NOAA Coastal Ocean Program
Decision Analysis Series No.21

COASTAL

The Potential Consequences of Climate Variability and Change

A Report of the National Coastal Assessment Group

For the U.S. Global Change Research Program

October 2000

DECISION ANALYSIS SERIES

The Decision Analysis Series has been established by NOAA's Coastal Ocean Program (COP) to present documents for coastal resource decision-makers which contain analytical treatments of major issues or topics. The issues, topics, and principal investigators have been selected through an extensive peer review process. To learn more about the COP or the Decision Analysis Series, please write:

NOAA Coastal Ocean Program
1315 East-West Highway
Silver Spring, Maryland 20910

phone: 301-713-3338
fax: 301-713-4044
web: www.cop.noaa.gov

Science for Solutions

NOAA's COASTAL OCEAN PROGRAM
Decision Analysis Series Number # 21

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

Report of the
Coastal Areas and Marine Resources Sector Team
U.S. National Assessment of the Potential Consequences of Climate Variability and Change
U.S. Global Change Research Program

Edited by
Donald F. Boesch
John C. Field
Donald Scavia

Assessment Team
Donald F. Boesch, Donald Scavia, Robert W. Buddemeier, Virginia Burkett,
Daniel R. Cayan, John C. Field, Michael Fogarty, Mark A. Harwell, Robert W. Howarth,
Curt Mason, Richard Park, Leonard Pietrafesa, Denise J Reed, C. Thomas Royer,
Ashbury H. Sallenger, Michael Spranger, and James G. Titus

October 2000

U.S. DEPARTMENT OF COMMERCE
Norman Y. Mineta, Secretary
National Oceanic and Atmospheric Administration
D. James Baker, Undersecretary for Ocean and Atmosphere
National Ocean Service
Margaret A. Davidson, Acting Assistant Administrator
National Centers for Coastal Ocean Science
Donald Scavia, Chief Scientist
Coastal Ocean Program
David Johnson, Director

Editors
Donald F. Boesch, University of Maryland Center for Environmental Science
John C. Field, University of Washington
Donald Scavia, National Ocean Service, NOAA

Assessment Team
Donald F. Boesch, University of Maryland Center for Environmental Science
Donald Scavia, National Ocean Service, NOAA
Robert W. Buddemeier, Kansas Geological Survey, University of Kansas
Virginia Burkett, National Wetlands Research Center, USGS
Daniel R. Cayan, University of California, San Diego
John C. Field, University of Washington
Michael Fogarty, National Marine Fisheries Service, NOAA
Mark A. Harwell, University of Miami
Robert W. Howarth, Cornell University
Curt Mason, National Ocean Service, NOAA
Richard Park, Eco-Modeling
Leonard Pietrafesa, North Carolina State University
Denise J Reed, University of New Orleans
C. Thomas Royer, Old Dominion University
Ashbury H. Sallenger, Center for Coastal Geology, USGS
Michael Spranger, University of Washington
James G. Titus, Office of Economy and Environment, USEPA

This publication should be cited as:
Boesch, D.F., J.C. Field, and D. Scavia, (Eds.) 2000. The Potential Consequences of Climate Variability and Change on Coastal Areas and Marine Resources: Report of the Coastal Areas and Marine Resources Sector Team, U.S. National Assessment of the Potential Consequences of Climate Variability and Change, U.S. Global Change Research Program. NOAA Coastal Ocean Program Decision Analysis Series No. # 21. NOAA Coastal Ocean Program, Silver Spring, MD. 163 pp.

Note to Readers

The Potential Consequences of Climate Variability and Change on Coastal Areas and Marine Resources was prepared by a team of scientists, co-chaired by Drs. Donald F. Boesch and Donald Scavia. The National Oceanic and Atmospheric Administration served as the lead agency for this sectoral team of the U.S. National Assessment of the Potential Consequences of Climate Variability and Change. This report is being used as a key resource the National Assessment's overview report.

The Coastal Ocean Program (COP) provides a focal point through which NOAA, together with other organizations with responsibilities for the coastal environment and its resources, can make significant strides toward finding solutions to critical problems. By working together toward these solutions, we can ensure the sustainability of these coastal resources and allow for compatible economic development that will enhance the well-being of the Nation now and in future generations. The goals of the program parallel those of the NOAA Strategic Plan.

A specific objective of the COP is to provide the highest quality scientific information to coastal managers in time for critical decision-making and in formats useful for these decisions. To help achieve this the COP inaugurated a program of developing documents that would synthesize information on issues that were of high priority to coastal managers. As a contribution to the Decision Analysis Series, this report provides a critical synthesis of the potential consequences of a changing climate during the 21st century on the coastal ocean and its living resources. A list of available documents in the Decision Analysis Series can be found on the inside back cover.

As with all of its products, the COP is very interested in ascertaining the utility of the Decision Analysis Series, particularly in regard to its application to the management decision process. Therefore, we encourage you to write, fax, call or e-mail us with your comments. Please be assured that we will appreciate these comments, either positive or negative, and that they will help us direct our future efforts. Our address and telephone and fax numbers are on the inside front cover. My Internet address is coastalocean@cop.noaa.gov.

David Johnson, Ph.D.
Director
NOAA Coastal Ocean Program

Acknowledgements

Many institutional colleagues contributed greatly to the development of this report in terms of ideas, examples and helpful criticism. The Coastal Areas and Marine Resources Assessment Team particularly thanks: Hector Galbraith, who contributed to the shorebirds case study; Jim Allen and Don Cahoon, who assisted in the assessment of coastal wetland impacts; Elizabeth Turner, who provided background information on GLOBEC; and Rob Thieler, who contributed to the section on predicting coastal evolution.

The authors also thank the National Assessment Synthesis Team for its stimulating leadership and its staff, which helped in so many ways. Particularly notable was the patient and dedicated assistance provided by Ben Felzer, Mike MacCracken, LaShaunda Malone, Melissa Taylor, and Justin Wettstein.

Peer reviewers of the report helped greatly in pointing out areas of over or under interpretation, inconsistencies, and important references. These reviewers included: Peter Becker, Suzanne Bricker, Ann Carlson, Mark Davis, Ben Felzer, William Fox, Vivian Gornitz, John Marra, Robert Morton, Susan Moser, Al Strong, Todd Tisdale, Elizabeth Turner, and Warren Wooster. All interpretations and conclusions in the report are those of the Assessment Team; it not should be inferred that they reflect the views of the reviewers.

Finally, we extend our gratitude to Jane Hawkey and Marc Suddleson for the copyediting and final production of the report and to Paul Grabhorn for the cover design.

Table of Contents

List of Figures and Tables

FIGURES

TABLES

Executive Summary

Coastal and marine ecosystems support diverse and important fisheries throughout the nation's waters, hold vast storehouses of biological diversity, and provide unparalleled recreational opportunities. Some 53% of the total U.S. population live on the 17% of land in the coastal zone, and these areas become more crowded every year. Demands on coastal and marine resources are rapidly increasing, and as coastal areas become more developed, the vulnerability of human settlements to hurricanes, storm surges, and flooding events also increases.

Coastal and marine environments are intrinsically linked to climate in many ways. The ocean is an important distributor of the planet's heat, and this distribution could be strongly influenced by changes in global climate over the 21st century. Sea-level rise is projected to accelerate during the 21st century, with dramatic impacts in low-lying regions where subsidence and erosion problems already exist. Many other impacts of climate change on the oceans are difficult to project, such as the effects on ocean temperatures and precipitation patterns, although the potential consequences of various changes can be assessed to a degree. In other instances, research is demonstrating that global changes may already be significantly impacting marine ecosystems, such as the impact of increasing nitrogen on coastal waters and the direct effect of increasing carbon dioxide on coral reefs.

