

# Climate Change Impacts on U.S. Coastal and Marine Ecosystems

Donald Scavia<sup>1</sup>  
National Ocean Service  
National Oceanic and Atmospheric Administration  
Silver Spring, Maryland 20910

John C. Field  
College of Ocean and Fisheries Science  
University of Washington

Donald F. Boesch  
Center for Environmental Studies  
University of Maryland

Robert W. Buddemeier  
Kansas Geological Survey  
University of Kansas

Virginia Burkett  
National Wetlands Research Center  
U.S. Geological Survey

Daniel R. Cayan  
Scripps Institute of Oceanography  
University of California, San Diego

Michael Fogarty  
National Marine Fisheries Service  
National Oceanic and Atmospheric Administration

Mark A. Harwell  
Rosenstiel School of Marine and Atmospheric Science  
University of Miami

Robert W. Howarth  
Oceans Program  
Environmental Defense

Curt Mason  
National Ocean Service  
National Oceanic and Atmospheric Administration

Denise J. Reed  
Department of Geology and Geophysics  
University of New Orleans

Thomas C. Royer  
Center for Coastal Physical Oceanography  
Old Dominion University

Ashbury H. Sallenger  
Center for Coastal Geology  
U.S. Geological Survey

James G. Titus  
Office of Economy and the Environment  
Environmental Protection Agency

<sup>1</sup> Corresponding Author

## Abstract

Increasing greenhouse gases projected for the 21st century are expected to lead to increased mean global air and ocean temperatures, with significant fluctuations at regional scales. The National Assessment of Potential Consequences of Climate Variability and Change (NAST 2001) was based on a series of regional and sector assessments. This paper is a summary of the coastal and marine resources sector review of potential impacts on shorelines, estuaries, coastal wetlands, coral reefs, and ocean margin ecosystems. This analysis considers the impacts of several key climate change drivers: sea level change; alterations in precipitation patterns and subsequent delivery of freshwater, nutrients, and sediment; increased ocean temperature; alterations in circulation patterns; changes in frequency and intensity of coastal storms; and increased levels of atmospheric CO<sub>2</sub>. While the potential impacts of climate change and variability will vary from system to system, it is important to understand that these impacts will be superimposed upon other ecosystem stresses (pollution, harvesting, habitat destruction, invasive species, land and resource use, extreme natural events), which may lead to more significant consequences.

**Key words:** Climate change, global change, climate impacts, coastal resources, shorelines, sea-level rise, coastal wetlands, estuaries, coral reefs, marine ecosystems.

## Introduction

The 158,000 km of coastline and 8.8 million km<sup>2</sup> of ocean within its territorial sea provide the U.S. with a wide range of essential goods and services through fisheries, vast storehouses of biological diversity, oil, gas, and mineral deposits, and unparalleled commercial and recreational opportunities. In addition to economic benefits derived from extracting goods, these ecosystems provide critical services, such as nutrient cycling, flood control, waste treatment, species refuge, genetic resources, and recreational and cultural activities. While these services typically lie outside traditional markets, Costanza et al. (1997) estimated that coastal and marine environments constitute over half of the value of global ecological services.

Over half of the U.S. population lives on the 17% of land considered coastal (Culliton 1998), and these areas become more crowded every year. Within the next 25 years, the coastal population is likely to increase by approximately 25%, or by 18 million people, with most of the growth occurring in the already crowded states of California, Florida, Texas and Washington (Boesch et al. 2000). This growth, along with rising affluence, is increasing demand for coastal and marine resources, which increases both the stress on those resources and their vulnerability to climate change and variability. Conversely, climate change will interact with these existing and increased stresses, potentially accentuating their negative impacts.

## Climate Change Forces

Climate change scenarios selected for the National Assessment are based on general circulation model (GCM) simulations conducted by the United Kingdom's Hadley Centre for Climate Prediction (HadCM2) and the Canadian Climate Centre (CGCM1), hereinafter referred to as the Hadley and the Canadian models, respectively (NAST 2001). The simulations incorporate similar, mid-range assumptions about future greenhouse gas emissions during the next 100 years, but differ in how they represent the effects of some important processes. On average over the U.S., the Hadley model projects a much wetter climate than does the Canadian model, while the Canadian model projects a greater increase in temperature than does the Hadley model. Output from these models should be viewed as two plausible climate futures rather than accurate predictions of what will happen at any particular location and time. It should also be noted that the current spatial resolution of GCMs is not sufficient to simulate changes in the geographical distribution of storms.

*Sea-level change.* During the last 100 years, globally averaged sea level has risen approximately 10-20 cm, or about 1 to 2 mm per year (IPCC 1996). Local rates of relative sea level rise vary from about 2 mm/yr in New England, Florida, and parts of the Gulf Coast, to 3-5 mm/yr in the mid-Atlantic, 5-10 mm/yr in parts of Texas and Louisiana, and anywhere from -10 to +2 mm/yr along the Pacific Coast (Nicholls and Leatherman 1996; Zervas 2001). These variations are caused by regional differences in groundwater and oil withdrawal, compaction of muddy soils, subsidence, isostatic rebound, and tectonic uplift. Over the next 100 years, global warming is expected to accelerate the rate of sea level rise by expanding ocean water and melting alpine glaciers (IPCC 2001). The full range of model projections,

from the most recent Intergovernmental Panel on Climate Change assessment (IPCC 2001), spans from 9 to 88 cm rise in global sea level by 2100. Model averages range more narrowly from 31 to 49 cm. These projections are broadly consistent with previous studies (IPCC 1996; Titus and Narayanan 1996; Wigley 1999) and the Canadian and Hadley models (Boesch et al. 2000; NAST 2001). It is important to note that, even if greenhouse gas emissions are stabilized, the rate of sea-level rise will likely continue to increase beyond 2100 because of the time it takes for oceans and ice sheets to approach equilibrium conditions with the atmosphere. Regional differences in land movement and impacts of climate change on atmospheric pressure and alongshore winds will continue to produce differences in local sea level relative to the land; however, uncertainty about local future sea levels is about 50% greater than for the global average (IPCC 2001) because current models are cannot reliably estimate whether particular areas will experience more or less of a rise.

*Coastal Storms.* The number of hurricanes in a given year can vary by a factor of three or more in consecutive years. Although trends in hurricanes and tropical cyclones cannot be attributed to current climate change, there is a strong inter-decadal mode in North Atlantic hurricane variability, showing greater activity along the East Coast and peninsular Florida between 1941 and 1965, and in the 1990s (Landsea et al. 1996). Timmermann et al. (1999) suggest that, in the future, the sea surface temperatures in the tropical Pacific are likely to resemble present-day El Niño conditions and, because fewer hurricanes occur in the Atlantic during El Niño years (Pielke and Landsea 1999), Atlantic hurricane frequency could decrease in the future. In contrast, during recent severe El Niño events (1982-83, 1997-98), Eastern Pacific winter storms tracked farther south than in previous years, causing extensive wave and storm damage, coastal erosion, and flooding in California (Griggs and Brown 1999).

While it may be difficult to identify climate change effects on hurricane frequency, hurricane wind strength could increase as a result of elevated sea surface temperatures. Knutson et al. (1998) showed increases in hurricane wind strength of 5-10% are possible with a 2.2°C warmer sea surface. For a moderate hurricane, such an increase in wind strength could translate into as much as a 25% increase in the destructive power of its winds. Wave height and storm surge would increase similarly, magnifying coastal impacts. Other research suggests that tropical cyclones could become more intense (Kerr 1999). Regardless of potential changes in frequency and intensity, coastal storms and resulting storm surges will be riding on a higher sea level, increasing the vulnerability of developed shorelines.

