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

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ABSTRACT: Increases in concentrations of greenhouse gases projected for the 21st century are expected to lead to increased mean global air and ocean temperatures. 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. The assessment considered the impacts of several key drivers of climate change: 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_2. Increasing rates of sea-level rise and intensity and frequency of coastal storms and hurricanes over the next decades will increase threats to shorelines, wetlands, and coastal development. Estuarine productivity will change in response to alteration in the timing and amount of freshwater, nutrients, and sediment delivery. Higher water temperatures and changes in freshwater delivery will alter estuarine stratification, residence time, and eutrophication. Increased ocean temperatures are expected to increase coral bleaching and higher CO_2 levels may reduce coral calcification, making it more difficult for corals to recover from other disturbances, and inhibiting poleward shifts. Ocean warming is expected to cause poleward shifts in the ranges of many other organisms, including commercial species, and these shifts may have secondary effects on their predators and prey. Although these potential impacts of climate change and variability will vary from system to system, it is important to recognize that they will be superimposed

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upon, and in many cases intensify, other ecosystem stresses (pollution, harvesting, habitat destruction, invasive species, land and resource use, extreme natural events), which may lead to more significant consequences.

Introduction

The 158,000 km of coastline and 8.8 million km^2 of ocean within its territorial sea provide the U.S. with a wide range of essential goods and services through fisheries, biological diversity, oil, gas, mineral deposits, and 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). 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). Population growth increases demand for coastal and marine resources, which increases both the stress on those resources and their vulnerability to climate change and variability. Climate change will interact with these existing and increased stresses, potentially accentuating their negative impacts.

In 1997, the U.S. Global Change Research Program (USGCRP) initiated an assessment of the significance of climate change for the U.S. This National Assessment of Potential Consequences of Climate Variability and Change (NAST 2001) drew on inputs from academia, government, the public and private sectors, and interested citizens, and 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.

Forces of Climate Change

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 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. 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 yr^{-1} (IPCC 1996). Local rates of relative sea-level rise vary from about 2 mm yr^{-1} in New England, Florida, and parts of the Gulf Coast, to 3–5 mm yr^{-1} in the mid-Atlantic, 5–10 mm yr^{-1} in parts of Texas and Louisiana, and anywhere from −10 to +2 mm yr^{-1} 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). 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. Uncertainty about local future sea levels is about 50% greater than for the global average (IPCC 2001).

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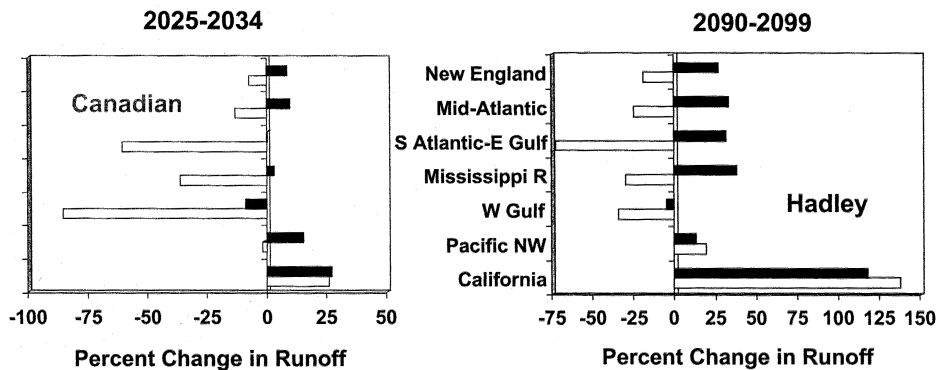
Fig. 1. Projected changes in average annual runoff for basins draining to coastal regions from the Canadian and Hadley Centre General Circulation Models (Data from Wolock and McCabe 1999).

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 the 1990s (Landsea et al. 1996), and this condition of higher activity may last for decades (Bengtsson 2001; Goldenberg et al. 2001). Timmermann et al. (1999) suggest that future 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. During recent severe El Niño events (1982–1983, 1997–1998), 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 1998).