Coastal erosion is already a widespread problem in much of the country and has significant impacts on undeveloped shorelines as well as on coastal development and infrastructure. Along the Pacific Coast, cycles of beach and cliff erosion have been linked to El Niño events that elevate average sea levels over the short term and alter storm tracks that affect erosion and wave damage along the coastline. These impacts will be exacerbated by long-term sea-level rise. Atlantic and Gulf coastlines are especially vulnerable to long-term sea-level rise as well as any increase in the frequency of storm surges or hurricanes. Most erosion events here are the result of storms and extreme events, and the slope of these areas is so gentle that a small rise in sea level produces a large inland shift of the shoreline. When buildings, roads and seawalls block this natural migration, the beaches and shorelines erode, threatening property and infrastructure as well as coastal ecosystems.

Estuaries are extremely productive ecosystems that are affected in numerous ways by climate. Climate change may result in a narrowing of the annual water temperature range of temperate zone estuaries, as winter temperatures increase while summer temperatures increase less because they are moderated by evaporative cooling. This could allow for species range shifts and increase the vulnerability of some estuaries to invasive species. Climate models forecast significant increases or decreases in precipitation and river runoff in various parts of the country and such changes will affect salinity and water circulation. Increased runoff would likely deliver increased amounts of nutrients such as nitrogen and phosphorous to estuaries while simultaneously increasing the stratification between warmer fresher and colder saltier water. This would increase the potential for algal blooms that deplete the water of oxygen and increase stresses on sea grasses, fish, shellfish, and benthic communities. Decreased runoff could diminish flushing, decrease the size of estuarine nursery zones, and allow predators and pathogens of shellfish to penetrate the estuary more deeply. However, changes in water delivery may have beneficial impacts to some systems as well.

Wetlands and mangroves are highly productive systems that are strongly linked to fisheries productivity; particularly in the Southeast, these habitats provide important nursery and habitat functions to many commercially important fish and shellfish populations. Infilling, subsidence, altered hydrology and curtailed supply of sediments have driven dramatic losses of wetlands in this region. In general, coastal wetlands are capable of surviving if they remain at the same elevation relative to the tidal range, which occurs if their soil accretion equals the rate of relative sea-level rise, or if the wetland is able to migrate inland. If this migration is blocked by bluffs, coastal development, or shoreline protective structures, then the wetland will be inundated and eventually lost as rising seas submerge the remaining habitat.

Coral reefs are also extremely valuable resources, providing numerous fisheries opportunities, recreation, tourism, and coastal protection wherever they exist. In addition, reefs are one of the largest global storehouses of marine biodiversity, with vast untapped resources of genetic and biochemical materials and scientific discoveries regarding the evolution of life. The last few years have seen unprecedented declines in the condition of coral reefs. The 1998 El Niño in particular was associated with record sea-surface temperatures and associated coral bleaching. There has also been an upsurge in the variety, incidence and virulence of coral diseases in recent years, with major die-offs reported in Florida and much of the Caribbean region. In addition, increasing atmospheric CO_2 concentrations reduce the alkalinity of surface waters, which in turn decreases the calcification rates of the reef-building corals. The result to coral reefs will very probably be weaker skeletons, reduced growth rates and increased vulnerability to erosion.

Climate change will have important implications for marine ecosystems that support ecologically and economically important fish populations. As a result of changes in ocean conditions, the distribution and abundance of major fish stocks will probably change substantially. Along the Pacific Coast, impacts to fisheries related to the El Niño/Southern Oscillation illustrate how climate directly impacts marine fisheries on short time scales. Elevated sea surface temperatures associated with the 1997-98 El Niño had a great impact on the distribution and abundance of market squid, California's largest fishery by volume. Landings fell to less than 1,000 metric tons in the 1997-98 season, down from a record-breaking 110,000 tons in the 1996-97 season. Many other unusual events occurred during this same El Niño as a result of elevated sea-surface temperatures. Examples include widespread sea lion pup deaths in California, catches of warm-water marlin in the usually frigid waters off Washington State, a series of anomalous plankton blooms, seabird die-offs along the Aleutian Islands, and poor salmon returns in Bristol Bay, Alaska.

Differentiating the effects of climate from human activities in all of these systems is extremely difficult. In general, anthropogenic disturbances often reduce the ability of systems to adapt, so that systems that might ordinarily be capable of responding to the stresses of climate variability and change are less able to do so. It is in this context that climate change will act as major force for coastal and marine environments, interacting with the cumulative impact of both natural and human-caused stresses on ecological systems and resources.

With few exceptions, the potential consequences of climate change are not yet being considered in a management context, despite the fact that it has been shown that planning protection or retreat strategies for coastal developments can substantially reduce the economic impacts of inundation and shoreline migration. Some of these exceptions are the coastal management programs in Maine, Rhode Island, South Carolina, and Massachusetts, which have implemented various forms of easement policies to ensure that wetlands and beaches can migrate inland as sea-level rises. However, scientific uncertainties and the long time scales relative to more immediate problems continue to act as barriers to the development and adoption of management responses. Thus, coping strategies should fully consider and integrate climate variability and change into coastal planning, and implement mitigation and adaptation mechanisms that offer the best chance for the long-term sustainability of coastal resources.

Chapter 1
Introduction

The issues and problems associated with coastal and marine resources, and their current or potential relationship to climate, have continued to receive a high level of national and international attention. Headlines draw attention to subjects ranging from disastrous hurricanes and one of the strongest El Niño events in recent history, to the latest collapse of marine fish stocks and massive coral reef die-offs associated with elevated sea surface temperatures. Thus it should come as no surprise that climate variability, and the potential consequences of future climate change, are of considerable interests to stakeholders, policymakers and the general public, especially as they may act as an additional stressor to coastal and marine resources.

The primary objective of this assessment is to detail the potential impacts to coastal and marine resources associated with climate variability and potential climate change. This is done within the guidelines generated by the National Assessment Synthesis Team, as described below. While the focus will be on the impacts of climate to coastal and marine resources, it has also proven necessary to focus on climate forcing mechanisms to set the stage for those impacts. In addition, individual case studies, which focus on specific ecosystems or issues, have been included to generate an understanding of specific examples of climate impacts.

1.1 THE U.S. NATIONAL ASSESSMENT

Congress mandated that the U.S. Global Change Research Program (USGCRP) to undertake a National Assessment of the Potential Consequences of Climate Variability and Change (P.L. 101-606). To meet this mandate, a process has been developed and applied by the National Assessment Synthesis Team (1998) to analyze and evaluate what is known about the potential consequences of climate variability and change in the context of other pressures on the public, the environment, and the nation's resources. The National Assessment Synthesis Team is a federal advisory committee, drawn from experts from academia, Federal and State agencies, non-governmental organizations, and the private sector.

The National Assessment has three primary components: (1) an analysis which considers the impacts on major economic sectors (water resources, agriculture, forests, coastal areas and marine resources, and human health); (2) regional analyses which identify and characterize potential impacts on some twenty selected geographical regions and are performed by teams of local experts from both public and private sectors; (3) reports that summarize climate model projections and the regional and sector assessments, drawing together these results in a comprehensive National Assessment. All of the regional, sector and synthesis analyses, to the degree possible, have used a common set of scenarios for climate change and socio-economic forecasts. These assessments examine potential consequences over the next 30 years as well as the next 100 years of significant secular changes in climate resulting from projected increases in atmospheric carbon dioxide concentrations. Potential consequences over all time frames consider the possibility of non-linear and threshold responses, especially as might be accompanied by changes in current modes of climate variability or the intensity and frequency of extreme events.