*Freshwater inflow.* The hydrologic cycle controls the strength, timing, and volume of delivery of freshwater and its chemical and sediment load to coastal ecosystems. That cycle is likely to change under a changing climate. However, in contrast to the general agreement among GCMs for direction, if not the pace, of temperature change, regional projections of precipitation vary considerable (NAST 2001). Simple water-balance models developed by Wolock and McCabe (1999) based on the precipitation and temperature projections of the Canadian and Hadley models provide some basis to forecast river runoff (Fig.1). For example the Hadley model projections result in a 34 % increase in total runoff along U.S. Atlantic and Gulf coasts by the last decade of the century, while the drier and hotter Canadian model projections result in a 32% decrease. While these differences illustrate significant uncertainty regarding future rainfall and runoff patterns, one should not average them and

assume that changes will be benign. Rather, these analyses suggest that significant changes in the delivery of freshwater into coastal environments may be significant, if highly uncertain. Also, both models predict that there will be an increase in extreme rainfall events, which can significantly increase the chemical and sediment load delivered to the coast. This increased “flashiness”, which has already begun during the 20th century, is likely to become more common, as could droughts and floods (Karl et al. 1995).

*Ocean Temperature and Ice Extent.* There now is strong evidence, based on analysis of five million ocean temperature profiles, for ocean warming over the past 45 years (Levitus et al., 2000). That analysis shows mean temperature of the upper 300 meters of the oceans has increased by 0.31°C, with the warming signal observable to depths of 3000 meters. Evidence now suggests that the signal was primarily due to climate change with anthropogenic causes, as opposed to climate variability (Levitus et al. 2001). These results are in strong agreement with projections of many general circulation models. In addition, Barnett et al. (2001) have calculated, with confidence exceeding 95%, that human-produced greenhouse gases are responsible for the horizontal and temporal character of the observed increase in ocean temperature. Arctic ice has seen significant declines, with aerial extent reduced by as much as 7% per decade over the last 20 years (Johannessen et al. 1999) and thinning by as much as 15% per decade (Rothrock et al. 1999). While this may be related to a decadal-scale mode of Arctic atmospheric variability, comparisons with GCM outputs suggest that the declines are related to anthropogenically induced global change (Vinnikov et al. 1999).

*Ocean Circulation.* Ocean currents, fronts, and upwelling and downwelling zones play significant roles in the distribution and production of marine ecosystems, and these features are likely to change in response to alterations in temperature, precipitation, runoff, salinity, and wind. For example, increased freshwater flux will increase stratification and potentially increase currents and decrease the vertical nutrient flux—leading to enhanced biological productivity in some systems by enabling organisms to remain longer in the photic zone. On the other hand, retention of phytoplankton in the photic zone improves the grazing success of zooplankton to the detriment of those phytoplankton populations. While changes like these are likely to influence biological productivity, region-specific changes are not yet predictable. While changes will occur on scales ranging from small-scale turbulent mixing to large-scale circulation, one of the most dramatic projections is the alteration in the deep-water “conveyor belt” circulation, with potentially dramatic feedback on large-scale climate patterns (Driscoll and Haug 1998; Broecker et al. 1999).

## Potential Impacts on Coastal and Marine Systems

Potential impacts of these climate-related drivers of change are outlined below for specific coastal and marine system types because it is the cumulative effects of these and other impacts that matter most. The systems are: shorelines and developed areas, wetlands, estuaries, coral reefs, and ocean margins and fishery resources.

**Shorelines and Developed Areas.** Natural processes continually change the beach, shoreline, embayment, and near-shore environments. Rivers carry sediments to the coast. Winds move unconsolidated sediments, reshape features along the shoreline, and produce waves that break at the shore. The angle between land and the breaking waves creates longshore currents that

transport sediment along the shore. Natural, climate, and human-induced changes to bathymetry; the timing and magnitude of river flows; inshore and offshore currents; and storm tracks, intensity, and duration are likely to produce significant changes in sediment deposition and erosion patterns. Experience shows that when river flow is stored or diverted, the resulting loss of sediment delivered to the coast can accelerate shoreline erosion. For example, the Brazos River in Texas now delivers only 30% of the volume of sediment to local beaches before dams were built on the river (Morton 1979). Changes in bottom bathymetry can focus or spread energy as waves approach the coast, producing changes in local and regional sediment movement and shoreline morphology. These changes may be natural or associated with activities like sand mining, or can be accidental such as on Mission Beach in California where shore erosion occurred after the removal of kelp (Hotten, 1988).

Rising sea level can inundate lowlands, erode beaches, cause barrier islands to migrate inland, increase coastal flooding, and increase the salinity of rivers, bays, and aquifers. Changes in the frequency of severe storms and increased rainfall intensity could further aggravate flooding and storm damage. Figure 2 shows that land most vulnerable to inundation is in Florida, Louisiana, North Carolina, Texas, and Maryland (Titus and Richman 2001). Even those states with relatively little low land, however, have shorelines that are vulnerable to erosion and storm damage.

The U.S. East and Gulf coasts illustrate the interactions between natural shoreline processes and human activities. Barrier islands and lagoons that separate the gently sloping coastal plain from the continental shelf rim much of these coasts. The islands bear the brunt of hurricanes and winter storms and protect the mainland from resulting wave action and erosion. With a rising sea level, the narrowest undeveloped islands slowly “roll over”, or move toward the mainland, through erosion on their seaward flank, over-washing of sediment across the island, and deposition in the quieter waters of the bay. Developed islands, by contrast, tend to be too wide to wash over. As sea level rises, the ocean sides erode and sand is deposited off shore, but buildings or extensive dune systems tend to prevent storms from washing sand toward the lagoons. This erosion threatens ocean-side homes along much of the Atlantic and Gulf Coasts as the low-lying areas on the lagoon side of the barrier island become increasingly submerged during extreme high tides, as sea level rises.

Storm-surge floods, waves, and coastal erosion are natural processes that pose hazards only when they affect people, homes, and infrastructure. These extreme natural events cause some of the most visible and costly impacts to shorelines, particularly in developed areas.

Hurricane Hugo caused an estimated \$9 billion in damages in 1989; Hurricane Andrew damaged \$27 billion in 1992; and Hurricane Georges damaged \$5.9 billion in 1998 (National Climatic Data Center). Because these estimates represent insured losses only, they underestimate the full costs of these events because they exclude uninsured costs to individuals, businesses, and public infrastructure, as well as impacts to natural resources and the environment (Heinz Center 2000). Winter storms also have significant impacts. For example the Halloween “nor’easter” of 1991 caused damages of over \$1.5 billion along the Atlantic Coast. A series of storms that battered the Pacific Coast during the 1997-98 El Niño caused an estimated \$500 million in damage in California alone (Griggs and Brown 1998). Good (1994) has shown that, over the past decades, rapid buildup of seawalls and revetments

along the central Oregon coast followed major El Niño events, as property owners attempt to protect their shorelines from erosion and damage.