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) and Knutson and Tuleya (1999) 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 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. 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). The Hadley model predicts 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 show a decrease of 32%. While these differences illustrate the uncertainty regarding future rainfall and runoff patterns, both models predict that there will be an increase in extreme rainfall events, which can increase significantly the chemical and sediment load delivered to the coast. This increased flashiness, which already has 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

Based on analysis of five million ocean temperature profiles, mean temperature of the upper 300 m of the oceans has increased by 0.31°C over the past 45 yr (Levitus et al. 2000) with the warming signal observable to depths of 3,000 m. Evidence 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. Barnett et al. (2001) 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. The aerial extent of arctic ice has declined by as much as 7% per decade over the last 20 years (Johannessen et al. 1999) and thinned 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. 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. Retention of phytoplankton in the photic zone improves the grazing success of zooplankton to the detriment of those phytoplankton populations. Although 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 deepwater conveyer 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

SHORELINES AND DEVELOPED AREAS

Natural processes continually change the beach, shoreline, embayment, and nearshore 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. When river flow is stored or diverted, the resulting loss of sediment delivered to the coast can accelerate shoreline erosion; the Brazos River in Texas now delivers only 30% of the volume of sediment to local beaches before dams were build 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
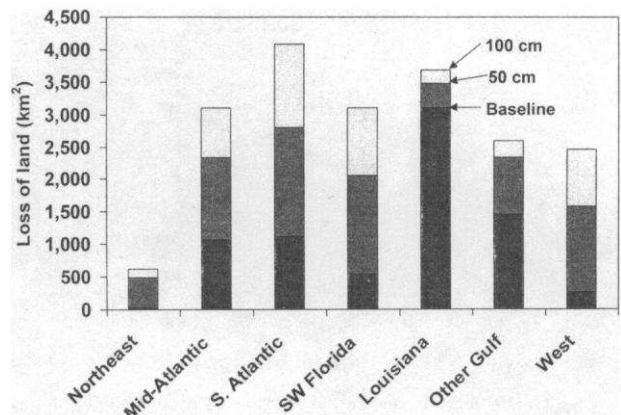

Fig. 2.   Estimated land loss for seven regions of the U.S. without shoreline protection based on projections of current rates (baseline) and sea-level rise of 50 and 100 cm over this century (Titus et al. 1991).

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. Land most vulnerable to inundation is in Florida, Louisiana, North Carolina, Texas, and Maryland (Fig. 2; Titus and Richman 2001). Even those states with relatively little low land 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 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 while the low-lying areas on the lagoon side of the barrier island become increasingly submerged during extreme high tides.

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 caused $27 billion damage in 1992; and Hurricane Georges caused $5.9 billion damage in 1998 (National Climatic Data Center 2001). These estimates represent insured losses only, 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. The November northeaster of 1991 caused damages of over $1.5 billion along the Atlantic Coast. A series of storms that battered the Pacific Coast during the 1997–1998 El Niño caused an estimated $500 million in damage in California alone (Griggs and Brown 1998). Good (1994) showed that 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), so the economic damages will continue to rise even without climate-induced changes in vulnerability. Additional climate-induced effects are likely. While there is no 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. 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 for the 100-year flood. This is also the level to which coastal structures must be built to qualify for support under the National Flood Insurance Program. Increased sea level could mean that a future 50-yr event may be more severe than today's 100-yr flood (Pugh and Maul 1999). Under such a scenario, FEMA (1991) 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. 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. 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_2 and tem-