The sectoral and regional assessments have generated, through workshops and quantitative analysis, substantive reports which assess the implications of the National Assessment scenarios. The Coastal Areas and Marine Resources Sector held three workshops and engaged in substantive discussion and thorough review in its attempt to generate the content envisioned by the National Assessment Synthesis Team. This report is the product of this work. Readers interested in the science behind climate change, climate change assessments, general circulation models and other impacts are directed towards the National Assessment Synthesis Team Overview (NAST 2000) and the Intergovernmental Panel on Climate Change (Houghton 1996) reports. Additionally, the products generated by the many regional assessments are invaluable with regard to more detailed region-specific analysis of potential impacts and consequences to localized communities, and interested parties are strongly encouraged to refer to these sources for additionally information.

1.2 METHODOLOGY

Most of the attention devoted to coastal areas and marine resources in past climate change assessments has focused on the potential impacts of accelerated sea-level rise for islands, shorelines, wetlands and coastal communities. While accelerated sea-level rise is indeed a significant consequence of climate change on marine systems, there are many other potential impacts associated with climate that affect a wide range of coastal and marine ecosystems and services. Indeed, there are other significant consequences of changes in biogeochemical cycles on a global scale not necessarily directly related to climate. For example, there are direct consequences to coral reefs and possibly submerged aquatic vegetation (SAV) of increasing atmospheric carbon dioxide levels, independent of the effect CO_2 has on climate. There are also consequences resulting from dramatic changes in the availability of nitrogen and other nutrients in coastal and marine systems resulting from anthropogenic activities.

Assessing the effects of climate variability and change on coastal areas and marine resources is made more difficult by the confounding effects of other human activities. Anthropogenic disturbance often results in the reduction in the adaptive capacity of systems to change and stress, and may mask the physical and biological responses of many systems to climate forces. For example, naturally functioning estuarine and coastal wetland environments would typically be expected to migrate inland in response to relative sea-level rise, as they have done throughout time. However, when such migration is blocked by coastal development, diking, filling, or hardening of upland areas, such habitat is gradually lost by “coastal squeeze” as rising sea-levels push the remaining habitat against developed or otherwise altered landscape. In a similar fashion, biological communities which might be able to tolerate and adapt to changes in temperature, salinity or productivity associated with variable climate regimes might be less able to do so under the cumulative effects of intensive harvest pressure, eutrophication, habitat loss, competition by non-native species and exposure to pollutants or toxins.

Thus, the second section of this assessment focuses on the general status and trends in coastal and marine resources, and in particular on evaluating current and future impacts associated with population concentration and growth in the coastal zone. This section also describes recent trends in the use and management of coastal and marine resources in fisheries, recreation, tourism, development and other societal sectors. From there it moves to a discussion of socio-economic scenarios and forecasts which were used in assessing how changes in demographics, land use, and economics may interact with future climate variability and change to affect coastal and marine resources.

A comprehensive review on climate forcing makes up the third section of this assessment. This has proven to be challenging, due in no small part to the difficulties in ascribing historical variability and model projections to specific effects in coastal systems. This assessment has focused on plausible projections of forcing mechanisms, including sea-level rise rates, changes in storm tracks and frequencies, alteration of freshwater flow regimes, shifts in coastal ocean temperatures ranges and extremes, changes in ocean current patterns and changes associated with large scale atmospheric processes. However, this assessment was not written to provide a review of all of the relationships between oceans, coastlines and climate; such an undertaking would necessarily fill volumes. The reader interested in further resources which address such topics in detail is referred to the IPCC reports (Houghton et al. 1996), as well as NRC (1998), Biggs (1996), Mann and Lazier (1996), and other references cited in this report.

The section on climate forcing is intended to provide a brief foundation for assessing the real and potential impacts of climate to various types of coastal and marine ecosystems. These section are intended to be the primary product of this assessment. Specifically, the five principal ecosystem types examined for the purposes of this assessment were coastal wetlands, estuaries, shorelines, coral reefs and ocean margins. While there is significant overlap in many of these ecosystem types, and there are of course further divisions within these ecosystems as well, this breakdown provides a framework for understanding what may be the most significant anticipated impacts on ecological systems. The human component of these systems in critical; indeed, for the section on shorelines the resources of principal focus are those developed coastal areas and human settlements which are vulnerable to climate impacts. These sections focus primarily upon impacts which are either already occurring or are likely based on past modes of climate variability, forcing scenarios and change thresholds.

To complement the sections on potential impacts, case studies have been inserted throughout the text of this assessment in order to provide specific examples of the complex set of interactions between the effects of climate and human activities. This will allow readers to understand better many of the general issues associated with climate and various coastal and marine ecosystem types, as well as to consider the interaction of multiple climate-related forces within specific regions.

Case studies have also, to the extent practicable, included discussion of potential response strategies which could be appropriate in coping with current and future modes of change. This assessment does not cover potential consequences to the shorelines and lacustrine resources of the Great Lakes region. These were considered by a separate regional assessment under the National Assessment.

Finally, the sections on ecological impacts and the case studies set the stage for drawing conclusions regarding the greatest vulnerabilities and opportunities for coastal areas and marine resources related to current climate variability and future climate change. In this section, the assessment team has attempted to highlight adaptation and coping strategies which could help society to prepare for future consequences. Quite understandably, much remains to be learned with regard to coping with future changes and their associated uncertainties. Thus the assessment concludes by detailing critical information and data gaps, providing direction for future research and assessments, and suggesting some basic principles which might be considered in the context of coastal resource management challenges already being faced.

Chapter 2
Coastal Areas and Marine Resources in Context

The United States has one of the longest and most diverse coastlines in the world, extending over 158,000 kilometers (over 95,000 miles), ranging in habitat type from the tropical Pacific in American Samoa to the permafrost and usually ice covered Arctic Sea in northern Alaska. Over half of this shoreline is found in Alaska. Within these coastal areas lie nearly 39,000 square kilometers (15,000 square miles) of coastal wetlands (high and low salinity marshes, mangroves, and forested wetlands such as baldcypress swamps) and 6500 square kilometers (2,500 square miles) of barrier islands. The United States also has management authority over living marine resources within some 8.8 million square kilometers (3.4 million square miles) of ocean within its territorial sea, including some 16,800 square kilometers (6,500 square miles) of coral reefs. All of these ecosystems support a wide array of habitats and an enormously diverse array of species and communities, and are of fundamental importance to human and societal well being.

Just a few of the ecological services provided by coastal habitats include flood control and water quality improvement by coastal wetlands; the tremendous productivity for fisheries and wildlife of wetlands, estuaries, and the coastal ocean; the buffering effects of storms by barrier islands; and the vast biodiversity in coral reef ecosystems. Coastal areas are used for a wide range of overlapping and often competing uses such as tourism, coastal development and residential living, commercial and recreational fisheries, aquaculture, navigation, trade, national defense, and mineral resource extraction. No less importantly, coastal and marine ecosystems are intrinsically linked to planetary biological and geochemical cycles. Subsequently the health and functioning of these ecosystems is critically important to the health of the planet as a whole.

Although a growing national and international awareness of the importance of the coasts and oceans has increased concern for the integrity of these resources, demands on coastal and marine environments are growing as population and affluence increase both within the United States and globally. In many instances this awareness has generated laws, agencies or programs to mitigate and reverse environmental decline and resolve conflicts. However, there is growing consensus that management on all levels (international, federal, state and local), has not been able to keep pace with the overall increase in pressure on coasts and marine areas (NRC 1997a). The trend of increasing population and pressure on the nation's coastline is certain to continue, intensifying pressure and stress on coastal and marine resources. Thus, the effects of climate change will be experienced concurrently with ongoing and growing pressures due to increasing population and development in most coastal areas.