Increasing economic damages over time have been shown to be largely a consequence of increased development and appreciation in value of coastal property (Pielke and Landsea 1999). This and similar studies indicate that the economic vulnerability of development to hurricane and storm activity will continue to rise independent of any climate induced changes in vulnerability. However, additional climate-induced effects are likely. While there is not yet any clear evidence for climate-induced changes in the frequency or intensity of hurricanes and coastal storms, there is little doubt that future waves and storms will be superimposed on a rising sea. This has been the case historically. For example, rising sea level was responsible for increasing the annual number of hours of extreme water levels from below 200 in the early 1900s to an average of 600 in the past decade for Atlantic City, New Jersey (Zhang et al. 1997). Levees, seawalls, and other coastal structures are typically designed with the “100-year flood” as a basis. This is also the level to which coastal structures must be built to qualify for support under the National Flood Insurance Program. However increased sea level could mean that a future 50-year event may be more severe than today’s 100-year flood (Pugh and Maul 1999). Under such a scenario, FEMA (1991) has estimated that the number of households in coastal floodplains could increase from 2.7 million to 6.6 million by 2100. In addition to increased erosion and flooding, a rising sea may also increase salinity of freshwater aquifers, alter tidal ranges in rivers and bays, change sediment and nutrient transport, and alter patterns of coastal chemical and microbiological contamination. Secondary impacts, including inundation of waste disposal sites and landfills, may introduce toxic materials into the environment, posing new threats to the health of coastal populations and ecosystems. While steep, rocky shoreline areas might experience relatively little change, low-lying, gently sloping areas could experience severe inundation.

While assessing the economic impact of sea-level rise is still somewhat speculative, the potential cost of a 50-cm rise could be between \$20 and \$200 billion by the year 2100; the cost of a 100-cm rise would be roughly twice that amount (Yohe 1989; Titus et al. 1991; Yohe et al. 1996; Neumann et al. 2000). The estimates vary widely because they are based on a wide range of assumptions and different means of calculating potential costs. For example, Yohe et al. (1996) assumed that only those areas that could be economically protected would be protected. However, all of these estimates are conservative because they do not include losses due to decreases in non-market ecosystem services, tourism, recreation, or the values of future development. It is possible that these costs could be reduced by an early response and efforts to mitigate the potential hazards, rather than reacting once the damage has been done.

**Coastal Wetlands.** Coastal marshes, mangroves, forested wetlands, mudflats, and estuarine beaches provide critical refuge and forage opportunities for wildlife, fishes, and invertebrates supporting the commercial and recreational livelihoods of many communities. Survival of these ecosystems under a changing climate depends primarily on their ability to adapt to change, but also on whether human activities impair their natural adaptive capacity. Natural biological and geological processes should allow responses to gradual changes, such as transitions from marsh to mangrove swamp as temperatures warm, as long as environmental thresholds for plant survival are not crossed. However, accelerated sea level rise also

threatens these habitats with inundation, erosion, and saltwater intrusion. Over the last six thousand years, coastal wetlands expanded inland as low lying areas were submerged, but often did not retreat at the seaward boundary because sediment and peat formation enabled them to keep pace with the slow rate of sea level rise. If landward margins are armored, effectively preventing inland migration, then wetlands could be lost if they are unable to accumulate substrate at a rate adequate to keep pace with future increased rates of sea level rise.

Although changes in sea level pose the most obvious threat to coastal wetlands, altered precipitation patterns, changes in watershed land use affecting the timing and delivery of water and sediment, and increases in atmospheric CO<sub>2</sub> and temperature may also have substantial impacts. Increased atmospheric CO<sub>2</sub> could increase plant production if other factors such as nutrients and precipitation are not limiting to plant growth. Curtis et al. (1989) showed that *Schoenoplectus americanus* (formerly *Scirpus olneyi*) primary productivity increased with increased CO<sub>2</sub> and Rozema et al. (1989, 1990) and others showed increased salt tolerance with elevated CO<sub>2</sub>. Increased CO<sub>2</sub> produced higher root-to-shoot ratios, growth rates, net assimilation rates, greater biomass, leaf area, stem length, and earlier ages at maturity in red mangrove seedlings (Farnsworth et al. 1996; Ball et al. 1997). Related research on the effects of elevated atmospheric CO<sub>2</sub> on agricultural, forest, and herbaceous wetland systems suggests that growth enhancement is likely; at least for seedlings, but the long-term impacts on productivity, nutrient cycling, and other ecosystem processes are uncertain.

Increased air, soil, and water temperature may also increase growth and distribution of coastal salt marshes and forested wetlands. For many species, including mangroves, the limiting factor for the geographic distribution is not mean temperature, but rather low temperature or freezing events that exceed tolerance limits (McMillan and Sherrod 1986; Snedaker 1995). For example, Harris and Cropper (1992) suggest that, although the northern limits of tropical and subtropical habitats (such as coastal red mangrove communities) would likely migrate up the Florida peninsula, dramatic changes were likely. However, a warmer climate might favor highly opportunistic exotic species, which have invaded Florida, over native species (Malcolm and Markham 1997).

Changes in the timing and volume of freshwater delivery to coastal wetlands will also be critical, yet perhaps the most difficult to assess. In contrast to uncertainties associated with regional impacts of climate change on hydrology (discussed above), it is clear that increased human population and coastal development will create higher demands for freshwater resources. While increased fresh water is likely to decrease osmotic stress and increase productivity, less fresh water may increase salinity stress. Wetlands may accommodate gradual increases in salinity as salt and brackish marshes replace freshwater marshes and swamps; however, sustained or pulsed changes in salinity can have dramatic negative effects. For example, *Panicum hemitomon*, a typical freshwater marsh species, grew at a reduced rate in water of 9 psu salinity in one study (McKee and Mendelsohn 1989), and had reduced carbon assimilation at 5 psu in another (Pezeshki et al. 1987). For high-salinity marshes, increased salinity could decrease productivity, but would not necessarily result in a habitat shift, because many *Spartina* and similar species tolerate wide salinity ranges (Adams 1963;

Webb 1983). Mangrove forests are confined to high salinity areas, although productivity has been shown to increase with the availability of fresh water (Pool et al. 1977). However, if mangroves were continually exposed to full strength, or near full strength, seawater then production would likely decline (Snedaker 1995).

Changes in delivery of fresh water will also affect sediment supply, which is needed to allow wetlands and mangroves to cope with rising sea level (Fig. 3; Reed 1990; 1995). This is particularly critical for areas where they are not able to migrate onto adjacent land because they are blocked by bluffs, coastal development, or shoreline protection structures. In steeply sloped or developed areas where inland migration is not possible, wetlands and mangroves will have to rely on vertical growth to adjust. Management actions to accommodate this vertical displacement could include modification of river discharge controls to increase sediment supply and facilitate substrate accumulation. While mangroves can migrate upslope, they may also expand seaward if sedimentation is sufficient (Woodroffe 1992). Mangrove responses will also depend on the forest type, environmental setting, and supply of fresh water and sediment. Peat production, which depends on adequate supply of fresh water to maintain root growth and sediments, has allowed mangroves to keep pace with sea-level rise (Snedaker 1995). However, the availability of sediment is critical and Ellison and Stoddart (1991) predict that low carbonate islands, such as those found in south Florida and many areas in the Caribbean, are particularly vulnerable to submergence because of limited input of land-derived sediment.

Even if low salinity marshes and forested wetlands can survive sea-level rise, they may become increasingly vulnerable to storm surge impacts. Guntenspergen et al. (1995) reported that, during Hurricane Andrew, large quantities of sediment moved into low-salinity marshes and smothered vegetation, salt water introduced into fresh marsh systems resulted in salt burn, and erosion of organic marsh substrates and the distribution of large quantities of wrack killed underlying vegetation. Although plants quickly re-established (except for scour areas and areas of thick wrack accumulation), changes in the frequency or magnitude of such storm impacts could threaten the long-term sustainability of low salinity wetlands that depend upon organic substrates. As mentioned above, even if frequency and intensity are unchanged, elevated sea levels will bring storm surges further inland. Thus, wetland response to sea-level rise will be case specific, dependent upon interactions between organic matter accumulation, hydrological changes, subsurface processes, and storm events (Reed 1995; Cahoon et al. 1995; Goodbred et al. 1998; Kuhn et al. 1999).