perature may also have substantial impacts. Increased atmospheric CO_2 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_2 and Rozema et al. (1990, 1991) and others showed increased salt tolerance with elevated CO_2. Increased CO_2 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_2 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). 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. 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 freshwater is likely to decrease osmotic stress and increase productivity, less freshwater may increase salinity stress. Wetlands may accommodate gradual increases in salinity as salt and brackish marshes replace freshwater marshes and swamps, although sustained or pulsed changes in salinity can have dramatic negative effects. *Panicum hemitomon,* a typical freshwater marsh species, grew at a reduced rate in water of 9 psu salinity in one study (McKee and Mendelssohn 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
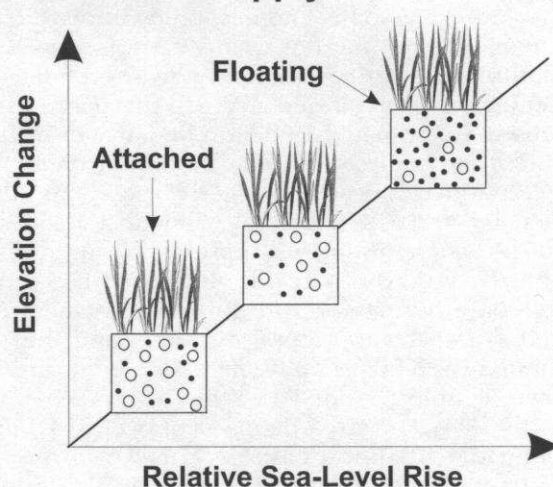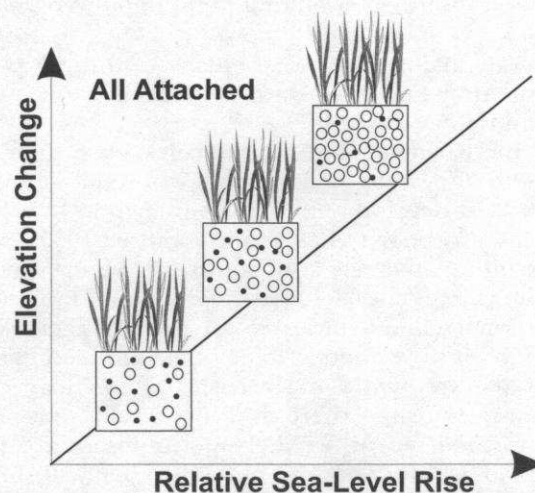

Fig. 3.   Response of coastal wetlands to concurrent changes in relative sea level and sediment supply (Reed 1999). Density of open circles indicates the amount of sediment; black dots indicate the amount of organic matter.

(Adams 1963; Webb 1983). Mangrove forests are confined to high salinity areas, although productivity has been shown to increase with the availability of freshwater (Pool et al. 1977). If mangroves were continually exposed to full strength, or near full strength, seawater then production would likely decline (Snedaker 1995).

Changes in delivery of freshwater 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 struc-

tures. 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 freshwater and sediment. Peat production, which depends on adequate supply of freshwater to maintain root growth and sediments, has allowed mangroves to keep pace with sea-level rise (Snedaker 1995). The availability of sediment is critical and Ellison and Stoddart (1991) predicted 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. Even if frequency and intensity are unchanged, elevated sea levels will bring storm surges further inland. Wetland response to sea-level rise will be case specific, dependent upon interactions between organic matter accumulation, hydrological changes, subsurface processes, and storm events (Cahoon et al. 1995; Reed 1995; Goodbred et al. 1998; Kuhn et al. 1999).

Some lessons may be learned from the Mississippi Deltaic 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 degraded rapidly 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 even more extensive land loss.

ESTUARIES

Estuarine impacts from climate change will be manifested 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 important 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 U.S. show symptoms of moderate to high eutrophication (Bricker et al. 1999).