2.1 COASTAL AREAS AND HUMAN POPULATIONS

Already, the majority of the population of the United States lives within 130 kilometers (80 miles) of the coast, and population growth in coastal areas is more rapid than in the country as a whole. Currently it is estimated that 53% of the total population of the United States lives in approximately 17% of the U.S. land area that is considered coastal (Culliton 1998). These coastal areas are becoming more crowded every year, by far surpassing the national population increase over the last 40 years. In 1960 there was an average of 72 people per square kilometer of coastal land (187 per square mile, excluding Alaska). By 1994 this had increased to some 105 people per square kilometer (273 per square mile) and by 2015 this figure is expected to rise to 126 people per square kilometer (327 per square mile; Culliton 1998). Coastal areas also include 19 of the 20 most densely populated counties in the country, 17 of the 20 fastest growing counties in the country, 16 of the 20 counties with the largest number of new housing units under construction and 18 of the 20 leading counties in per capita income.

To put real numbers on these projections, based on the mid-range population projections used in the National Assessment (NAST 2000), over the next 25 years population gains of some 18 million people are projected to occur in the coastal states of Florida, California, Texas, and Washington (NPA 1999). Note that we have considered “coastal” counties to be those included in state coastal zone management plans; whereas Culliton classified as coastal all counties located either entirely or partially within coastal watersheds. Thus, the absolute numbers may vary slightly between these two estimates, although the trends and implications are certainly consistent. Table 2.1 shows projected growth in coastal counties on a state-by-state basis between 2000 and 2025. Similarly, Figure 2.1 shows these same changes graphically for all coastal counties in the U.S., and Figure 2.2 shows projected economic growth for the same counties. With this ongoing population growth, as well as increased wealth and affluence, rapidly increasing demands on coastal areas and marine resources for both aesthetic enjoyment and economic benefits will continue.

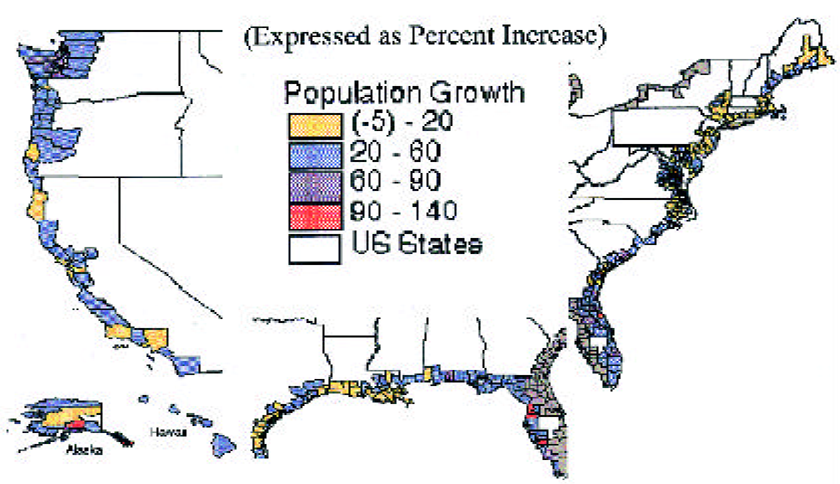

Figure 2.1. Projected percentage increase in population for coastal counties of the United States between 2000 and 2025 (NPA 1999).

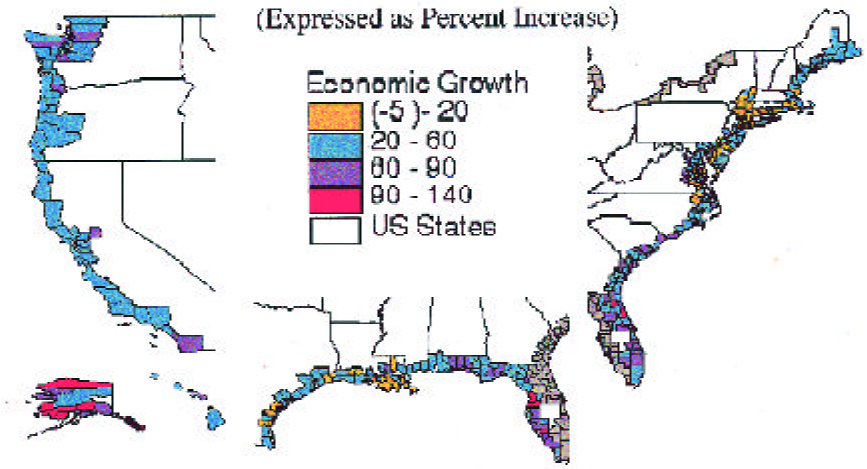

Figure 2.2. Projected economic growth for coastal counties of the United States between 2000 and 2025, as a percentage of current economic output (NPA 1999).

Table 2.1. Population Projections for Coastal Counties (in 1000's of persons) and Percent Change from 1999 Baseline (NPA 1999).

State	Current	2005	2010	2015	2020	2025	Total % Change
Alabama	549	569	594	619	645	672	22.4
Alaska	555	602	666	732	800	870	56.9
California	25208	26175	27475	28892	30419	32032	27.1
Connecticut	2043	2032	2027	2033	2047	2070	1.3
Delaware	749	762	778	797	819	842	12.4
Florida	14663	15800	17248	18751	20297	21889	49.3
Georgia	546	572	607	644	682	721	32.2
Hawaii	1212	1261	1327	1398	1473	1550	27.9
Louisiana	2738	2801	2887	2981	3082	3190	16.5
Maine	761	785	817	850	886	923	21.3
Maryland	3419	3467	3553	3663	3795	3944	15.4
Massachusetts	4659	4696	4765	4860	4979	5116	9.8
Mississippi	353	366	385	406	428	451	27.6
New Hampshire	407	433	462	489	514	539	32.5
New Jersey	7303	7291	7305	7357	7437	7545	3.3
New York	13623	13477	13376	13373	13443	13577	-0.3
North Carolina	823	864	917	973	1031	1091	32.4
Oregon	1331	1412	1512	1614	1719	1826	37.2
Pennsylvania	2827	2794	2777	2785	2811	2853	0.9
Rhode Island	997	1001	1012	1029	1052	1079	8.3
South Carolina	955	1024	1112	1202	1295	1389	45.4
Texas	5365	5659	6034	6426	6833	7255	35.2
Virginia	3308	3430	3595	3771	3955	4145	25.3
Washington	4137	4432	4810	5203	5610	6029	45.7
Total	**98529**	**101706**	**106040**	**110851**	**116054**	**121597**	**24.4**

This large and growing population pressure in coastal areas is responsible for many of the current pressures on coastal resources. For example, the Environmental Protection Agency (1996) estimated that nearly 40% of the nation's surveyed estuaries are impaired by some form of pollution or habitat degradation. Some 30 to 40% of shellfish growing waters in the nation's estuaries have harvest prohibited or restricted each year, primarily due to bacterial contamination from urban and agricultural runoff and septic systems (Alexander 1998). Additionally, over 3,500 beach advisories and beach closings occurred in the United States in 1996, primarily due to storm-water runoff and sewage overflows (NRDC 1997). Population pressures and land and resource uses farther inland also have detrimental impacts on coastal resources. Effluent discharges as well as agricultural runoff have caused significant nutrient over-enrichment in many coastal areas. Sewage and siltation can be significant drivers of coral reef degradation in Hawaii, Florida and U.S. affiliated islands of the Pacific and Caribbean. Dams, irrigation projects and other water control efforts have further impacted coastal ecosystems and shorelines by diverting or otherwise altering the flow of water, sediments and nutrients.

