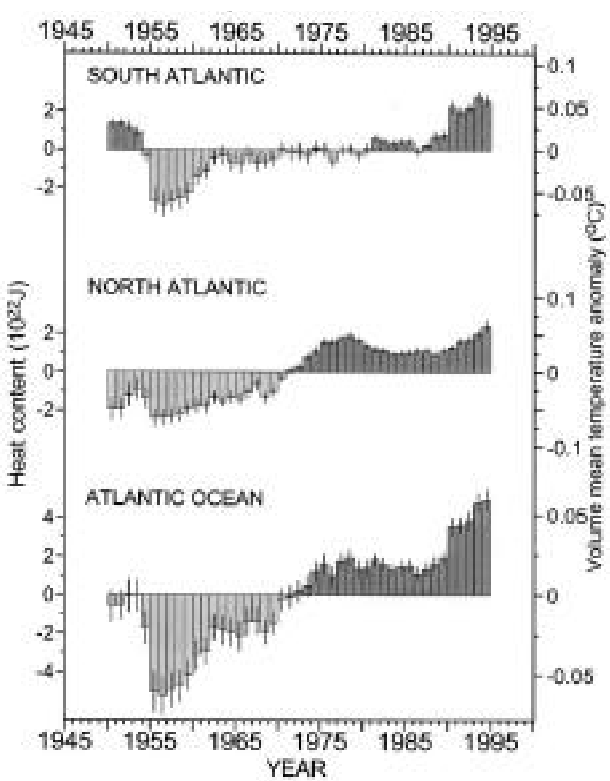

Figure 5: A comprehensive analysis of over 5 million temperature profiles by Levitus, et al. (2000) reveals a pattern of warming in both the surface and the deep ocean over the last 40 years. The largest warming has occurred in the upper 300 meters (984 feet), which have warmed by an average of 0.31°C (0.56°F), with additional warming as deep as 3000 meters (9843 feet). See Color Figure Appendix

The ecosystem responses to increased ocean temperatures can change productivity both directly and indirectly. Ocean temperature changes will affect not only the metabolic rate of organisms but also sea level, currents, movement of larvae, erosion rates, substrate structures, turbidity, water column stratification, nutrient cycling, and subsequently production (McGowan, et al., 1998;Rice,1995). With population changes, community dynamics will change, altering such things as predator-prey relationships. Ocean temperature increases will affect the distribution of marine species, likely with a poleward migration of tropical and lower latitude organisms. The result could be major changes in the composition, function, and productivity of marine ecosystems, including potential impacts to marine biodiversity. For example, observable changes in the distribution and abundance of intertidal species along the California coast have been documented by Sagarin et al. (1999) which are consistent with warming trends. Similarly, large interannual and interdecadal temperature changes in the North Pacific have already been associated with changes in the mixed layer depth over the North Pacific and diminished biological productivity (McGowan et al., 1998).

Increases in temperature will also result in further melting of sea ice in polar and subpolar regions. Recent observations in the Arctic have already shown significant declines in ice extent, which has been shrinking by as much as 7% per decade over the last 20 years (Johannessen et al.,1999) as well as ice thickness, with Arctic sea ice thinning (and subsequently decreasing in volume) by as much as 15% per decade (Rothrock et al.,1999). Additionally, record low levels of ice extent occurred in the Bering and Chukchi seas during 1998, the warmest year on record (Maslanik et al.,1999). While a possible mechanism could be related to the Arctic Oscillation, a decadal scale mode of atmospheric variability in the Arctic, some comparisons with GCM outputs strongly suggest that these observed declines in sea ice are related to anthropogenically induced global warming (Vinnikov et al.,1999). The reduction and potential loss of sea ice has enormous feedback implications for the climate system as well;ice and snow are highly reflective surfaces that reflect the vast majority of the Sun's incoming radiative heat back to outer space. By contrast, open oceans reflect only 10 to 20% of the Sun's energy. Thus,the conversion of the Arctic ice cap to open ocean could greatly increase solar energy absorption,and act as a positive feedback to global warming.

Ocean Currents

Major ocean current systems play a significant role in the dispersal of marine organisms and in the production characteristics of marine systems. These current systems are likely to be affected in critical ways by changes in global and local temperatures, precipitation and runoff, and wind fields. Similarly, oceanic features such as fronts and upwelling and downwelling zones will be strongly influenced by variations in temperature,salinity, and winds. These changes will be manifest on scales ranging from the relatively small spatial and temporal scales characteristic of turbulent mixing processes to very large scales characteristic of the deep water "conveyor belt"circulation,with potentially dramatic feedback influences on climate patterns. Changes occurring on this spectrum of spatial and temporal scales have important implications for overall levels of biological productivity in the ocean,and are critical to understanding the implications of global climate change on living marine resources.

The Global Ocean Conveyor Belt

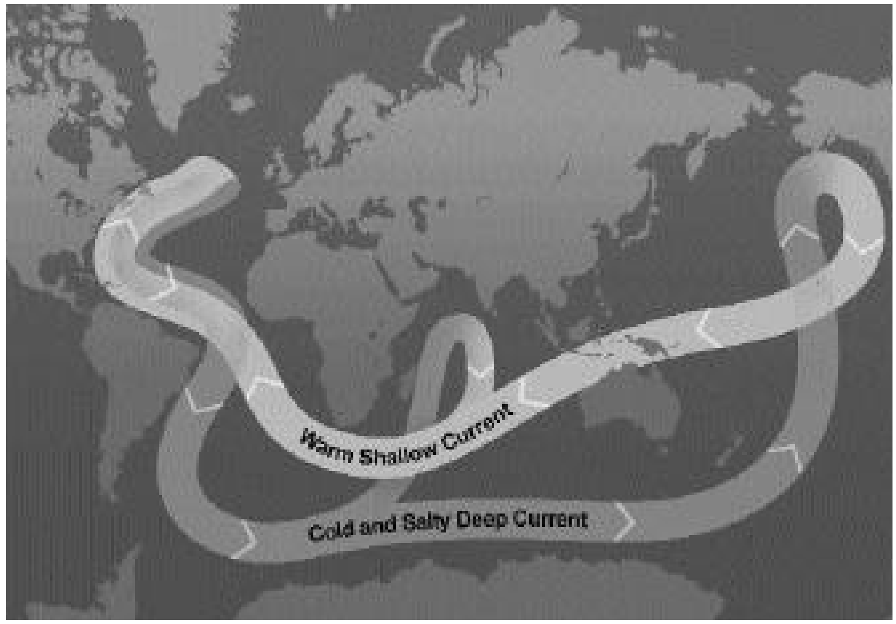

Figure 6: The ocean plays a major role in the distribution of the planet's heat through deep sea circulation. This simplified illustration shows this "conveyor belt" circulation which is driven by differences in heat and salinity. Records of past climate suggest that there is some chance that this circulation could be altered by the changes projected in many climate models, with impacts to climate throughout lands bordering the North Atlantic (Modified from Broecker, 1991).See color figure appendix.