Climate change will likely influence the vulnerability of estuaries to eutrophication 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; Buskey et al. 1998). 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 eva-potransporation. 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). Impacts in regions experiencing decreased precipitation may be exacerbated because water managers will likely store more freshwater within the watershed in response to drought. The effects of altered residence times can be considerable. Even at their fastest growth rates, phytoplankton populations are only able to double once or twice per day. In estuaries with water residence times of less than a day, phytoplankton are generally flushed from the system as fast as they can grow, reducing the estuary's susceptibility to eutrophication. If residence times increase as a result of altered freshwater delivery, susceptibility will increase. 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 1970s, water residence times were less than one day, but 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 modify salinity regimes. 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; Rabalais et al. 2002). There is considerable interannual variability in nutrient load driven by variation in precipitation and river flow (Fig. 4). Spring floods in 1993 resulted in the greatest nitrogen delivery ever recorded, and the
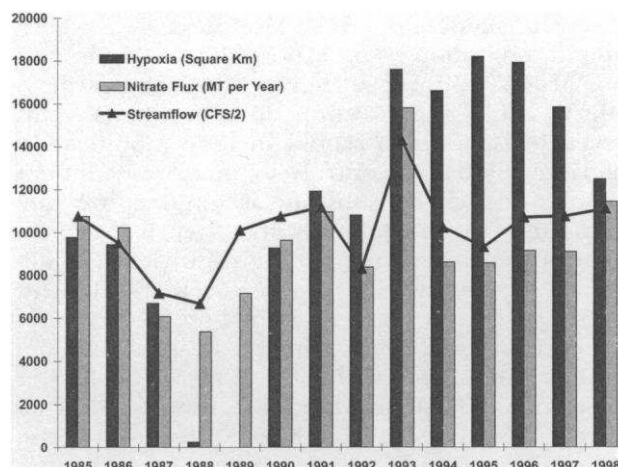

Fig. 4. Relationship among annual Mississippi River stream flow, nitrate loads (Goolsby et al. 1999), and aerial extent of hypoxia (Rabalais et al. 1999) in the Gulf of Mexico.

aerial extent of the hypoxic zone was twice the average of the preceding 8 yr, while the extent of hypoxic waters was small during 1988, concurrent with a 52-yr 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). 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, overfishing, and toxic chemical contamination (Wilkinson and Buddemeier 1994).
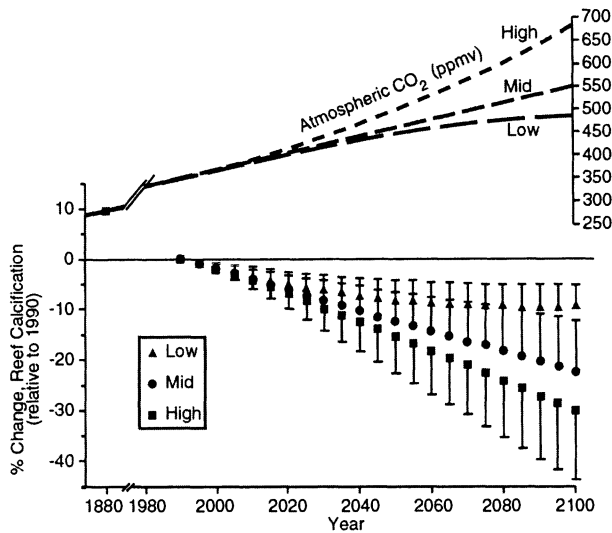
Fig. 5. Reductions in coral calcification rates suggested by model results of increasing atmospheric carbon dioxide (Gattuso et al. 1999).

Most of these stresses interact in complex ways, with both acute and chronic stresses playing critical roles (Kinsey 1988; Hughes and Connell 1999). Coral reef communities are generally regarded as stress-adapted with disturbance playing a key role in sustaining their overall high biodiversity (Connell 1997). Reef communities damaged by acute episodic events will recover if other environmental factors remain generally favorable, and coral communities may persist under sub-optimal conditions in the absence of acute stresses. But once a chronically stressed reef is severely damaged, recovery is unlikely (Hughes 1994). This is important because chronic stresses, such as nutrient loading and overfishing, 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_2. Carbon dioxide, dissolved in seawater, reduces alkalinity and calcium carbonate concentrations which, in turn, decreases calcification rates of reef-building corals and coralline algae. Calcification rates are likely to decline by 17% to 35% by the year 2100 (Fig. 5, Gattuso et al. 1999; Kleypas et al. 1999a,b) 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, bioerosion, some forms of predation, and the corals' ability to compete for space. The effect of increased atmospheric CO_2 will be greatest at the northern and southern margins of coral distributions because CO_2 is more soluble in