Thus, the list of ongoing stresses to coastal environments is very long and growing. A committee established by the National Research Council to identify priorities for coastal ecosystem science, generated one short list of key threats to the integrity of coastal ecosystems. These include eutrophication, habitat modification, hydrologic and hydrodynamic disruption, exploitation of resources, toxic effects, introduction of non-indigenous species, global climate change and variability, shoreline erosion and hazardous storms, and pathogens and toxins affecting human health (NRC 1994). While this list is not entirely inclusive, the synergies of these ongoing and increasing stresses with climate are key themes and will be exemplified in the sections on impacts and in the case studies below.

2.2 THE IMPORTANCE OF COASTAL RESOURCES TO SOCIETY

Despite these ongoing stresses to coastal environments, the oceans and coastal margins provide unparalleled economic opportunities and revenues. One estimate suggests that as many as one out of every six jobs in the U.S. is marine related, and nearly one-third of the gross domestic product (GDP) is produced in coastal areas (NOAA 1998; NRC 1997a). In 1996, approximately $590 billion worth of goods passed through U.S. ports; over 40% of the total value of U.S. trade and a much larger percentage by volume. New technology has also spurred vast new industries dependent on coastal and marine resources. In the growing field of marine biotechnology, recent research has yielded five drugs originating from marine organisms with a cumulative total potential market value of over $2 billion annually (NOAA 1998).

Fisheries, both commercial and recreational, are a tremendously important economic activity in coastal areas. The U.S. is the world's fifth largest fishing nation and the third largest seafood exporter. Total landings of marine stocks have averaged about 4.5 million metric tons per year over the last decade. Estimates are that the total long-term potential yield – the maximum average catch that could be achieved from all of the nation's fisheries – is over 8 million metric tons per year for U.S. stocks (NMFS 1999). Ex-vessel value, the amount that commercial fishers are actually paid for their catch, was estimated at approximately $3.5 billion for 1997. The total cumulative (direct and indirect) economic contribution of recreational and commercial fishing has been estimated at over $40 billion per year (NRC 1999). However, nearly 30% of the commercially fished species for which trends are known were considered overfished in 1998, while the status of the vast majority of stocks remains unknown (NMFS 1998). Catastrophic fish population collapses and economic disasters have struck most regions of the country. For example in January 2000, the West Coast groundfish fishery joined the New England groundfish fishery in being declared in serious trouble by the Secretary of Commerce. Such fishery collapses have dramatic impacts to both marine ecosystems and the coastal communities which have long been dependent upon these marine resources.

Coastal tourism also generates enormous revenues to coastal communities. Travel and tourism are multi-billion dollar industries in the U.S., representing the second largest employer in the nation (after health care), employing as many as 6 million people (NOAA 1998). It has been estimated that the U.S. receives over 45% of the developed world's travel and tourism revenues, which generate as much as $58 billion per year in tax revenues for all levels of government (Houston 1996). Oceans, bays and beaches are among the most popular tourist destinations in the nation, surpassing even national parks and historic sites in terms of their visitation. As many as 180 million people visit the coast each year for recreational purposes in all regions of the country, and many regions depend upon tourism as a key economic activity. For example one study estimated that in the San Francisco Bay area alone tourism has been estimated to generate over $4 billion a year (USEPA 1997). Clean water, healthy ecosystems and access to coastal areas are critical to maintaining tourism industries, ironically, however, these industries themselves often pose additional impacts to coastal environments and local communities (Miller and Auyong 1991).

As coastal populations increase, the vulnerability of developed coastal areas to natural hazards is also expanding. The most recent numbers indicate that there are an estimated 276,000 households located in areas considered high hazard due to storm surge, and an additional 2.4 million households located in flood plains adjacent to high risk zones (FEMA 1991). Disaster losses are currently estimated at about $50 billion annually in the U.S., compared to just under $4.5 billion in 1970. As much as 80% of these disasters were storms, hurricanes and tornadoes (as opposed to geologically related disasters such as earthquakes and volcanoes) and most of these had their greatest impacts on coastal communities. For example, in the last decade alone Hurricanes Hugo, Andrew and Georges caused, respectively, an estimated $9 billion, $27 billion and $5.9 billion, in damages to coastal communities. Meteorologists and climatologists are constantly improving predictive capability, reducing the risks of death and injury to coastal populations through improved forecasts and preparedness by coastal communities. However, the growing concentration of population and development in coastal areas will ensure that future damages from hazards will continue to rise independent of ongoing and future climatic influences.

In addition to direct economic benefits, coastal and marine ecosystems, like all ecosystems, have characteristic properties or processes which directly or indirectly benefit human populations.

Costanza et al. (1997) have attempted to estimate the economic value of seventeen ecosystem goods and services in sixteen biomes, or ecosystem types, including nutrient cycling, disturbance regulation, waste treatment, food production, raw materials, refugia for commercially and recreationally important species, genetic resources, and opportunities for recreational and cultural activities. For example, the societal values of estuaries, tidal marshes, coral reefs and coastal oceans were estimated at $22,832, $9,990, $6,075 and $4,052 per hectare respectively. On a global basis, the authors suggested that these environments were of a disproportionately high value; covering only some 6.3% of the world's surface area but responsible for some 43% of the estimated value of the world's ecosystem services. These results suggest that the oceans and coastal areas contribute the equivalent of some $21 trillion per year to human activities globally (Costanza 1999).

The approach of Costanza et al. (1997) to valuation is not universally accepted, and the authors themselves agree that ecosystem valuation is difficult and fraught with uncertainties. However, the magnitude of their estimates, and the degree to which coastal and marine ecosystems rank as amongst the most valuable to society, serve to place the importance of the services and functions of these ecosystems in an economic context. As fisheries declines, ongoing problems with coastal eutrophication and increasing storm damages indicate, the capacity of coastal systems to provide these essential services and buffer against the continuing pressures from human development and activities is decreasing. Continuing population growth and development are likely to decrease the resilience of these systems further. It is in this context that climate change will act as an additional stress on these environments, further increasing the vulnerability of both these ecosystems and the coastal communities that depend upon them.

Chapter 3
Climate Forces

Coastal and marine environments are intrinsically linked to, and affected by, climate on all time scales. Precipitation patterns and freshwater runoff, sea surface temperatures and ocean currents, wind, solar radiance, tides, long-term sea-level changes, and numerous additional forcing factors all influence and shape the geophysical and biological nature of coastal landforms, habitats, and ecosystems. Covering some 71% of the earth's surface, the oceans play a critical role in the climate system. They are the major receiver and distributor of incoming solar radiation, with major ocean currents moving heat energy polewards from the equator. Evaporation of water vapor from the surface of the oceans provides latent heat energy to the atmosphere and fuels the hydrological cycle as well as the generation of storms, hurricanes and cyclones. The oceans modulate seasonal and longer variations in climate, and act as a feedback mechanism for weather and climate across all temporal and spatial scales.

Mean temperatures in the ocean directly affect sea-level through thermal controls, and indirectly through feedbacks which partially control the amount of the earth's water tied up in glaciers, ice sheets and the hydrological cycle. The oceans also store heat through thermohaline circulation, in which heat energy in surface waters is transported and distributed into the deep ocean for thousands of years. The oceans are also one of the largest reservoirs of carbon in the biogeochemical system, and moderate the extent of change by acting as a sink for increasing atmospheric carbon dioxide. The oceans are thought to be taking up about one third of the carbon dioxide released by anthropogenic emissions (Siegenthaler and Sarmiento 1993). While speculation as to how the role of the coasts and oceans might change relative to future global change remains difficult, the potential for significant and extreme change should not be discounted.