Research suggests that the processes of formation and circulation of deep-water through the so-called conveyor-belt circulation (see Figure 6) could be strongly influenced by changes in temperature and salinity, with significant implications for the North Atlantic region and global ocean circulation (Broecker et al.,1999;Taylor 1999). Generally warm,saline surface waters are transported northwards by the Gulf Stream,ultimately feeding the Norwegian,East Greenland,and West Greenland currents. Here winter air-sea interactions cool the already highly saline water masses, resulting in a rapid increase in density. This rapid increase in density drives convection,in which the heavier, denser water sinks and flows away from the polar regions to fill the deep ocean basins,driving deep sea thermohaline circulation.

Increased temperature or decreased salinity (resulting from changes in precipitation patterns or melting ice sheets) at high latitudes could result in a reduction in the deep-water formation by decreasing the density of surface waters,with important consequences for this convective system (Schmittner and Stocker, 1999;Broecker, 1997). Hadley Centre models have suggested a decline in the strength of deep-water circulation of approximately 25% under some scenarios (Wood et al., 1999). Such a decline could lead to a general cooling throughout the North Atlantic region, resulting from a reduction in transport of warmer waters from lower latitudes (Driscoll and Haug,1998). Additionally, a complete cessation of the conveyor belt circulation is possible,which could cause winter temperatures throughout the North Atlantic to fall abruptly by as much as 9˚F (5˚C). Sedimentary records in the northern Atlantic suggest that past circulation shutdowns have occurred in extremely short time intervals,associated with abrupt climate shifts and dramatic cooling in Europe. Ironically, the result would likely be further acceleration of global warming trends as a result of a decrease in the oceanic uptake of carbon dioxide that would follow weakening or cessation of thermohaline circulation (Sarmiento and Le Quere,1996).

KEY ISSUES

1. Shoreline Systems,Erosion,and Developed Coastal Areas
2. Threats to Estuarine Health
3. Coastal Wetland Survival
4. Coral Reef Die-offs
5. Stresses on Ocean Margins and Marine Fisheries

Coastal and marine resources are uniquely influenced by the long-term climate dynamics described above. For the purposes of this Assessment,the potential impacts on five principal ecosystem types were evaluated:shorelines,estuaries,coastal wetlands,coral reefs,and ocean margins/marine fisheries. While there is significant overlap between some of these ecosystem types,and also further divisions that could be made within these ecosystems, this breakdown provides a methodology for understanding what may be the most significant generic impacts on ecological systems. These are consequences which are either ongoing or could be reasonably expected on the basis of past climate variability, forcing scenarios,and change thresholds. In addition,individual case studies were conducted in order to provide specific examples of the complex set of interactions between the effects of climate and human activities; results from several of these case studies have been incorporated here.

1. Shoreline Systems, Erosion, and Developed Coastal Areas

Storms,hurricanes,typhoons,and similarly extreme atmospheric phenomena along coasts produce high winds that in turn generate large waves and currents. Storms and hurricanes produce storm surges that temporarily raise water levels by as much as 23 feet (7 meters) above normal. Although these events are sporadic,they are a primary cause of beach erosion and shoreline impacts throughout the US. Hurricanes account for far more insured losses of property than do other hazards such as earthquakes and wildfires. Sea-level rise increases the vulnerability of shorelines and floodplains to storm damage by increasing the baseline water level for extreme storms and coastal flooding events. In addition to storm and flooding damages,specific impacts associated with sea-level rise could include increased salinity of estuaries and freshwater aquifers,altered tidal ranges in rivers and bays, changes in sediment and nutrient transport which drive beach processes,and the inundation of waste disposal sites and landfills which could reintroduce toxic materials into coastal ecosystems.

Individual hurricanes have resulted in enormous economic impacts,particularly to the Southeast. Hurricane Hugo in 1989 caused an estimated $9 billion in damages;Hurricane Andrew in 1992 caused an estimated $27 billion in damages;and Hurricane Georges in 1998 caused an estimated $5.9 billion in damages (Source:National Climatic Data Center). However, hurricanes are not the only storm threat to coastal inhabitants and property owners. Extratropical winter storms have significant impacts as well,such as the Halloween “nor’easter”of 1991 which caused damages amounting to over $1.5 billion along the Atlantic Coast. Along the Pacific Coast, extratropical storms battered California causing an estimated $500 million in damage during the 1997-98 El Niño (Griggs and Brown,1999). As coastal population and property construction increases,the economic vulnerability of human developments in coastal areas to hurricane and storm activity will continue to rise,and will be aggravated by any climate-induced changes in the frequencies or intensities of these events.

Coastal erosion is already a widespread problem throughout much of the country (Figure 7),and has significant impacts to both undeveloped shorelines and coastal development and infrastructure. In addition to storms and extreme events,interannual modes of variability such as ENSO have been shown to impact many shorelines. For example,along the Pacific Coast,cycles of beach and cliff erosion have been linked to El Niño events,which elevate average sea levels over the short term and alter the frequency, intensity, and direction of storms impacting the coastline. During the 1982-83 and the 1997-98 El Niños,impacts were especially severe along shorelines throughout California,Oregon,and Washington (Komar, 1999;Kaminsky et al.,1999). Good (1994) has shown that along the central Oregon coast,a rapid buildup of seawalls and revetments routinely followed major El Niño events of the last two decades,as coastal property owners attempted to protect their shorelines from increasing erosion.

Atlantic and Gulf coastlines are especially vulnerable to sea-level rise, as well as to changes in the frequency and severity of storms and hurricanes. Most of the East and Gulf coasts are rimmed by a series of barrier island and bay systems which separate the gently sloping mainland coastal plains from the continental shelf. These islands bear the brunt of forces from winter storms and hurricanes,protecting the mainland from wave action. However, these islands and coastlines are not stable but are instead highly dynamic systems that are highly sensitive and respon-

Figure 7: A general classification scheme of shoreline erosion rates throughout the US. (modified from Dolan et al., 1985). See Color Figure Appendix

sive to the rate of relative sea-level rise as well as the frequency and severity of storms and hurricanes.

In response to rising sea levels,these islands typically "roll over" towards the mainland,through a process of beach erosion on their seaward flank and overwash of sediment across the island. Human activities block this natural landward migration through the construction of buildings, roads,and seawalls;as a result,shorelines erode,increasing the threat to coastal development and infrastructure. Subsequent impacts include the destruction of property, loss of transportation infrastructure,increased coastal flooding,negative effects on tourism,saltwater intrusion into freshwater aquifers,and impacts to fisheries and biodiversity. Such impacts will unquestionably further modify the functioning of barrier islands and inland waters that have already been impacted by pollution,physical modification, sediment starvation by dams,and material inputs related to human activities.