cooler waters. 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°C 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°C 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, Caribbean, eastern Pacific, and elsewhere (Williams et al. 1987; Glynn and de Weerdt 1991; Milliman 1993). 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 but 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 yr 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 (Done 1999; Harvell et al. 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. Alterations in temperature, carbonate saturation, and other climate-driven conditions may increase vulnerability to disease.

Changes in sediment, freshwater, and nutrient

loads, as described for estuaries and wetlands, will also affect 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 MARGIN ECOSYSTEMS 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 U.S. commercial fisheries was $3.5 billion 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 movement of ranges for tropical and lower latitude organisms. Along the Northeast coast, cod, American plaice, haddock, Atlantic halibut, redfish, and yellowtail flounder ranges may all move northward, with mid-Atlantic species, such as butterfish 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; these poleward adjustments 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 (Hobrook et al. 1997; Sagarin et al. 1999) along the California Coast.

Other habitat requirements may prevent or limit movement for some species, requiring them to accommodate to higher temperatures (Colton 1972). Because growth, survival, and reproductive output function most efficiently within fairly narrow temperature optima (Brander 1995; Jobling 1996; Cox and Hinch 1997; Marshall and Frank 1999), energetic costs associated with living at sub-optimal temperatures may result in loss of regional populations. By using fisheries and oceanographic data, thermal limits of Pacific salmon, and temperature projections from the Canadian model, Welch et al. (1998) suggested that by 2090 virtually none of the Pacific Ocean may lie within the thermal limits of sockeye salmon (*Onchorynchus nerka*), and that their distribution, and potentially that of other sal-

monids, may be restricted 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). 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). 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). Impacts of these potential changes on sea turtle populations have not been assessed but all marine turtle species found in U.S. waters are listed as endangered species.

Because temperature changes will affect the extent and distribution of polar and subpolar ice, marine mammals and seabirds that use ice shelves and flows as platforms for reproduction, pupping, resting, molting, and migration will also be affected. 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 1994). 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 (Stirling 1997; Tynan and DeMaster 1997) and would presumably be greatly affected by a reduction of the extent of sea ice. 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 (Niebauer 1991; Wheeler et al. 1996). 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 temperature effects on ice distribution, changes in atmospheric dynamics, air temperature, wind stress, and freshwater runoff will al-

ter 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 reduced replenishment of nutrients. 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 et al. 1995). Related physical and biological changes in the marine environment are associated with a reoccurring pattern of inter-decadal 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 correlated with salmon production. The connections between freshwater inflow and production are uncertain but seem to differ from those in the California Current system. 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 affect 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 and therefore 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 (1990) hypothesized that intensified temperature differentials between land and sea, expected under most warming scenarios, will strengthen alongshore winds and increase upwelling. Gucinski et al. (1990) suggested that reduced latitudinal temperature gradients, due to enhanced warming at higher latitudes, will decrease wind field strength, leading to reduced coastal upwelling. Whichever outcome prevails, 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. Forecasts of changes in atmospheric CO_2, air temperature, and sea level are becoming more reliable as model and data resolution increase, but potential changes in the timing and strength of regional river runoff, coastal ocean and estuarine temperatures, and coastal circulation remain uncertain.

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, although the use of sediment to artificially assist wetland accretion is rare. 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 discour-

age 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. 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 other 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 wetlands.

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 wet-

lands may help meet longer-term goals in a wetter future. In a drier 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. At the same time, increasing CO_2 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 overenrichment, overfishing, 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.

Conclusions

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, overfishing, 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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