The climate forces that have consequences for coastal areas and marine resources can be grouped into the following five categories: temperature, ocean currents and dynamics, atmospheric storms, freshwater inputs from land, and sea level variations. These forces interact, however, and a given region will experience the consequences of multiple climate forces. Separate assessment teams within the National Assessment considered the consequences of climate variability and change from a regional perspective. These regional assessments were aggregated for even larger super-regions of the nation for which key issues were identified in the National Assessment Overview (NAST 2000). Table 3.1 provides a thumbnail summary of the key issues identified for these super-regions that involve coastal areas and marine resources, listed under the five primary climate forces. The lack of mention of a climate force issue for a region does not necessarily mean that it is not an issue for the region, merely that it did not rise to the high level of concern meriting attention in the National Assessment Overview. Nonetheless, this summary indicates that for all regions of the nation bordering on the ocean there are multiple concerns and that some concerns are in common among the regions while others are different.

Table 3.1. Key issues involving coastal areas and marine resources identified in the National Assessment Overview for major U.S. regions. Wholly inland regions, including the Great Lakes, are not included.

Region	Temperature	Ocean Currents	Coastal Storms	Freshwater Inputs	Sea-level Rise
Northeast	Stresses on estuaries and bays resulting from sea-level rise		Threats of storm surge on urban transportation	Changes in amount and timing of runoff to estuaries	Coastal wetland loss and limits to migration
Southeast			Hurricane risks to coastal development and storm surge flooding	Water quantity and quality	Coastal wetland and barrier loss; saline intrusion in swamp forests
West				Changes in and competing uses for water resources	Loss of coastal wetlands in San Francisco Bay
Pacific Northwest		Effects of climate variability on salmon		Changing in timing of flows	Impacts on coastal erosion
Alaska	Continued loss of sea ice	Sensitivity of marine ecosystems and fisheries; regime shifts			
Islands in the Caribbean and Pacific	Coral bleaching		Changes in cyclone activity		Erosion, inundation and salt-water intrusion

3.1 OCEAN TEMPERATURES

Atmospheric and oceanic processes work together on a variety of time scales to control both air and surface ocean temperature. The time scales range from the quite predictable diurnal variations caused by solar input and tides, to the much less predictable interdecadal and centennial scale fluctuations. Although atmospheric systems alone become unpredictable beyond several weeks, it has been suggested that with atmosphere-ocean coupling, multi-decadal variations in climate models can be projected (Griffies and Bryan 1997). However, any estimation of future ocean temperatures resulting from either climate variability or change are dependent upon understanding both the coupling between the atmospheric and oceanic processes, as well as improvements in projecting the future variations in those forcing functions. The coupling between these processes is regionally or locally controlled, whereas the climate change models have a more global orientation. Nonetheless, the General Circulation Models (GCMs) used to project future climate conditions provide output in the form of ocean basin temperatures that can be used in considering consequences.

3.1.1 Historical Trends

Perhaps the most important and most frequently measured ocean parameter, due in no small part to its effect on the temperature of the overlying atmosphere, is sea surface temperature (SST). Few records of sea surface temperature exist, although anecdotal, paleoecological and paleochemical studies from prior to the 20th century, hold clues as to earlier temperature changes. However, strong evidence for ocean warming over the last half-century was recently published by Levitus et al. (2000), who evaluated some five million profiles of ocean temperature taken over the period 1948 to 1998. Their results indicate that the mean temperature of the oceans between 0 and 300 meters has increased by 0.31°C over that period, which corresponds to an increase in heat content of approximately 1 x 10^{23} joules of energy. Furthermore, the warming signal was observable to depths of some 3000 meters (Figure 3.1), and the total heat content between 300 and 3000 meters increased by an additional 1 x 10^{23} joules of energy. Although the authors could not conclude that the signal was primarily one of climate change, as opposed to climate variability, they note that their results are in strong agreement with those projected by many general circulation models.

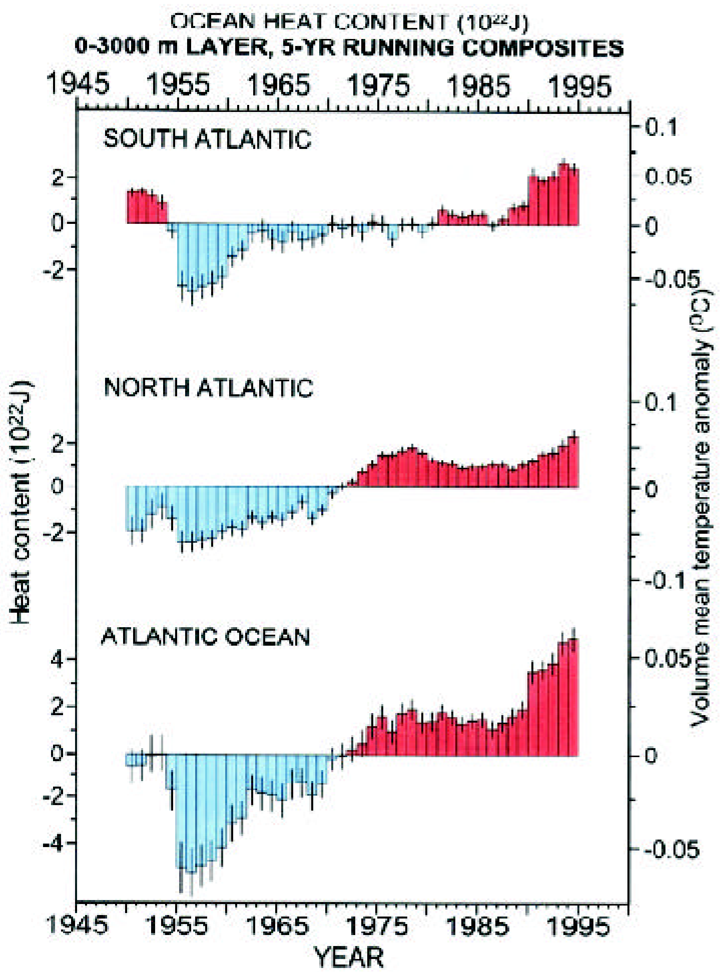

Figure 3.1. Changes in the heat content of the upper 3000 m of the Atlantic Ocean between 1948 and 1998 (Levitus et al. 2000). Vertical lines represent ± 1 SE.

Sea surface temperature is now conveniently measured throughout the globe using remote sensing platforms such as satellites using the Advanced Very High Resolution Radiometer (AVHRR), ships of opportunity, moored and drifting buoys and sampling stations at coastal sites. Since the mid-1970s SST has been measured globally with satellites, however there are often considerable difficulties with these techniques. Coverage is hindered by clouds, and the construction of long time series is complicated by intercalibrations between satellites, the temporal drift in the sensors, and the intercomparison of conventional SST measurements with the satellite measurements of long wave radiation (Wick et al. 1992; Weinreb et al. 1990; Emery et al. 1993).

In addition to the errors in precision, there are sampling errors caused by high frequency fluctuations in the ocean temperature. SST changes daily from solar heating and diurnal coastal sea breezes. Diurnal and semidiurnal tides will create short-term changes in SST from mixing and advection. On longer time scales, the seasonal cycle in SST closely follows the solar heating cycle with the range in the seasonal variability generally increasing with latitude. The ranges are greatest in the coastal regions and are affected by many small-scale nearshore processes. These high frequency changes may alter data sets, appearing as low frequency fluctuations. Because the ocean is vastly undersampled by conventional means, caution should be exercised in addressing decadal and interdecadal ocean temperature changes from these data sets.