Barrier islands are certainly not the only coastlines at risk. Private property on mainland and estuarine shorelines, harbor installations, other water-dependent activities and infrastructure,transportation infrastructure, recreational areas, and agricultural areas are all particularly vulnerable to inundation and increased erosion as a result of climate change, especially in low-lying areas. Assessing the total economic impacts from sea-level rise on coastal areas and on a national scale is still somewhat speculative. Nevertheless, a study by Yohe et al. (1996) quantified the economic costs (protection plus abandonment) to coastal structures with a one meter sea-level rise. This analysis estimated costs of as much as $6 billion (in 1990 dollars) between 1996 and 2100. However, this number represents market-valued estimates only, which are derived from property-value appreciation,market adaptation, and protection costs. As such, this is a minimum cost estimate, as it does not include the lost ecosystem services value of non-market resources, such estuaries and tidal wetlands, or the costs to communities resulting from reductions in coastal economic activities such as fishing,tourism,and recreation. A comprehensive review of the potential cost of sea-level rise to developed coastlines was recently completed by Neumann et al. (2000); and should be referred to for a wider range of estimates of the potential economic consequences of sea-level rise to developed areas.

Many coastal structures were designed with the 100- year flood as their basis. This flooding level determines the elevations to which the federal projects are built,such as the Army Corps of Engineers

South Florida Case Study

The natural South Florida ecosystem was largely defined by a high degree of variability in rainfall both within and across years. The region originally supported a mosaic of multiple interactions among many different ecosystem types,including freshwater, wetland,mangrove,estuarine,and coral habitats all intimately coupled by the regional hydrology. All of these ecosystems now severely impacted by a large and very rapidly growing human population perched along a very narrow strip of coastal land. Tourism in South Florida is a multibillion-dollar-a-year industry, and the existence of the Everglades,Biscayne National Park and the Florida Keys National Marine Sanctuary illustrate the high value society places on this unique environment.

The South Florida region is vulnerable to multiple climate change stresses,as sea-level rise, changes in the frequency of freezing events,hurricanes,droughts and associated fires,sea surface temperatures and many others all affect the full diversity of ecosystems. The responses of all of these ecosystems will be significantly modified or constrained by human development. In particular, South Florida has developed one of the world's largest water management systems with the primary objectives of dampening hydrological variability, providing flood protection,and supplying water to urban and agricultural systems (Harwell,1998;US COE 1994). This alteration of hydrological functions has caused serious degradation to the ecosystems,which were formerly adapted to natural modes of variability but have been made more vulnerable as a result of human disturbance and development.

Any significant change to the precipitation regime could have major consequences to coastal ecosystems; already the Everglades and associated systems are not considered sustainable due to regional hydrologic alterations. While a massive and costly restructuring of the water management system is currently underway, a reduced precipitation regime could further increase multi-year droughts,increase fire frequency and intensity, reduce water supply to urban users,and increase estuarine hypersalinity. Thus, global climate change can be expected to exacerbate the effects of natural and anthropogenic stresses on South Florida,making the current challenge of restoring and sustaining its ecosystems even greater.

levees that protect New Orleans. It is also the level to which coastal structures must be built to qualify for flood insurance through the Federal Emergency Management Agency's (FEMA) Flood Insurance Program. If sea level rises,the statistics used to design these structures change. For example,what was once considered a 50-year flood could become as severe as a 100-year flood following an increase in sea level (Pugh and Maul,1999). Coastal insurance rates would have to be adjusted to reflect the change in risk. Furthermore,FEMA has estimated that the number of households in the coastal floodplain could increase from 2.7 million currently to some 6.6 million by the year 2100,as a result of the combination of sea-level rise and rapidly growing coastal populations and development (FEMA,1991). Again,it is clear that the vulnerability of coastal developed areas to natural disasters can be expected to rise throughout the 21st century, even independent of climate-induced changes in risk.

2. Threats to Estuarine Health

Estuaries are among the most productive coastal ecosystems, critical to the health of a great many commercial and recreational fisheries, and are affected in numerous ways by climate variability and change. Warmer spring and fall temperatures will alter the timing of seasonal temperature transitions, which affect a number of ecologically important processes and will thus impact fisheries and marine populations. As referenced above in the section on freshwater forcing, the amount and timing of freshwater flow into estuaries greatly influence salinity, stratification, circulation, sediment, and nutrient inputs. Thus, increases in winter-spring discharges in particular could deliver more excess nutrients as well as contaminants to estuaries, while simultaneously increasing the density stratification. Both of these would increase the potential for algal blooms (including potentially harmful species) and the development of hypoxic (low oxygen) conditions, which could in turn increase stresses on sea grasses and affect commercial fishing and shellfish harvesting.

Currently, nutrient over-enrichment is one of the greatest threats to estuaries in the US,with over half the nation's estuaries having at least some of the symptoms of moderate to high states of eutrophication (Bricker et al.,1999). Eutrophication has multiple impacts to estuaries,as well as other coastal ecosystems,including more frequent and longer lasting harmful algal blooms,degradation of seagrass beds and coral reefs,alteration of ecological structure,decreased biological diversity, and the loss of fishery resources resulting from low oxygen events. In this instance, climate change is only one aspect of human-accelerated global environmental change, and particularly for estuaries,the broader effects of global change have to be considered. Specifically, human activities have altered the biological availability of nitrogen through the production of inorganic fertilizer, the combustion of fossil fuel,and the management of nitrogen-fixing agricultural crops. As a result,since the 1960s the world has changed from one in which natural nitrogen fixation was the dominant process to a situation in which human-controlled processes are at least as important in making nitrogen available on land.

This increased availability has led to an increase in the delivery of nitrogen to coastal marine systems, particularly estuaries (Vitousek et al.,1997). The delivery of nutrients has been closely linked to variability in streamflow; for example,in the Gulf of Mexico,increases in freshwater delivery from the Mississippi River are closely linked with increases in nutrient delivery and the subsequent development of hypoxia. The spring floods of 1993 resulted in the greatest nitrogen delivery ever recorded in the Gulf of Mexico (Rabalais et al.,1999),and the areal extent of the resulting hypoxic zone was twice as large as the average for the preceding eight years. However, the response of individual estuaries to changes in freshwater and nutrient delivery will differ significantly as related to variation in water residence times,stratification,and the timing and magnitude of inputs. Yet because the solubility of oxygen in warmer waters is lower than in cooler waters,any additional warming of estuaries during summer months would be likely to aggravate the problems of hypoxia and anoxia that already plague many estuaries.

With few exceptions,the potential consequences of climate change to estuarine ecosystems are not yet being considered in long-term estuarine and coastal zone management. In the Mid-Atlantic,estuaries are already in a degraded environmental condition,but are currently the subject of substantial societal commitments for their restoration through pollution reduction,habitat rehabilitation,and more sustainable use of living resources. An increase in winter-spring precipitation that delivers additional nutrients to estuaries such as the Chesapeake Bay would make achieving the management goals of reducing nutrient inputs and improving dissolved oxygen levels more difficult. More efficient nutrient management practices and more extensive restoration of riparian zones and wetlands would be required to meet current nutrient goals in seasonally wetter watersheds. However, it should be recognized that climate change is expected to bring about alterations to many estuaries for which mitigating responses may not exist.