Some lessons may be learned from the Mississippi Delta Plain where rapid subsidence already produces rapid rates of relative sea-level rise. These wetlands provide critical nursery areas for finfish and crustaceans, including many commercially important species, and serve as important buffers for storm surge. Many components of this diverse ecosystem are being rapidly degraded by accelerated subsidence caused by groundwater removals, oil and gas withdrawals, reduction in sediment supply from river dams and levees, and increased vulnerability to salinity and wave action from dredged navigation channels (Boesch et al. 1994). In some areas of coastal Louisiana, wetlands accrete material sufficiently to keep pace with current rates of relative sea-level rise, but in other areas marshes fail to maintain their elevation, gradually becoming waterlogged as plants and soils are submerged for longer

periods on each tide. Eventually plants die and soil integrity is lost, allowing rapid erosion of the remaining marsh substrate. As a result, coastal Louisiana experiences the greatest wetland loss in the nation. Changes have occurred so rapidly in 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. In areas currently maintaining their elevation, increased sea level rise will likely result in similar ecological thresholds being crossed and thus even more extensive land loss.

Estuaries. Estuarine impacts from climate change will be manifest through exacerbation of current stresses, including those imposed by a significantly altered nitrogen cycle (Howarth et al. 1996; Vitousek et al. 1997). These impacts will be significant because nitrate-driven eutrophication is one of the greatest threats to the integrity of many estuaries (Vitousek et al. 1997; NRC 2000; Cloern 2001); over half of the estuaries in the United States show symptoms of moderate to high eutrophication (Bricker et al. 1999). Eutrophication, defined as an increase in supply of organic matter due to flux from external sources or production within the system (Nixon, 1995), can lead to greater phytoplankton biomass, decreased water clarity, anoxic and hypoxic bottom waters, more frequent and longer lasting harmful algal blooms, degraded sea grasses and corals, altered planktonic and the benthic community structures, and loss of biotic diversity and fisheries (Jørgensen and Richardson 1996; NRC 2000).

Estuaries vary significantly in their vulnerability to eutrophication, and climate change will likely influence that vulnerability in several ways, including changes in mixing characteristics caused by alterations in freshwater runoff, and changes in temperature, sea level, and exchange with the coastal ocean (Kennedy 1990; Peterson et al. 1995; Moore et al. 1997; Najjar et al. 2000). A direct effect of changes in temperature and salinity may be seen through changes in suspension feeders such as mussels, clams and oysters. The abundance and distribution of these consumers may change in response to new temperature or salinity regimes and they can significantly alter both phytoplankton abundance and water clarity (Alpine and Cloern 1992; Meeuwig et al. 1998; NRC 2000).

Changes in freshwater inflow, air temperatures, and precipitation patterns can also influence water residence time, nutrient delivery, dilution, vertical stratification, and control of phytoplankton growth rates (Malone 1977; Cloern 1991, 1996; Howarth et al. 2000). Future estuarine temperature ranges are likely to narrow, because winter temperatures will increase, while evaporative cooling and increased cloudiness will moderate higher summer temperatures. Increased air temperature may also lead to earlier snowmelt and the resulting peak in freshwater inflow. In those cases, summer flows may be reduced as a result of greater evapotranspiration. This would increase estuarine salinity and modify stratification and mixing, thus influencing biotic distributions, life histories, and biogeochemistry.

Decreased freshwater runoff will increase estuarine water residence time, whereas increased runoff will decrease residence time (Moore et al. 1997). The effects of altered residence times can be significant. Even at their fastest growth rates, phytoplankton populations are only able to double once or twice per day. Consequently, estuaries with water residence times less than a day, phytoplankton are generally flushed from the system as fast as they can grow, reducing

the estuary's susceptibility to eutrophication. However, if residence times increase as a result of altered freshwater delivery, susceptibility will increase. For example, Howarth et al. (2000) attributed accelerated eutrophication in the Hudson River estuary, at least in part, to longer summer water residence time as a result of lower freshwater delivery. During the wet summers of the 1970's, water residence times were less than one day. However, low freshwater runoff during the summers of 1995 and 1997 increased residence times to several days, resulting in 10-fold greater rates of phytoplankton production.

Increased and earlier freshwater inflow can also significantly modify salinity regimes. For example, in the San Francisco Bay/Delta watershed, increasing air temperatures have already led to earlier snowmelt, shifting freshwater flows from spring to winter, contributing to an overall rise in estuarine salinities (Dettinger and Cayan 1995). If this effect strengthens significantly over the next century, increased winter flows and decreased spring flows will decrease salinities in the wet season and dramatically increase salinity levels in the dry season, further stressing an ecosystem already heavily impacted by a wide range of problems.

Changing precipitation patterns can also influence nutrient delivery. Nitrogen delivered by the Mississippi River system to the Gulf of Mexico has increased approximately three-fold over the past four decades and is the dominant factor in the massive hypoxic area off the coast of Louisiana (CENR 2000). There is considerable inter-annual variability in nutrient load, driven by variation in precipitation and river flow (Fig. 4). For example, the 1993 spring floods resulted in the greatest nitrogen delivery ever recorded, and the aerial extent of the hypoxic zone was twice the average of the preceding eight years. By contrast, the extent of hypoxic waters was small during 1988, concurrent with a 52-year low in the flow of the Mississippi River (Rabalais et al. 1999). The effects of precipitation variability on delivery of nitrogen may also be magnified by land use practices. Nitrate tends to build up in soils during dry years, largely as a result of reduced uptake of soil nutrients by crops, and is flushed into streams at much larger rates during subsequent wet years (Goolsby et al. 1999). Thus, wet years that follow dry years tend to produce the largest fluxes of nitrate from the catchment to the Gulf of Mexico. If future precipitation regimes are more variable, a trend suggested by many climate models, this could increase the net impacts to coastal areas affected by nutrient over-enrichment and eutrophication.

*Coral Reef Ecosystems.* Like most marine communities, coral ecosystems are subject to interacting marine, terrestrial, and atmospheric influences over wide spatial and temporal scales. Longer-lived organisms may survive for centuries, and many reef communities turn over on decadal time scales (Done 1999), making it difficult to separate environmental variability from other impacts. Environmental boundaries for reef communities (Smith and Buddemeier 1992) are defined by temporal and spatial distributions of temperature, calcium carbonate saturation state, salinity, light, sediment, nutrients, and physical energy regime (waves, currents, storms)—all potentially influenced by both natural and human processes. Human activities can also lead to physical destruction, over fishing, and toxic chemical contamination (Wilkinson and Buddemeier 1994).

Most of these stresses interact in complex ways, with both acute and chronic stresses playing critical roles (Hughes and Connell 1999; Kinsey 1988). Coral reef communities are generally

regarded as stress-adapted, with disturbance playing a key role in sustaining their overall high biodiversity (Connell 1997). Thus, reef communities, damaged by acute episodic events, will recover if other environmental factors remain generally favorable. Conversely, coral communities may persist under sub-optimal conditions in the absence of acute stresses. However, once a chronically stressed reef is severely damaged, recovery is unlikely (Hughes, 1994). This is important because chronic stresses, such as nutrient loading and over fishing, are likely to increase the vulnerability of coral ecosystems to climate-related acute stresses such as high-temperature episodes.