In addition to the results of Levitus et al. (2000) described above, historical trends in SST from 1900 to 1991 have also suggested a pattern of warming along the coasts, although this pattern may have been associated with cooling in the offshore (ocean gyre) waters (Cane et al. 1997). Similarly, Strong et al. (2000) using AVHRR data collected since 1984, noted cooling at the center of most basins and apparent warming near the edges of many basins coincident with major ocean currents. Their results also suggested statistically significant warming throughout much of the tropics and in the mid-latitude Northern Hemisphere, and downward trends (although not statistically significant) in major ocean regions over the Southern Hemisphere.

3.1.2 Future Projections of Sea Surface Temperature

It is convenient to separate the problem of ocean temperature projections into East and West Coast segments since the climate forcings are distinct for each. The two climate models used are the Canadian Global Coupled Model (CGCM1) and the Hadley Centre Coupled Model – version 2 (HadCM2). The models are run for 1%/year compounded increase in equivalent CO_2 with IS92a sulfate aerosols. These versions of the climate models are better equipped to handle hydrology, radiation and cloud cover than their earlier versions.

The modeled temperatures are skin temperatures, yet the uncertainty in projections of ultimate changes in sea surface temperatures is large. The diagnostic output of the Canadian model suggests that the largest U.S. coastal air temperature increases during the 21^{st} century will take place off of southern California with an amplitude of 4 to 5°C (Felzer and Heard 1999; NAST 2000). Elsewhere along the U.S. coastline the air temperature increases will be of the order of 3 to 4°C. The greatest temperature increases in the southern California region will occur in winter (December-February;

DJF) while in summer, the increase will be 3-4°C. For the mid-Atlantic region of the east coast of the U.S., there will be a slightly greater increase in the temperatures in summer (4-5°C) than in winter (2-3°C). In general, the Hadley model temperature increases in coastal areas are projected to be less than, but similar in regional distribution to, those of the Canadian model.

Future changes in SST will depend on the exchange of heat between the ocean and atmosphere, the vertical stratification of the water column and the horizontal and vertical advection of heat. The air-sea heat exchange involves a wide range of physical processes, such as sensible heat flux, latent heat flux and long and short wave radiation and heat of fusion from ice formation. The differences in these heat fluxes, advection and mixing processes all help to determine the sea surface temperature. Other air-sea processes, such as precipitation and wind, will also influence the upper layer density structures. Estimates of global climate change influences on winds, precipitation and ocean currents are sometimes considered more precise than surface temperature estimates because they are based on the fundamental equations of motions (B. Felzer, personal communication). Despite this, sea surface temperatures, especially in the coastal regions, are not well projected with the global climate change models.

3.1.3 Air-Sea Interactions and Atmospheric Forcing

As a consequence of global climate change, it is projected that the hydrologic cycle will be intensified, with increased precipitation and evaporation, and varying impacts to coastal runoff. Solar radiation and freshwater inputs result in density differences between surface and deeper waters that have important effects on the stability of the water column and on nutrient regeneration. The result is a layering or stratification with lower density water on the surface and higher density water below. Increases in precipitation and runoff combined with warmer surface temperatures increase the intensity of stratification. This has the potential for both positive and negative effects.

The development of well-defined stratified areas has been linked to the population structure of marine organisms. The development of retentive zones defined by stratified waters and associated fronts can be important in maintaining planktonic organisms within regions where the probability of survival is enhanced. However, strong stratification can impede mixing and nutrient regeneration, potentially resulting in a decrease in primary production in some areas. Increased temperatures and enhanced stratification have been implicated in a decline in production in the California Current system during the last two decades (McGowan et al. 1998). In general, we can expect increased stratification in coastal locations that will be subject to increased runoff and river discharge. In contrast, in open ocean waters, it is likely that higher levels of evaporation could lead to increased salinity, reduced stratification and an increase in the mixed layer depth.

Increased temperatures and river runoff could lead to an earlier onset of stratification and the timing of phytoplankton blooms. This earlier development could lead to a shift in phytoplankton species composition, favoring smaller forms such as dinoflagellates and increasing the number of links in the food web (Mann and Lazier 1996).

Wind stress increases (associated with increased cyclonic activity) will enhance the vertical mixing, tending to decrease the vertical stratification and possibly acting as a negative feedback to SST. With increased cyclonic activity, there may also be increased vertical advection driven by coastal convergences or divergences that depend on the coastal orientation and wind direction. Generally, a coastal convergence will increase the upper layer temperatures with increased stratification. Coastal divergences usually bring cooler, upwelled water to the surface. In addition to the vertical advection of heat, increased coastal winds will also alter the horizontal advection. An enhanced winter low pressure system off the West Coast, as well as a weakened subtropical high in over the southwest, are projected for winter months by the Canadian and Hadley models. These might also contribute to a more northward flow, as well as an onshore flow with coastal convergences. The density contrast between the coastal and offshore waters may also be increased, further enhancing the alongshore (northward) baroclinic flow. These processes may all contribute to increases in coastal sea surface temperature.

In contrast to the West Coast, enhanced low pressure systems off the East Coast projected by the two GCMs for winter (DJF) suggest an increased southward flow (both direct wind driven and baroclinic flow) along with an enhanced onshore component and coastal convergence. This southward transport should advect cooler water from the north along the East Coast, although coastal convergence will increase the upper layer stratification. It is likely that the vertical advection (convergence/downward flow) will be more important here than the horizontal advection and will increase the upper layer temperature. The variations of the SSTs from the two coasts is consistent with the surface temperatures projected from the global climate models that suggest that the surface temperature increases will be less on the East coast than for West coast waters.

Increased anticyclonic atmospheric activity along the West and East coasts could possibly have the opposite effects from the increased cyclonic activity. The increased summer anticyclonic system along the West Coast could increase southward transport, reduce northward baroclinic flow and subsequently enhance upwelling; all of these processes could reduce average summer SST. On the East Coast, there could be increased northward transport, decreased southward baroclinic flow and increased coastal divergence (upwelling). The alongshore flow changes could increase surface water temperatures, while increased upwelling might tend to reduce SSTs. The complex interactions of ocean margin currents, density stratification and upwelling, and surface warming make future temperature predictions in the coastal ocean very uncertain.

In contrast to continental shelf waters, the future temperature regime of more confined coastal bays and estuaries will be determined more directly by changes in air temperature. Consequently, the temperatures of these shallow waters are expected to track more closely the projections of regional air temperatures by the GCMs. Thus, it is expected that considerably warmer conditions will prevail for much of the United States. This will probably be more so in winter than in summer, when evaporative cooling is expected to moderate the coupling between air and shallow-water temperatures.

3.1.4 Changes in Sea Ice Extent

Increases in temperature will also result in further melting of sea ice in polar and subpolar regions, with direct effects on the input of fresh water into these systems with attendant effects on buoyancy-driven flow and stratification. Winter sea ice covers as much as 15 million square kilometers (nearly 6 million square miles) in the Arctic, nearly twice the total land area of the U.S. Presently, the area of sea ice shrinks down to approximately 7 million square kilometers (nearly 3 million square miles) during the summer. The reduction and potential loss of sea ice has enormous feedback implications for the climate system; ice and snow are highly reflective surfaces, returning 60 to 90% of the sun's incoming radiative heat back to outer space. By contrast, open oceans reflect only 10 to 20% of the sun's energy. Thus, the conversion of the Arctic ice cap to open ocean could greatly increase solar energy absorption, and act as a positive feedback to global warming.

Observations in the Arctic have already shown significant declines in ice extent, and recent work suggests that the declines may be occurring at a much greater rate than previously thought, with ice extent shrinking by as much as 7% per decade over the last 20 years (Johannessen et al. 1999). Other observations suggest that these rates may be underestimating the actual loss of volume of sea ice. By some estimates, Arctic sea ice has been thinning (and subsequently decreasing in volume) by as much as 15% per decade (Rothrock et al. 1999). Additionally, record low levels of ice extent occurred in the Bering and Chukchi seas during 1998, the warmest year on record. During 1998 the late summer ice extent in this region declined by as much as 25%; less than had been recorded over the previous 45 years (Maslanik et al. 1999). This followed both low ice extent in the 1997 season as well as anomalous atmospheric conditions throughout the region between the summer of 1997 and the fall of 1998. However, preliminary estimates from the 1999-2000 ice season suggest that this season has had the most extensive initial ice coverage observed in the Bering Sea over the last 20 years (Stabeno 2000).