3. Coastal Wetland Survival

Coastal wetlands are some of the most valuable ecosystems in the nation as well as some of the most threatened. By providing habitat, refuge, and forage opportunities for fishes and invertebrates,marshes and mangroves around the coastal US are the basis of many communities' economic livelihoods (Costanza et al., 1997;Mitsch and Gosslink, 1993). The role of wetlands in nutrient uptake,improving water quality, and reducing nutrient loads to the coastal ocean is widely recognized, as is their value in providing recreational opportunities and protecting local communities from flooding — either by dampening storm surges from the ocean or providing storage for river floodwaters. Climate variability and change compound existing stresses from human activities (Markham,1996),such as dredging and/or filling for development,navigation or mineral extraction,altered salinity and water quality, and the direct pressures of increasing numbers of people living and recreating in close proximity.

These ecosystems are sensitive to a number of climate related variables. Changes in atmospheric temperatures and carbon dioxide concentrations generally result in increased plant production, although the response varies considerably among species. Increases in freshwater discharge would generally benefit many coastal wetlands,and decreases might result in salinity stress for some communities,particularly in the western Gulf of Mexico where already limited freshwater inputs are expected to decrease dramatically. For coastal wetlands facing current or future relative sea-level rise, increased sediment delivery will be necessary for vertical accumulation of the substrate.

Coastal wetlands can cope with changes in sea level when they are capable of remaining at the same elevation relative to the tidal range,which can occur if sediment buildup equals the rate of relative sea-level rise or if the wetland is able to migrate. Migration occurs when the wetland moves upslope along with the tidal range,with the seaward edge of the wetland drowning or eroding and the landward edge invading adjacent upslope communities

(Figure 8). However, if wetlands are unable to keep pace with relative sea-level change, or if their migration is blocked by bluffs, coastal development, or shoreline protection structures, then the wetland will become immersed and eventually lost as rising seas submerge the remaining habitat.

Currently, many US coastlines are areas of coastal subsidence where both natural and human-induced processes strongly influence wetlands. Coastal Louisiana has experienced the greatest wetland loss in the nation, where a combination of anthropogenic (human-caused) and natural factors have driven losses between 24 and 40 square miles per year during the last 40 years. As approximately 25% of the nation's brackish and freshwater coastal wetlands are found in Louisiana, this constitutes as much as 80% of the total loss of these wetlands in the US (Boesch et al., 1994). Changes have occurred so rapidly in the many bald cypress forests near New Orleans that they have been converted directly to open water rather than being gradually overtaken by salt marsh. Once lost to open water, these wetlands become extremely difficult to restore. The remaining 3.5 million acres of wetlands in South Louisiana provide critical nursery areas for finfishes and crustaceans, particularly shrimp and crabs, which make up the bulk of the state's multimillion dollar seafood industry. Additionally, these coastal wetlands serve as important buffers against storm surges, protecting inland residential and commercial infrastructure from severe flooding. Thus, if climate change exacerbates the current rate of sea-level rise, those regions of coastal Louisiana where marshes are on the margin of survival will suffer, and even more extensive land loss will result.

Processes Affecting Wetland Migration

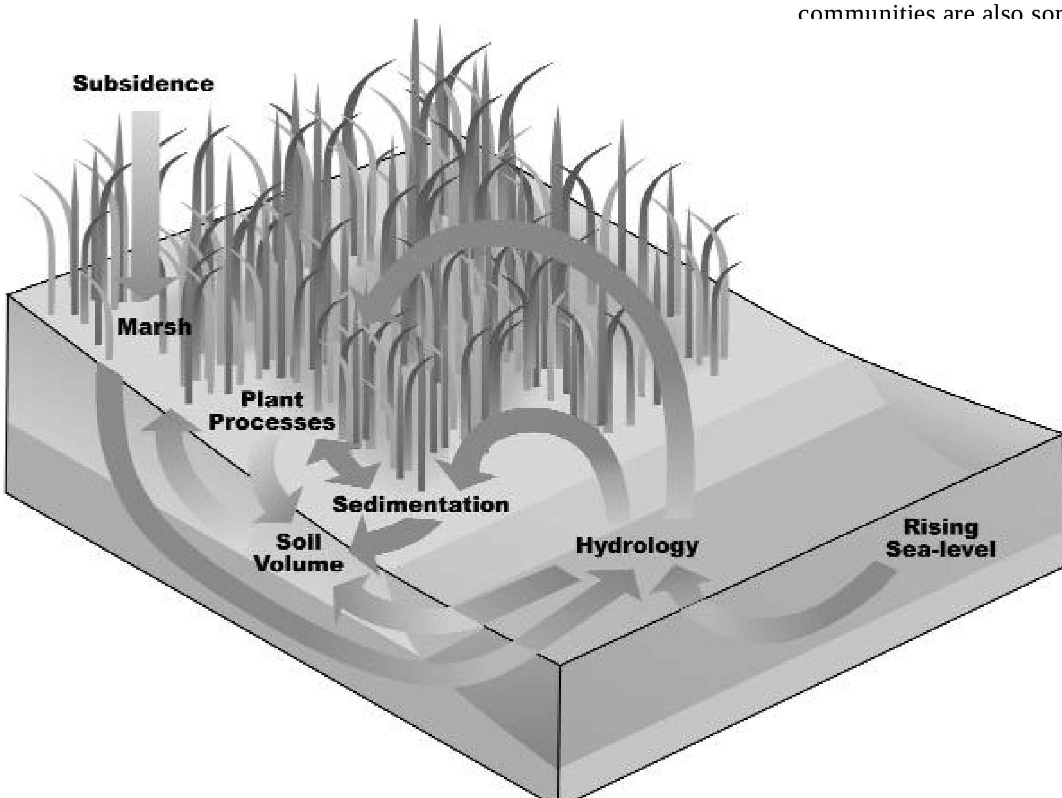

Figure 8: The rate of sea-level rise is projected to accelerate 2 to 5 fold over the next 100 years. The delivery of sediments to coastal wetlands is extremely important in determining the potential of these systems to maintain themselves in the face of current and future sea-level changes (based on Reed, 1995). See Color Figure Appendix

4. Coral Reef Die-Offs

Although coral reefs might seem exotic to many residents of the US, these ecosystems play a major role in the environment and economies of two states (Florida and Hawaii) as well as most US territories in both the Caribbean and the Pacific. Coral reefs are valuable, if often over-utilized, economic resources for many tropical coastal regions, providing numerous fisheries opportunities, recreation, tourism, and coastal protection (Wilkinson and Buddemeier, 1994). It is widely recognized that reefs and related communities are also some of the largest storehous-

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Coral bleaching, which occurs when symbiotic algae that live in the corals themselves are expelled from their hosts due to high sea surface temperatures, has been occurring with increasing frequency in the last several decades, notably during El Niño events. The 1998 El

Niño in particular was associated with unprecedented high sea surface temperatures and thus the most widespread coral bleaching ever observed (Strong et al.,2000;Wilkinson et.al.,1999;Hoegh-Guldberg, 1999). In many past bleaching events,both the algae and the corals are capable of recovery;however, warming events in 1998 resulted in unusually high levels of mortality from which many reefs have yet to recover. In addition to bleaching effects, there has been an upsurge in the variety, incidence, and virulence of coral diseases in recent years,with major die-offs reported,particularly in Florida and the Caribbean region. The causes of these epizootics are not known,but they suggest that coral ecosystems and organisms are weakened and vulnerable.