Coral reef calcification rates are sensitive to the carbonate mineral saturation state of ambient surface water, which is depressed by rising concentrations of atmospheric CO<sub>2</sub>. Carbon dioxide, dissolved in seawater, reduces alkalinity and calcium carbonate concentrations. This, in turn, decreases calcification rates of reef-building corals and coralline algae. Recent studies suggest that calcification rates are likely to decline between 17 and 35% by the year 2100 (Fig.5, Gattuso et al. 1999; Kleypas et al. 1999a, 1999b) and as much as one-third of that decrease may already have occurred. The resulting reduced skeletal density and/or growth rate will increase reef vulnerability to physical damage, bio-erosion, some forms of predation, and the corals' ability to compete for space. The effect of increased atmospheric CO<sub>2</sub> will be greatest at the northern and southern margins of coral distributions because CO<sub>2</sub> is more soluble in cooler waters. Therefore, these effects will be most severe at higher latitudes, reducing the ability of reefs to expand their ranges poleward as might otherwise be expected in response to ocean warming.

While accurate predictions of large-scale changes in sea surface temperatures (SST) are not available, they might rise by 1 to 3 °C over this century, although not uniformly (Pittock 1999). Reef ecosystems will be susceptible to changes in the frequency and/or magnitude of temperature extremes because many coral species live near their upper limits of thermal tolerance. Bleaching can occur when these thermal tolerances are exceeded and the corals' symbiotic algae (zooxanthellae) are subsequently expelled, slowing or halting growth, skeletal accretion, and sexual reproduction, and increasing the susceptibility to pathogens (Glynn 1996). Satellite data show an increase in the extent of tropical ocean 'hotspots'—areas 2 to 3° C above average water temperatures (Strong et al. 2000)—and these hotspots have been useful predictors of bleaching events. Warm events over the last several decades have led to extensive bleaching in the Florida Keys, the Caribbean, the Eastern Pacific, and elsewhere (Williams et al. 1987; Glynn and de Weerd 1991; Milliman 1993). More recently, unprecedented high sea surface temperatures and perhaps the most widespread coral bleaching ever observed have been associated with the 1998 El Niño (Wilkinson et al. 1999; Hoegh-Guldberg 1999). In the past, many coral communities have recovered from bleaching events; however the 1998 events resulted in unusually high mass mortality and many reefs have yet to recover. If the high-frequency SST variation of the past 20 years continues, and is superimposed on a general warming trend, accelerated bleaching and mass mortality events could increase dramatically in many tropical reefs.

Lethal epizootics are poorly understood features of recent coral declines. Population explosions of predatory macro-organisms such as *Acanthaster planci* (the Crown of Thorns starfish) have been important for decades, but there have been recent reports of a sharp rise in

bacterial, fungal, and viral diseases, especially in Caribbean and Florida reef systems (Harvell et al. 1999; Done 1999). These large-scale losses and shifts in community structure, associated with disease, are thought to be unprecedented in the Holocene and Late Pleistocene (Aronson et al. 1998; Greenstein et al. 1998). The introduction and success of pathogens are influenced by environmental conditions that favor their growth and propagation, and by the condition of the corals. While it is not clear to what extent this will be a factor in coral health, alterations in temperature, carbonate saturation, and other climate-driven conditions may increase vulnerability to disease.

Changes in sediment, fresh water, and nutrient loads, as outlined above with respect to estuaries and wetlands, will also impact coral ecosystems adjacent to coastal watersheds (Jickells 1998; Moffat 1998; Lapointe, 1999). Negative impacts can be expected in areas where changes in land use and precipitation patterns lead to increased sedimentation, eutrophication, or algal growth.

*Ocean Margins and Fishery Resources.* Altered temperature, salinity, precipitation, wind fields, and sea level will affect the distribution, abundance, and production of marine organisms, with potential impacts on commercial and recreational fisheries that support a multibillion dollar U.S. industry. These fisheries are socially and culturally significant in many coastal communities. In 1999, the estimated dockside value of US Commercial fisheries was \$3.5 billion dollars with a total estimated value-added of \$27 billion to the U.S. economy (NMFS 2000). Recreational fisheries also substantially add to the economies of coastal communities.

Changes in ocean temperature are likely to drive poleward migrations of tropical and lower latitude organisms. Along the Northeast coast, cod, American plaice, haddock, Atlantic halibut, redfish, and yellowtail flounder may all migrate northward, with mid-Atlantic species, such as butterfish, herring, mackerel, and menhaden extending their ranges into the Gulf of Maine (Murawski 1993). Many of these species provide an important forage base for other fishes, marine mammals, and sea birds; therefore, these migrations may have significant secondary effects on trophic interactions and relative distribution of predators and prey. Temperature shifts may also drive modifications in the distribution and abundance of intertidal and temperate reef species (Sagarin et al. 1999; Hobbrook et al. 1997) along the California Coast.

However, other habitat requirements may prevent or limit migration for some species, requiring them to accommodate higher temperatures (Colton 1972) and the energetic costs associated with living in sub-optimal temperatures may result in loss of regional populations. Most species have an optimum temperature range for growth and metabolism (Jobling 1996). Increasing temperature towards the optimum can enhance growth, survival, and reproductive output, while increases beyond the optimum will reduce growth and metabolism. Positive relationships have been documented between temperature and haddock growth and recruitment success (Marshall and Frank 1998) and cod growth (Brander 1995). In contrast, temperatures above optimum were shown to reduce growth rates in Fraser River sockeye salmon, presumably due to increased metabolic demand or changes in food availability (Cox and Hinch 1997). Based on fisheries and oceanographic data, thermal limits of Pacific

salmon, and temperature projections from the Canadian model, Welch et al. (1998) suggest that by 2090 virtually none of the Pacific Ocean may lie within the thermal limits of sockeye salmon (*Onchorynchus nerka*) restricting the distribution of these fish, and potentially other salmonids, to marginal seas such as the Bering Sea and the Sea of Okhotsk.

When temperature thresholds are exceeded, immune systems of stressed individuals can be weakened, leading to disease outbreaks (Harvell et al. 1999). For example, sea urchin diseases, documented in unusually warm waters in both tropical and temperate areas, have decreased sea urchin abundance, resulting in cascading effects on benthic algae (Scheibling and Stephenson 1984). The northward extension of the MSX and Dermo diseases of oysters has also been linked to increased temperature. Harmful algal blooms have been associated with ENSO events and both warm and cool water temperature extremes (Hallegraeff 1993; Harvell et al. 1999). Gender distribution of sea turtles may be altered by higher temperature in tropical and reef ecosystems. Because sea turtle gender is determined in part by ambient temperatures at critical stages in embryonic development, elevated temperatures may lead to a preponderance of females (Mrosovsky and Yntema 1980; Mrosovsky and Provancha 1992). While impacts of these potential changes on sea turtle populations have not been assessed; all marine turtle species found in U.S. waters are listed as Endangered Species.

Increased temperature is likely to continue to thin polar and subpolar ice and to change their spatial distributions. These changes will impact marine mammals and seabirds that use ice shelves and flows as platforms for reproduction, pupping, resting, molting, and migration. Significant reduction in ice edge extent could have deleterious effects on marine mammals that depend upon these systems (Tynan and Demaster 1997). Walrus are vulnerable to changes in sea ice extent, as floating ice provides them with a means of transportation and allows them to feed over large areas (Alexander 1992). Ringed seals depend upon the stability of fast ice for raising their young; they and the polar bears which prey upon them are the only marine mammals that regularly occupy landfast Arctic ice (Tynan and DeMaster 1997; Stirling 1997) and would presumably be greatly affected by a reduction of the extent of sea-ice extent. Anecdotal evidence suggests that the availability of walrus, polar bears, and other marine mammals to native hunters in the Arctic has already been declining (Weller and Anderson 1998). Ice edges also support highly productive regions where physical and biological processes encourage substantial phytoplankton blooms and high levels of zooplankton and arctic cod production (Wheeler 1996; Niebauer 1991). Migration of belugas, narwhals, and harp seals to ice edge regions have all been linked to surges in abundance of Arctic cod in these areas during summer blooms.