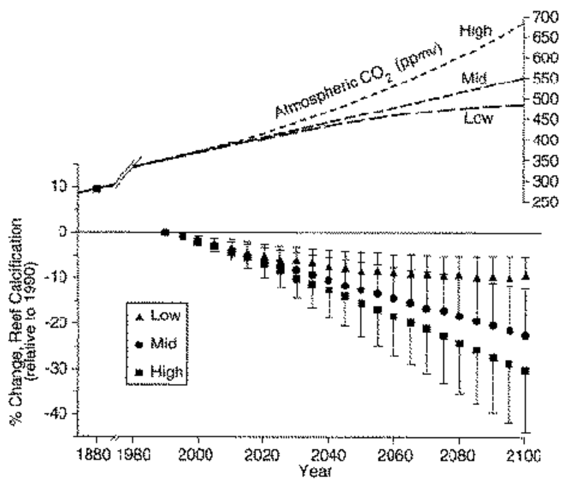
One of the most significant unanticipated direct consequences of increased atmospheric carbon dioxide concentration is the reduction of carbonate ion concentrations in seawater. Carbon dioxide acts as an acid when dissolved in seawater, causing seawater to be less alkaline. A drop in alkalinity subsequently decreases the amount of calcium carbonate (aragonite) which can be dissolved in seawater, which in turn decreases the calcification rates of reef-building corals and coraline algae (Figure 9) (Kleypas et al.,1999a;Gattuso,1999). The impacts on coral reefs are weaker skeletons, reduced growth rates,and an increased vulnerability to erosion,with a wide range of impacts on coral reef health and community function. Additionally, the effects of increasing atmospheric carbon dioxide on the concentration of carbonate ions is greatest at the margins of coral distributions,due to the fact that carbon dioxide is more soluble in cooler waters. Thus, these effects will be most severe at high latitudes,so coral reefs at the margins of their distribution are not expected to expand their ranges as might otherwise be predicted by some ocean warming scenarios (Figure 10).

Human-induced disturbances have already taken a significant toll on coral reef systems,from activities such as over-fishing,the use of destructive fishing techniques, recreational activities,ship groundings, anchor damage,sedimentation,pollution,and eutrophication. Thus,the future for many coral reefs appears bleak. The synergy of stresses and the response time scales involved to restore reefs make integrated management essential but difficult. Given trends already in motion,some of the more marginal reef systems will almost certainly continue to deteriorate,making allocation of resources an important policy issue. The demise or continued deterioration of reef communities will have profound social and economic implications for the US,as well as serious political and economic implications for the world.

5. Stresses on Ocean Margins and Marine Fisheries

Projected changes in the marine environment have important implications for marine populations and fisheries resources. In addition to their economic value,marine fisheries hold a special social and cultural significance in many coastal communities. However, over-fishing and habitat loss have already taken serious tolls on the nation's fisheries and the communities that depend upon them. Currently some 33% of the stocks for which trends are known are either over-fished or depleted (NMFS,1998),and for the vast majority of stocks,an accurate assessment of their status is unknown. The possible effects of climate change range from shifts in distribution to

Effects of CO_2 on Coral



Bleached coral.

Figures 9: Increasing levels of atmospheric CO_2 are projected to decrease carbonate ion concentrations in seawater, which will decrease the calcification rates of many coral building species and impact coral reef health (Gattuso et al., 1999).

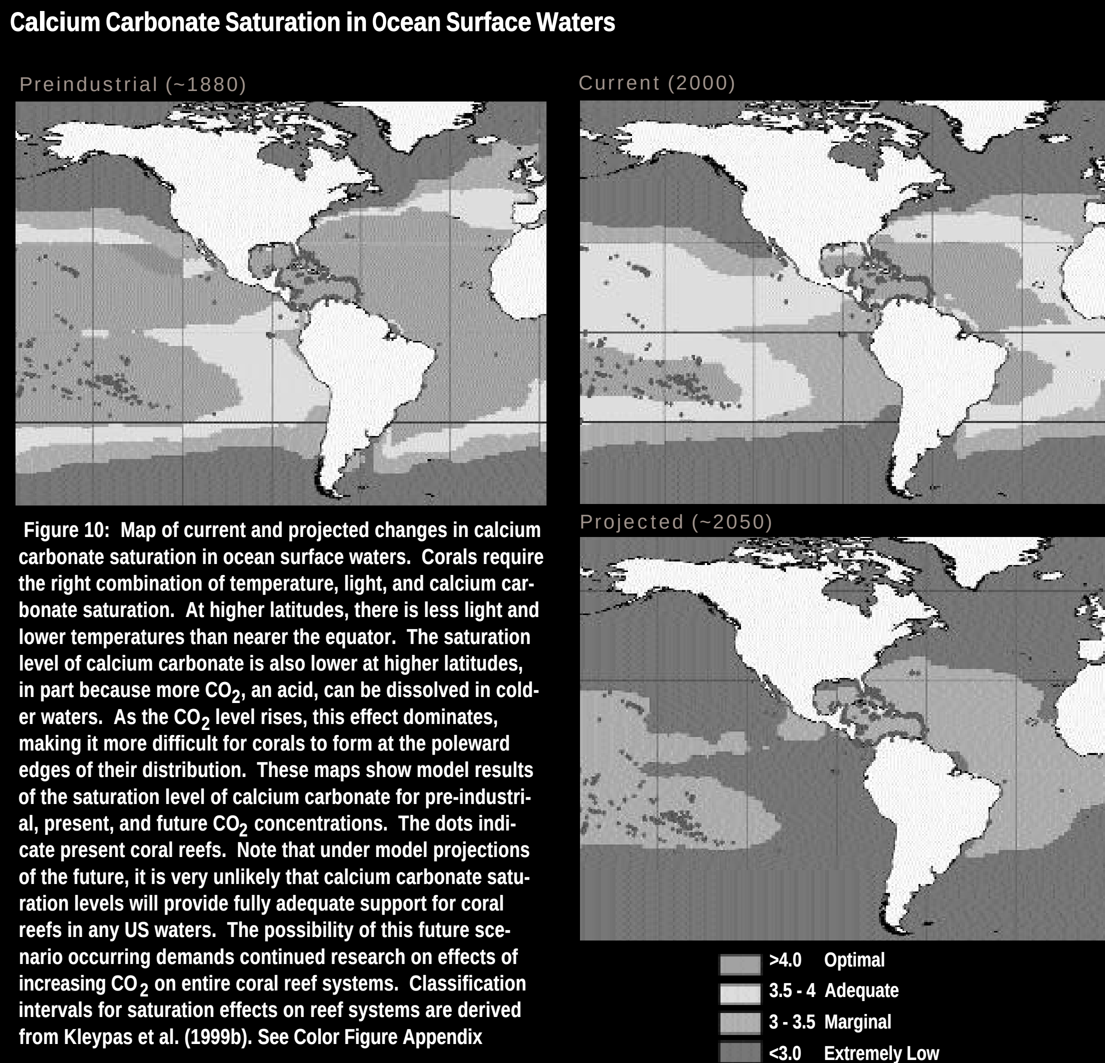


Figure 10: Map of current and projected changes in calcium carbonate saturation in ocean surface waters. Corals require the right combination of temperature, light, and calcium carbonate saturation. At higher latitudes, there is less light and lower temperatures than nearer the equator. The saturation level of calcium carbonate is also lower at higher latitudes, in part because more CO_2, an acid, can be dissolved in colder waters. As the CO_2 level rises, this effect dominates, making it more difficult for corals to form at the poleward edges of their distribution. These maps show model results of the saturation level of calcium carbonate for pre-industrial, present, and future CO_2 concentrations. The dots indicate present coral reefs. Note that under model projections of the future, it is very unlikely that calcium carbonate saturation levels will provide fully adequate support for coral reefs in any US waters. The possibility of this future scenario occurring demands continued research on effects of increasing CO_2 on entire coral reef systems. Classification intervals for saturation effects on reef systems are derived from Kleypas et al. (1999b). See Color Figure Appendix

changes in survival and growth rates,with direct implications for fishery yields.

Changes in climate forcing will have important effects in ocean margin ecosystems through expected changes in the distribution and abundance of marine organisms and in fundamental changes in the production characteristics of these systems. Changes in temperature,precipitation,wind fields, and sea level can all be expected to affect oceanographic conditions in the ocean margins with direct ramifications for marine life in these areas. Physiological effects of temperature and salinity changes can also be expected with potentially important consequences for growth and mortality of marine species (Jobling,1996). Impacts to marine ecosystems and fisheries associated with El Niño events illustrate the extent to which climate and fisheries can interact. For example,the high sea surface temperatures and anomalous conditions associated with the 1997-98 El Niño had a tremendous impact on marine resources off of California and the Pacific Northwest. Landings of market squid,California's largest fishery by volume and second largest in value, fell from over 110,000 metric tons in the 1996-97 season to less than 1000 metric tons during the 1997-98 El Niño season (Kronman, 1999). Amongst the many other events associated with this El Niño were high sea lion pup mortalities in California (Wong,1997),poor reproductive success in seabirds off of Oregon and Washington,and unexpected catches of warm-water marlin off of the Washington coast (Holt,1997). Even further north were rare coccolithophore blooms,massive seabird die-offs along the Aleutian Islands,and poor salmon returns in Alaska's Bristol Bay sockeye salmon fishery (Macklin,1999).

Climate change is likely to cause even greater impacts to marine populations. Poleward shifts in distribution of marine populations can be expected with increasing water temperatures (Murowski, 1993). Species at the southern extent of their range along the East Coast can be expected to shift their distribution to the north with important overall consequences for ecosystem structure. Cod,American plaice,haddock,Atlantic halibut, redfish,and yellowtail flounder all would be expected to experience some poleward displacement from their southerly limits in the Gulf of Maine and off New England under increasing water temperatures (Frank et al., 1990). Thus,the loss of populations or sub-populations due to shifts in temperature under these constraints is likely, with regional impacts to communities that depend on local populations. An expansion of species commonly occurring in the middle Atlantic region,such as butterfish and menhaden, into the Gulf of Maine could also be expected.

In the Pacific, Welch et al.(1998) suggest that projected changes in water temperatures in the North Pacific could possibly result in a reduction of suitable thermal habitat for sockeye salmon. The most surprising prediction is that under scenarios of

Understanding Global Climate and Marine Productivity

The US Global Ocean Ecosystems Dynamics (US GLOBEC) research program is operated in collaboration between the NOAA/National Ocean Service (NOS) Coastal Ocean Program and the NSF Biological Oceanography Program. GLOBEC is designed to address the questions of how global climate change may affect the abundance and production of marine animals. Two large marine regions have been the subjects of intensive research,the Northwest Atlantic and the Northeast Pacific. In the Atlantic program,the overall goal is to improve the predictability and management of the living marine resources of the region. This is being done through improved understanding of ecosystem interactions and the coupling between climate change, the ocean's physical environment and the ecosystem components (Figure 11). Particularly crucial physical drivers are the North Atlantic Oscillation and the salinity variations derived from flows from the Labrador Sea. A major objective of this program is to apply the understanding of the physical processes that affect the distribution, abundance and production of target species. This information will be used in the identification of critical variables that will support ecosystem-based forecasts and indicators as a prelude to the implementation of a long-term ecosystem monitoring strategy.

Remarkable changes have been observed in recent decades in the Northeast Pacific. Concurrent changes in atmospheric pressure and ocean temperatures indicate that in 1976 and 1977 the North Pacific shifted from one climate state or regime to another that persisted through the 1980s. Analysis of records of North Pacific sea surface temperature and atmospheric conditions show a pattern of such regime shifts lasting several years to decades. Although the important linkages are poorly understood,there is growing evidence that biological productivity in the North Pacific responds quite strongly to these decadal-scale shifts in atmospheric and oceanic conditions by alternating between periods of high and low productivity. Some of the key issues being addressed in this region concern the evaluation of life history patterns,distributions, growth rates,and population dynamics of higher trophic level species and their direct and indirect responses to climate variability. Additionally, the program seeks to better understand complex ecosystem interactions,such as how the North Pacific ecosystem is structured and whether higher trophic levels respond to climate variability solely as a consequence of bottom-up forcing.

Climatic Pathways Affecting the Abiotic Environment and Biological Processes

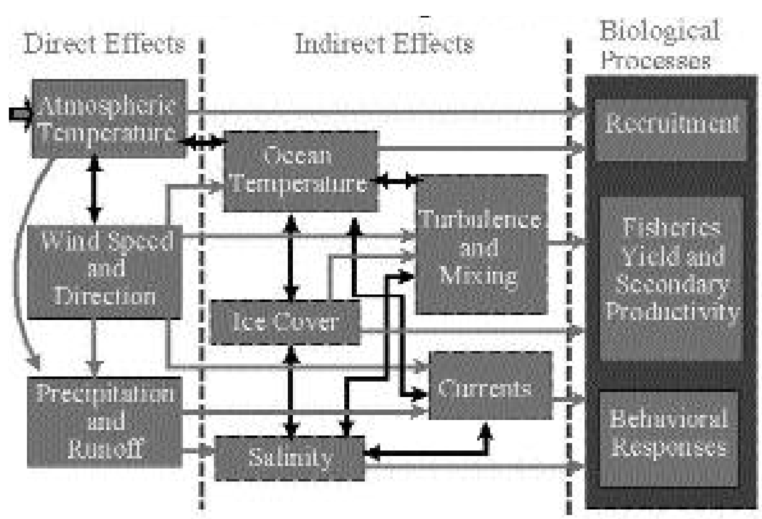


Figure 11: Biological processes in the ocean are related to climate in many ways, both directly and indirectly. Improvements in our understanding of the direct and indirect effects of climate on biological processes in the oceans are essential to predicting how marine populations might respond to future change Source: US GLOBEC.

future climate,none of the Pacific Ocean is projected to lie within the thermal limits that have defined the distribution of sockeye salmon over the last 40 years. Under such scenarios,the distribution of all species of salmonids could be restricted to marginal seas in the North Pacific region (see also the Pacific Northwest chapter and Mantua et al.1997 for more information on interactions between salmon and climate variability). Conversely, higher sea surface temperatures will be beneficial for other species.