In addition to direct temperature effects, changes in atmospheric dynamics, air temperature, wind stress, and freshwater runoff will alter water column stratification. Increased stratification produced by higher sea-surface temperatures and increased freshwater runoff will increase the energy required to mix water vertically, resulting in a shallower mixed layer, less mixing with deeper water, and therefore reduced replenishment of nutrients. For example, reduced productivity in the North Pacific during low wind regimes has also been linked to changes in the strength of the Aleutian Low Pressure System (Polovina 1995). Related physical and biological changes in the marine environment are associated with a reoccurring pattern of interdecadal climate variability, referred to as the Pacific (inter)

Decadal Oscillation, or PDO (Mantua et al. 1997). In this region, decreased subarctic gyre mixed layer depths, increased stratification of the upper ocean, and closely related warming of surface temperatures appear to have led to large-scale changes in productivity (Freeland, et al. 1997), including an apparent doubling of zooplankton biomass in the subarctic gyre between the 1950s and the 1980s (Brodeur and Ware 1992) and a contrasting 70% decline in zooplankton abundance in the California current during roughly the same period (Roemmich and McGowan 1995). McGowan et al. (1998) attributed these long-term declines in zooplankton populations in the California Current to increased water temperatures resulting in an intensification of stratification, and an overall lowering of mixing and nutrient regeneration in the upper water column.

Within the Gulf of Alaska, decreases in the upper layer salinity from increased precipitation and glacial melt, are likely to increase the stratification and poleward baroclinic flow on the eastern boundary (Royer et al. 2001). Coastal freshwater discharge and the PDO are well correlated with salmon production. The connections between freshwater inflow and production are uncertain but seem to differ from those in the California Current system. Here, increased stratification seems to increase productivity, though increased water temperatures might eventually limit North Pacific salmon production (Welch et al. 1998). A considerable volume of research indicates that this decadal scale climate variability has had substantial impacts throughout the North Pacific on the productivity and species composition of both lower and higher trophic levels, including many forage species, most populations of Pacific salmon, and many sea birds and marine mammal populations (McGowan et al. 1998; Anderson and Piatt 1999; Hare et al. 1999).

Potential changes in transport, turbulence, and upwelling may impact species that depend on ocean currents for transport of their early life history stages. Among the more dramatic examples is transport of American and European eel larvae to the Gulf Stream from the spawning grounds in the Sargasso Sea. Similarly, longfin squid larvae are transported from natal areas in the South Atlantic Bight northward in the Gulf Stream. Factors that affect the velocity and position of the Gulf Stream relative to the continental shelf regions will affect larval transport and subsequently impact recruitment to coastal locations. A reduction in wind-driven forcing in the major current systems such as the Gulf Stream can also reduce formation of meanders and rings that can affect losses of continental shelf biota.

The potential effect of climate change on upwelling systems has been subjected to two interpretations. Based on empirical evidence for increased alongshore wind stress (and a derived upwelling index) over the last five decades, Bakun (1989) hypothesized that intensified temperature differentials between land and sea, expected under most warming scenarios, will strengthen alongshore winds and increase upwelling. In contrast, Gucinski et al. (1990) suggest that reduced latitudinal temperature gradients, due to enhanced warming at higher latitudes, will decrease wind field strength, leading to reduced coastal upwelling. Whichever outcome dominates, it seems very unlikely that the present situation will be preserved.

## Adaptation and Coping Strategies

There are significant uncertainties in forecasts of some important climate forces on coastal and marine systems, particularly at regional scales. While forecasts of changes in atmospheric CO<sub>2</sub>, air temperature, and sea level are becoming more reliable as model and data resolution increase, potential changes in the timing and strength of regional river runoff, coastal ocean and estuarine temperatures, and coastal circulation remain uncertain. However, enough is known to begin to prepare for such changes.

*Shorelines*. Coastal communities have two general approaches for dealing with sea-level rise: hold back the sea or allow the shore to retreat. Holding back the sea with dikes, seawalls, bulkheads, and revetments generally sacrifices beach, wetlands, and other intertidal zones but leaves dry land relatively unaffected. Along bay shores, shoreline armoring is the most common way to hold back the sea. Delaware, Mississippi, and New Jersey regularly nourish these bay-shore beaches, however, the use of sediment to artificially assist wetland accretion is rare. By contrast, many coastal states have major programs to place additional sand onto their ocean beaches to counteract shoreline erosion.

There are also two ways to ensure human activities do not impede the natural inland migration of shorelines as sea level rises: prevent or discourage development in vulnerable areas, or use rolling easements, which allow development, but prevent structures that lead to loss of wetlands and beaches. Setback lines for coastal development and rolling easements would have to be based on sea-level rise and subsidence projections that include local land movements. Anticipating the consequences of sea level rise now is likely to preserve more natural shorelines than reacting later, because once an area is developed it is too late, and even rolling easements require a lead time of a few decades to be effective.

*Wetlands and Mangroves*. While projected increases in sea level are unlikely to have near-term catastrophic impacts on coastal wetlands and mangroves, when combined with other stresses, long-term consequences may be severe, particularly in areas already experiencing high rates of relative sea level rise. Wetland and mangrove survival depend on their ability to accrete soil or to migrate inland to keep pace with the rising sea. However, sediment supplies limit accretion and developed shorelines limit migration. In areas where easements for upland migration are not feasible, wetlands will have to rely on vertical adjustment. Action to accommodate this could include adjustments in controls of river discharge and sediment supply to facilitate accumulation of substrate, but may be in conflict with social desires for flood control and water supply. Better river management is particularly important in Louisiana, where the Mississippi River provides enough sediment to sustain thousands of square kilometers of wetlands in the face of a rising sea, but human activities prevent that sediment from reaching the wetland.

*Estuaries*. Individual estuaries are likely to respond to changes in sea level, temperature, and freshwater and nutrient delivery in different ways, based on their physical properties (e.g., flushing times). While many degraded estuarine systems have associated substantial societal commitments for restoration through pollution reduction, habitat rehabilitation, and more sustainable use of living resources, few of the restoration plans take into account longer-term, climate-influenced changes in precipitation, runoff regimes, nutrient loads, and salinity. Water management and land-use policies should anticipate changes in the amount and

seasonal distribution of water availability, human demand, and the needs of the estuarine ecosystems. Improved land use practices, such as more efficient nutrient management, and more extensive restoration and protection of riparian zones and wetlands may help meet longer term goals in a wetter future. In a dryer future, estuarine needs will have to be considered in water allocation decisions.

*Coral ecosystems.* Almost all coral reefs that are in good condition are isolated from human populations (Miller and Crosby 1998). While degraded reefs typically suffer from combinations of natural and anthropogenic stresses, the latter are clearly the short-term drivers because coral ecosystems have been able to cope with natural change and variability in the past. Additional anthropogenic stresses are pushing individual reefs across critical thresholds; while at the same time, increasing CO<sub>2</sub> and climate warming are providing a less hospitable environment at global scales. With increases in these longer-term, less controllable climate pressures, the key strategy for corals is to reduce stresses from other, direct anthropogenic pressures such as nutrient over-enrichment, over-fishing, and sedimentation.

*Fisheries.* To cope with climate-induced change and variability, managers must begin to take into account longer time-scale effects in fishery management strategies. Sustainable yields are tied directly to the state of the environment, and exploitation and environmental variability can interact to destabilize harvested populations. Environmental change that results in reduced productivity can lead to a decline or collapse of populations under levels of exploitation that are sustainable under more favorable conditions (Rice 1995). Rather than consider exploitation and environmental change separately, managers must recognize their interaction and adjust their strategies accordingly. Under periods of projected low productivity, allowable exploitation rates must be reduced to account for reduced recruitment rates. Under periods of projected high productivity, harvest limits can be increased.