For example, changes in the abundance of sardine and anchovy populations appear to be strongly linked to global climate shifts (Lluch-Belda et al., 1992). The California sardine population was recently declared “recovered,” decades after its near disappearance from Pacific waters. The recovery has in part been related to an increase in sea surface temperatures off the Pacific Coast observed over the last 20 years (California Department of Fish and Game,1999). Sardines are once again found in large

Predicting Coastal Evolution at Societally-Relevant Time and Space Scales

One of the most important applied problems in coastal geology today is determining the response of the coastline to sea-level rise. Prediction of shoreline retreat and land loss rates is critical to the planning of future coastal zone management strategies,and assessing biological impacts due to habitat changes or destruction. Presently, long-term (~50 years) coastal planning and decision-making has been done piecemeal,if at all, for the nation's shoreline. Consequently, facilities are being located and entire communities are being developed without adequate consideration of the potential costs of protecting them from or relocating them due to sea-level rise-related erosion, flooding and storm damage.

The prediction of future coastal evolution is not straightforward. There is no standard methodology, and even the kinds of data required to make such predictions are the subject of much scientific debate. A number of predictive approaches could be used, including: 1) extrapolation of historical data, (e.g., coastal erosion rates),2) inundation modeling, 3) application of a simple geometric model (e. g., the Bruun Rule), 4) application of a sediment dynamics/budget model, or 5) Monte Carlo (probabilistic) simulation. Each of these approaches,however, has its shortcomings or can be shown to be invalid for certain applications. Similarly, the types of input data required vary widely, and for a given approach (e.g., sediment budget), existing data may be indeterminate or simply not exist.

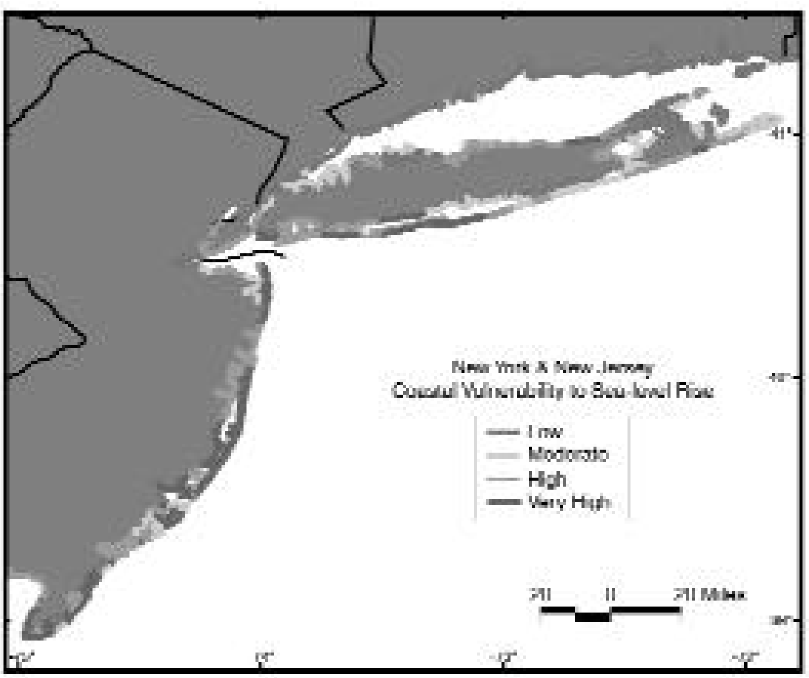


Figure 12: These preliminary results illustrate the relative vulnerability to sea-level rise along the New York and New Jersey coastline as assessed by ongoing USGS research. Note that the vulnerability mapped here is likely to change as methodologies in this pilot program are critically evaluated and improved (Source: USGS). See Color Figure Appendix

The relative susceptibility of different coastal environments to sea-level rise,however, may be quantified at a regional to national scale (e.g.,Gornitz et al.1994) using basic data on coastal geomorphology, rate of sea-level rise, and past shoreline evolution (Figure 12). A pilot project is underway at the US Geological Survey, Coastal and Marine Geology Program to assess the susceptibility of the nation's coasts to sea-level rise from a geologic perspective. The long-term goal of this project is to predict future coastal changes with a degree of certainty useful to coastal management, following an approach similar to that used to map national seismic and volcanic hazards. This information has immediate application to many of the decisions our society will be making regarding coastal development in both the short- and long-term.

numbers as far north as British Columbia (Hargreaves et al.,1994),and their recovery has led to a concurrent resurgence of the fishery long ago immortalized in John Steinbeck's *Cannery Row*.

ADAPTATION STRATEGIES

Assessing the effects of climate variability and change on coastal and marine resources is especially difficult given that human activities are generally responsible for the greatest impacts on coastal and marine environments. The nature of climate effects — both detrimental and beneficial to resources in question — are likely to vary greatly in the diverse coastal regions of the US. Anthropogenic disturbance often results in a reduction in the adaptive capacity of systems to cope with change and stress, making the real or potential impacts of climate difficult to observe. It is in this context that climate change acts as an increased stress on coastal and marine environments,adding to the cumulative impact of both natural and anthropogenic stress on ecological systems and resources.

This is most abundantly clear in coral reef systems. Coral reefs,both in US waters and worldwide,are clearly stressed,and many are degraded to the point of destruction. The prospects for the future are that in many, if not most,instances,the levels of both climate-related stress and local or regional stress resulting from anthropogenic impacts will increase. The implication for coral reefs is that local and regional reef protection and management efforts must be even more effective in controlling local stresses,to provide some compensation for large scale impacts. If local and regional anthropogenic stresses continue or increase,many of the reefs that are heavily used or affected by humans will be poor candidates for survival. This would result in substantial impacts to the communities and regional economies that depend upon healthy reefs for fisheries,subsistence, recreation,and tourism.

For responding or adapting to sea-level rise,three groups of strategies have been discussed,these being:(planned) retreat,accommodation,and protection (IPCC,1996). A retreat strategy would prevent or discourage major developments in vulnerable coastal areas and could include rolling easements,which allow development but explicitly prevent property owners from preventing the upland migration of wetlands and beaches. An accommodation strategy might elevate land surfaces or human structures,modify drainage systems,or otherwise change land use practices,thus allowing many coastal ecosystems to be maintained. A protection strategy could utilize beach nourishment and dune stabilization,as well as dikes,seawalls,bulkheads, and revetments,to form a barrier between water and land. This might generally lead to a loss of natural functions for beaches, wetlands,and other intertidal zones,but would be capable of roughly maintaining the coastline in place.

In areas where beaches or wetlands must migrate inland in response to sea-level change,it has been shown that planning and implementing protection or retreat strategies for coastal developments can substantially reduce the long-term economic impacts of inundation and shoreline migration. While some regulatory programs continue to permit structures that block the migration of wetlands and beaches,others have tried to decrease economic motivations for developing in vulnerable areas,or have experimented with retreat strategies. For example,coastal management programs in Maine, Rhode Island,South Carolina,and Massachusetts have implemented various forms of rolling easement policies in an attempt to ensure that wetlands and beaches can migrate inland as sea-level rises. Several other states require coastal counties to consider sea-level rise in their coastal management plans. However, the difficulties and obstacles facing coastal managers in effectively implementing setback and rolling easement policies are substantial. Many of the programs initiated to date are not mandatory, and the effectiveness of state coastal zone management programs often varies significantly.

While the potential impacts of sea-level rise have begun to initiate concern and some discussion of potential response strategies,the broader ramifications of changes in temperature,freshwater discharges,and the frequency and intensity of storm events,have scarcely been assessed. For example,in estuaries such as Chesapeake Bay, a particular focus of restoration efforts is the reduction of nutrient over-enrichment,or eutrophication,from both point discharges and diffuse sources throughout the watersheds draining into the estuaries. However, efforts to reduce eutrophication will have to contend with multiple climate change-related problems such as sea-level rise,increased winter-spring discharges but reduced summer runoff, warmer sea surface temperatures,and greater shoreline erosion.

For marine fisheries,adaptations to changes in the production characteristics of exploited populations will include adjustments in the recommended harvest levels and/or exploitation rates and in the size or age at which fish and invertebrate populations are first harvested. The limiting level of exploitation (which is the rate at which the risk of population collapse is high) for a population is directly related to the rate of recruitment at low abundance levels. Thus,environmental changes that result in a reduction in recruitment rates must be countered by reductions in exploitation rates. Conversely, some higher levels of exploitation should be sustainable for some stocks under favorable environmental conditions. Adaptation to changes in the composition of fish stocks will also be necessary; regional markets will undoubtedly have to adjust to shifts in species composition due to changes in the availability of different species. Additionally, changes in distribution are likely to lead to more complex conflicts regarding the management of transboundary stocks and species.

Although much remains to be learned in order to confidently project impacts of climate change on coastal areas and marine resources,the trends and relationships already apparent suggest that the managers,decision makers,and the public must take climate change impacts into account. To be successful,this will have to be done in the context of coastal and resource management challenges already being addressed, for example:

- Strategic adaptation of coastal communities (e.g., barrier islands and other low-lying areas) to sea-level rise and increased storm surge.
- Adaptive management of coastal wetlands to improve their prospects of soil building to keep up with sea-level rise and allow their migration over adjacent lowlands.
- Comprehensive and forward-looking water use and management policies that factor in requirements for coastal ecosystems,such as reduced nutrient and pollutant delivery.
- Control procedures to reduce the risk of invasions by non-indigenous species.
- Fishery management regimes that incorporate knowledge of fluctuations in productivity and populations resulting from varying modes of climatic variability.
- Controls on impacts such as runoff from land and unsustainable fishing pressures that reduce the resilience of coral reef ecosystems.

In general,many of the strategies which might be appropriate for coping with future climate change have been or are currently being discussed or implemented in response to current stressors on coastal and marine environments. The future impacts of climate will be deeply integrated with the ongoing impacts resulting from human activities;thus, attempts to manage or mitigate the effects of climate must be tightly coupled with management of human behavior at all spatial and temporal scales. Most importantly, those who are or will likely be affected by climate impacts must be made aware of the risks and potential consequences that future change will pose to their communities and their livelihoods.

CRUCIAL UNKNOWNS AND RESEARCH NEEDS

Direct human impacts dominate the changes occurring in most coastal areas,making it difficult to separate climatic effects from these direct stresses. In most areas,study of climate-related coastal impacts is only beginning. Consequently, for nearly all coastal and marine ecosystems considered in this Assessment,knowledge is inadequate to assess potential impacts fully and to determine effective adaptations. The Assessment has identified six important areas for research related to climate impacts on coastal and marine systems.

Coastal Hazards and the Physical Transformations of Coastlines and Wetlands. The significant erosion of beach fronts,barrier islands,and coastal marshes, coupled with accelerated sea-level rise,increases the vulnerability of coastal life and property to storm surge. Regardless of projected changes in the frequency and severity of coastal storms (hurricanes and nor'easters),storms will be riding on a higher sea level in the future. Research and assessments are needed to fully evaluate the vulnerability of human and natural coastal systems to the combined effects of sea-level rise,land subsidence,and storm surge. This information is required for rational responses in coastal protection,setbacks,and mitigation approaches to sustaining coastal wetlands.

Changes in Freshwater Loads to Coastal Ecosystems. Because of the importance of changes in land-use patterns and freshwater inflow to coastal ecosystems,particularly estuaries and wetlands,and to key species like Pacific salmon,considerable effort is needed to improve assessments of the impact of changes in the extent and timing of freshwater runoff. While contemporary GCM estimates of potential runoff vary widely, it is clear that changes are likely to occur and that the impacts could be substantial. Thus,new research is needed to assess the consequences of changes in runoff and the attendant changes in nutrient,contaminant,and sediment supply, circulation,and biological processes.

Decline of Coral Ecosystems. The decline of coral ecosystems is significant and global. Contributions to this decline include changes in ocean temperatures, levels of atmospheric CO_2, and a series of more direct anthropogenic stress (e.g., over-fishing, eutrophication, and sedimentation). Increased effort is needed to adequately understand and predict the cumulative effects of these multiple stresses on coral ecosystems. It is important in this work to recognize the significance of the full ecosystem (including e.g., sand beds, sea grasses, and the water column) associated with corals, and not only the coral reefs alone.

Alterations and Geographic Shifts in Marine Ecosystems. Changes in ocean temperature and circulation (e.g., ENSO, PDO, and NAO), coupled with changes in nutrient supplies (driven by changes in freshwater fluxes and arctic ice dynamics), are likely to modify patterns of primary productivity, the distribution and recruitment success of marine fish, the reproductive success of protected species, and the economic viability of marine fisheries. While research on environmental variability and marine ecosystems is advancing (e.g., in GLOBEC), the current effort is limited to relatively few important regional ecosystems. More research is needed to understand and predict potential changes and regional shifts for all important coastal and US marine ecosystems, including the socioeconomic impacts to fishing communities.

Loss of Arctic Sea Ice. Loss of sea ice in Arctic regions will have widespread regional impacts on coastal environments and marine ecosystems. Recent dramatic reductions in the extent of sea ice in the Arctic Ocean and Bering Sea have led to more severe storm surges because the larger open water areas are capable of generating much larger waves. This has led to unprecedented erosion problems both for Native villages and for oil and gas extraction infrastructure along the Beaufort Sea coast. Reductions in sea ice also result in a loss of critical habitat for marine mammals such as walrus and polar bears, and significant changes in the distribution of nutrients supporting the base of the food web. Research to better understand how changing ice regimes will affect the productivity of polar ecosystems, and to assess the long-term consequences of these impacts is essential, both to sustain marine ecosystems and to develop coping strategies for the Native communities that depend on hunting for their food and other aspects of their culture.

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