Climate change likely over the next century will have many consequences for most U.S. coastal and marine ecosystems, and some of these may substantially alter human dependencies and interactions with these complex and linked systems. The climatic effects will be superimposed upon, and interact with, a wide array of current stresses, including excess nutrient loads, over fishing, invasive species, habitat destruction, and toxic chemical contamination. While the ability of these ecosystems to cope with or adapt to climate change or variability is compromised by extant stresses, the inverse is also likely to be true—ecosystems will be better suited to deal with climate variability and change if other stresses are significantly reduced.

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Fig. 1: Projected changes in average annual runoff for basins draining to coastal regions from the Canadian and Hadley Centre General Circulation Models (Adapted from Wolock and McCabe 1999).

Figure 2: Estimated land loss for seven regions of the U.S. without shoreline protection based on projections of current rates (baseline) and sea-level rise of 50 cm and 100 cm over this century (after Titus et al. 1991)

Figure 3: Coastal wetlands response to concurrent changes in relative sea-level and sediment supply (adapted from Reed 1999).

Figure 4: Relationship among annual Mississippi River stream flow, nitrate loads (Goolsby 1999), and aerial extent of hypoxia (Rabalais et al. 1999) in the Gulf of Mexico.

Figure 5: Reductions in coral calcification rates suggested by model results of increasing atmospheric carbon dioxide (Gattuso et al. 1999)

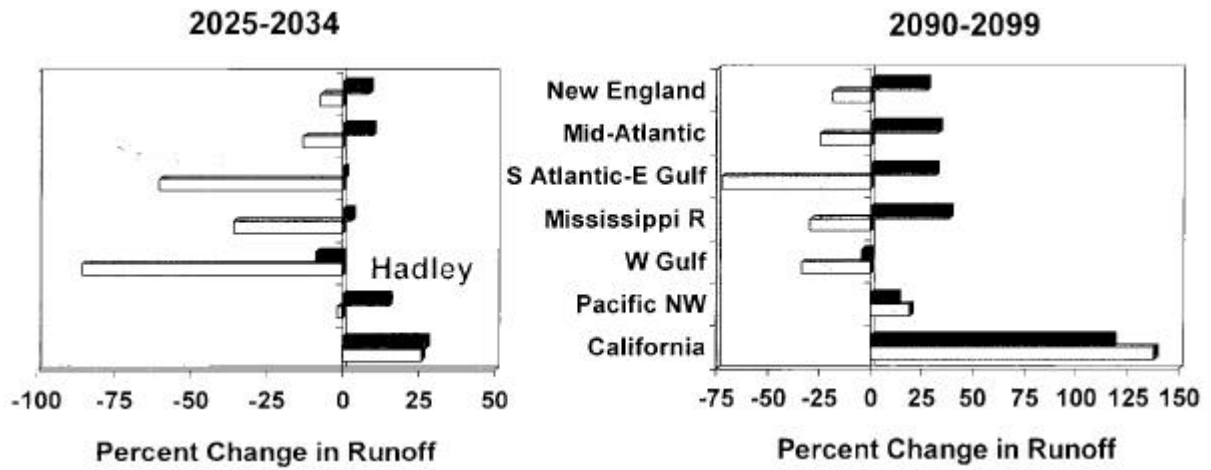


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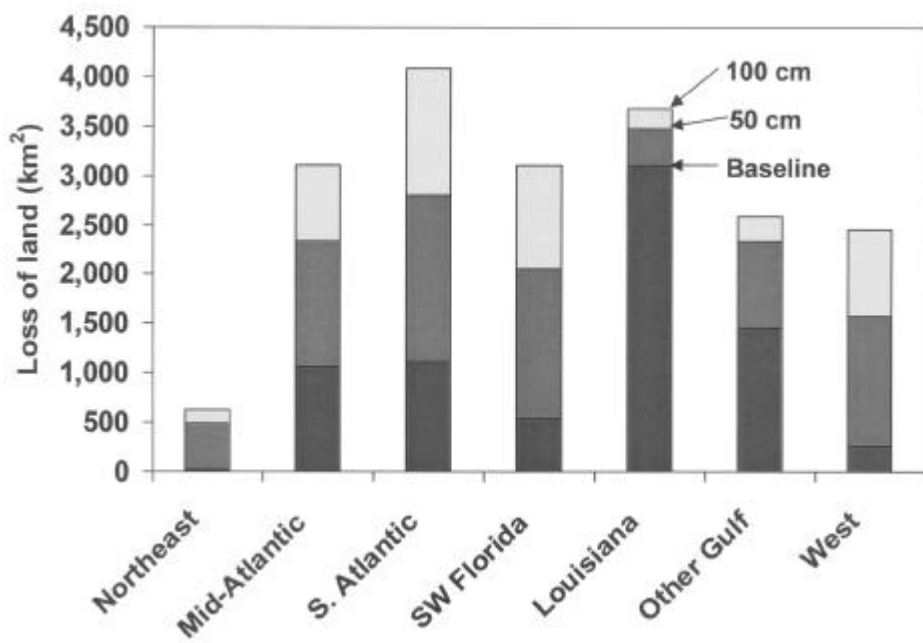


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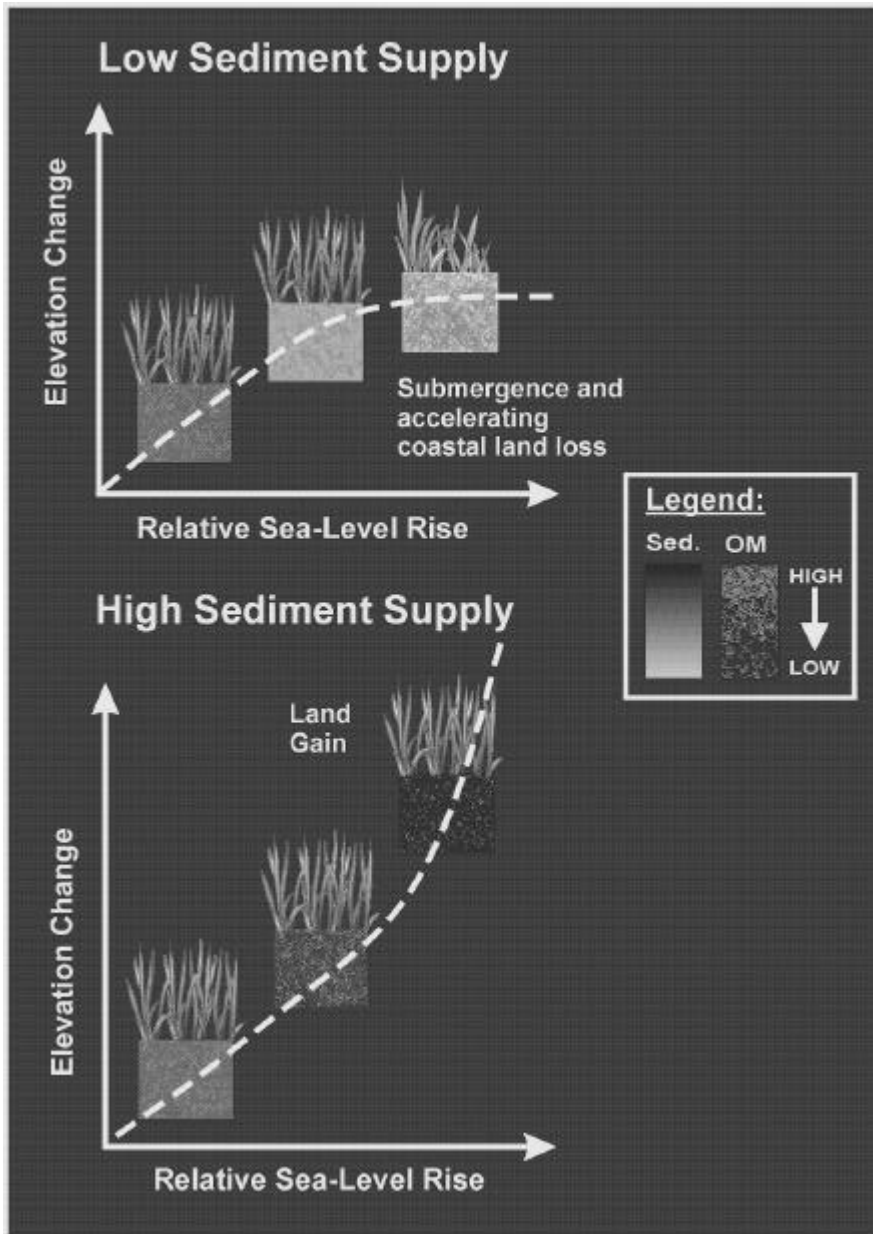


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### Mississippi River flow and nitrate load and Gulf Hypoxia

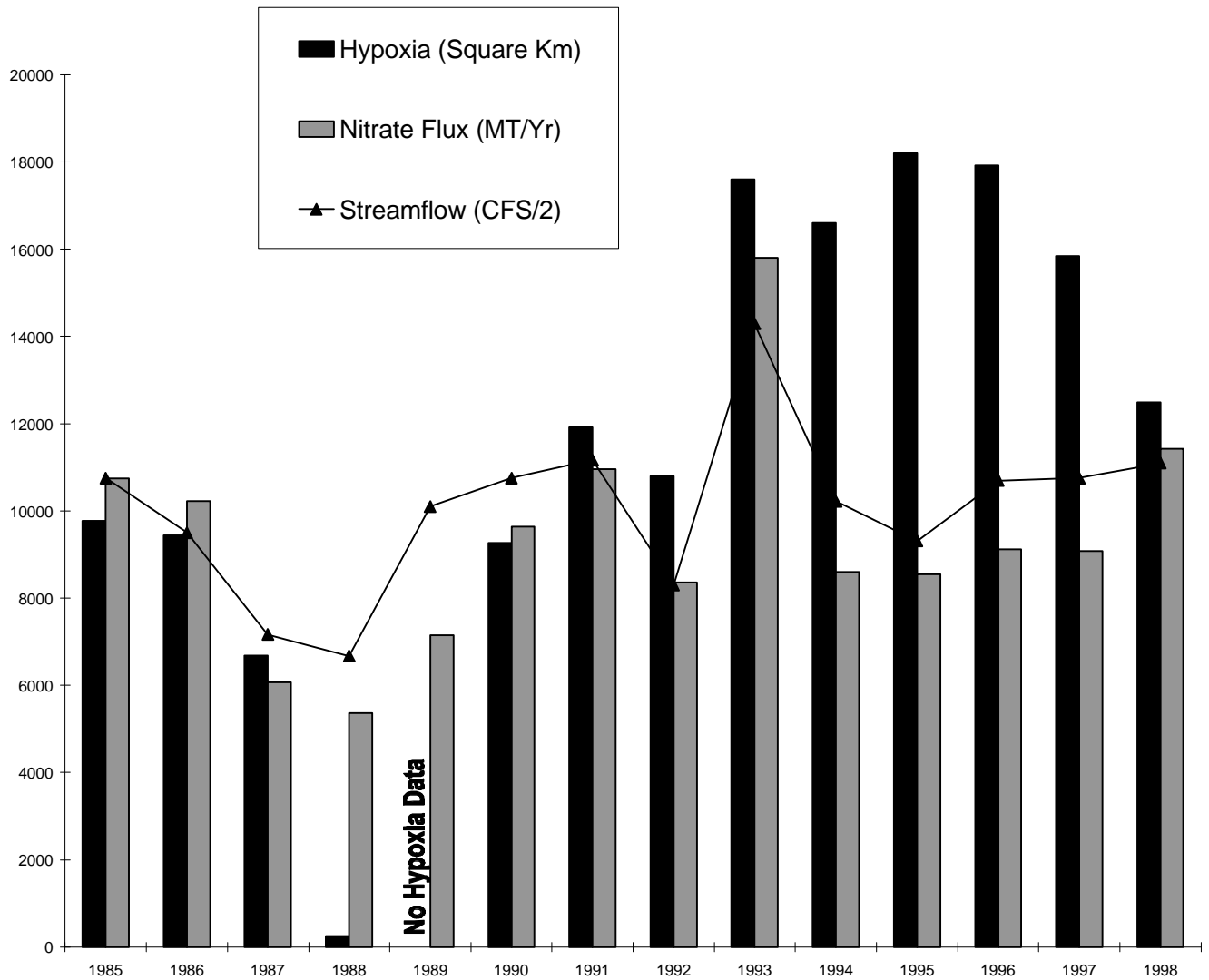


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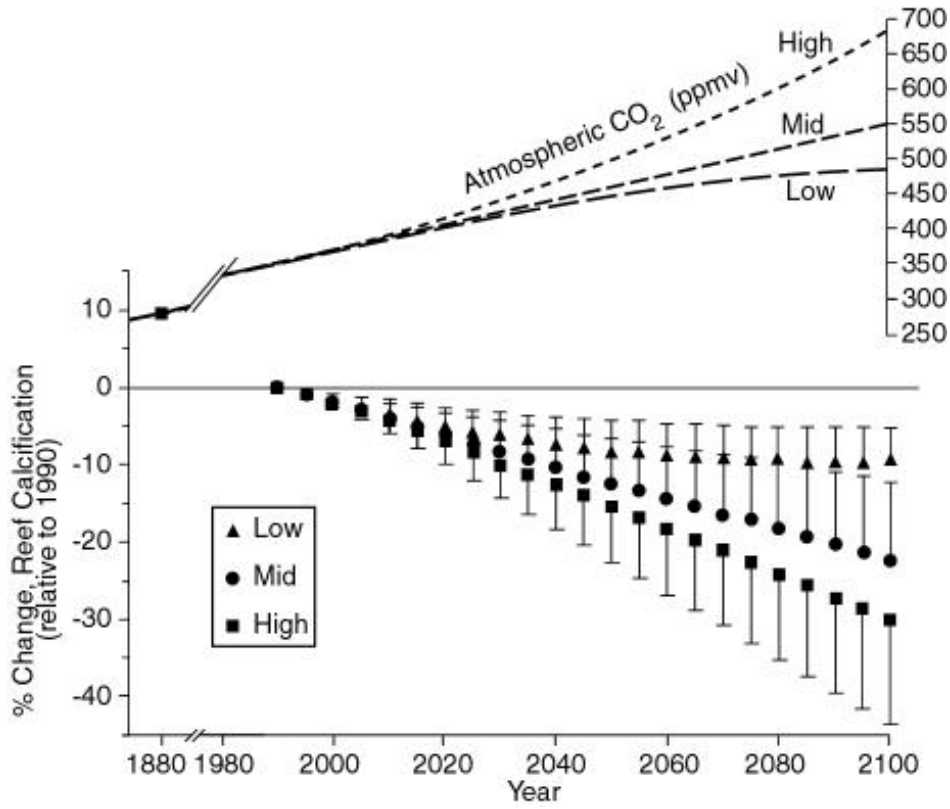


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