Some have suggested that a possible mechanism for observed sea ice declines may be interdecadal variability associated with the Arctic Oscillation, a decadal scale mode of variability in atmospheric pressure over the Arctic pole. However, comparisons with other GCM outputs (the Geophysical Fluid Dynamics Laboratory model and the Hadley Centre model) strongly suggest that these observed declines in sea ice are related to anthropogenically induced global warming (Vinnikov et al. 1999). Additionally, these two models strongly suggest continued and accelerated declines in ice extent and thickness over the next century; in the Canadian model Arctic sea ice almost melts entirely by 2100 (Figure 3.2). If the observed decreases in sea ice are a result of global warming, then further retreat of Arctic ice cover can be expected and in the worst case scenario a complete loss of Arctic sea ice could occur during the next century. However, if the observed trends are related to interannual variability, they might be expected to moderate the extent of ice loss, or possibly reverse the observed trend in the relatively near future. Ongoing trends in sea ice loss will have dramatic consequences for both the climate system and Arctic ecosystems (Hunt et al. 1999).

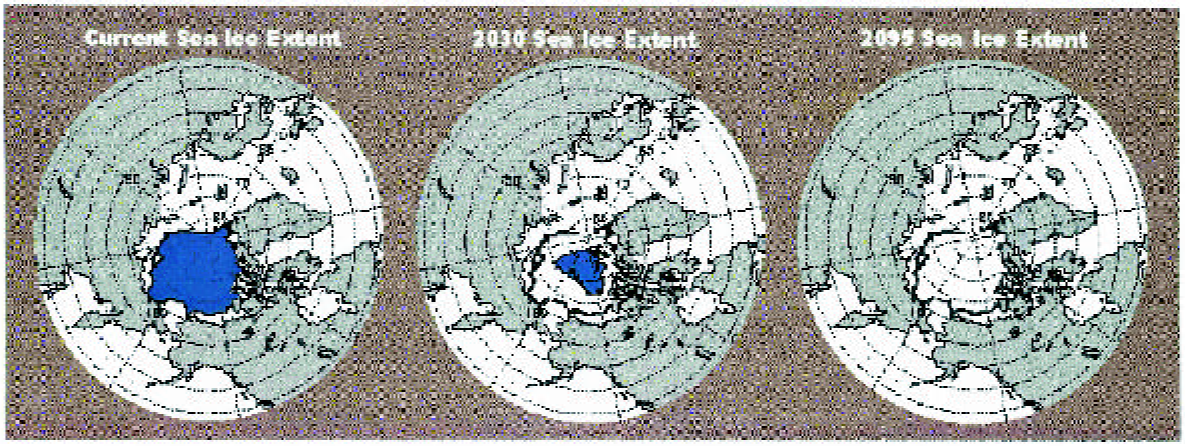

Figure 3.2. Change in the extent of summer sea ice in the Arctic projected by the Canadian Climate Center model.

3.2 OCEAN CURRENTS

Major ocean current systems can be affected in critical ways by changes in global and local temperatures, precipitation and runoff, and wind fields. Similarly, oceanic features such as fronts and upwelling and downwelling zones will be strongly influenced by variations in temperature, salinity, and winds. These changes will be manifest on scales ranging from the relatively small spatial and temporal scales characteristic of turbulent mixing processes, to those of the deep ocean circulation with global-scale changes occurring over millennia. Some of the potential pathways for the impact of these forcing variables on oceanic dynamics and possible biological responses are depicted in Figure 3.3. Changes in processes occurring on this spectrum of spatial and temporal scales are critical to understanding the implications of global climate change on ocean dynamics and for living marine resources. The physical structures and processes under consideration in this section have important implications for overall levels of biological productivity in the ocean.

3.2.1 Dominant Patterns of Ocean Circulation

Ultimately, input of solar energy drives circulation patterns in the world-ocean. Major current systems of importance in North America are shown in Figure 3.4. The amount of incoming solar radiation varies between the equator and high latitude regions, and this differential drives the tradewinds, which in turn create subtropical ocean circulation patterns with characteristic clockwise gyres in the north Atlantic and Pacific oceans. At high latitudes, subpolar gyres develop (with counterclockwise flow) under the influence of the prevailing westerly winds. In the Atlantic, the North Equatorial Current flows westward, ultimately feeding regional current systems such as the Antillies, the Loop Current in the Gulf of Mexico, and the Florida Current. Along the western boundary of the subtropical Atlantic gyre, the rapidly flowing Gulf Stream extends northward, ultimately traversing the northern Atlantic where it feeds the North Atlantic Current and the Azores Current. The subpolar gyre in the North Atlantic results in the strong, southward flowing Labrador

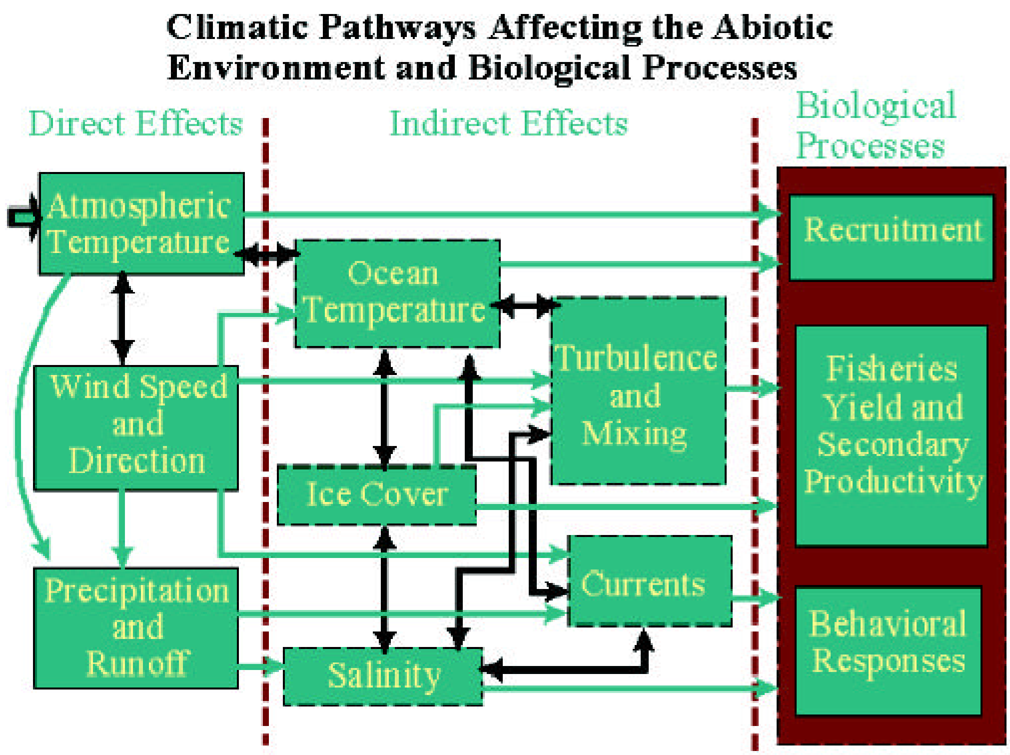

Figure 3.3. Climatic forces have many direct and indirect effects on important biological processes in the ocean.

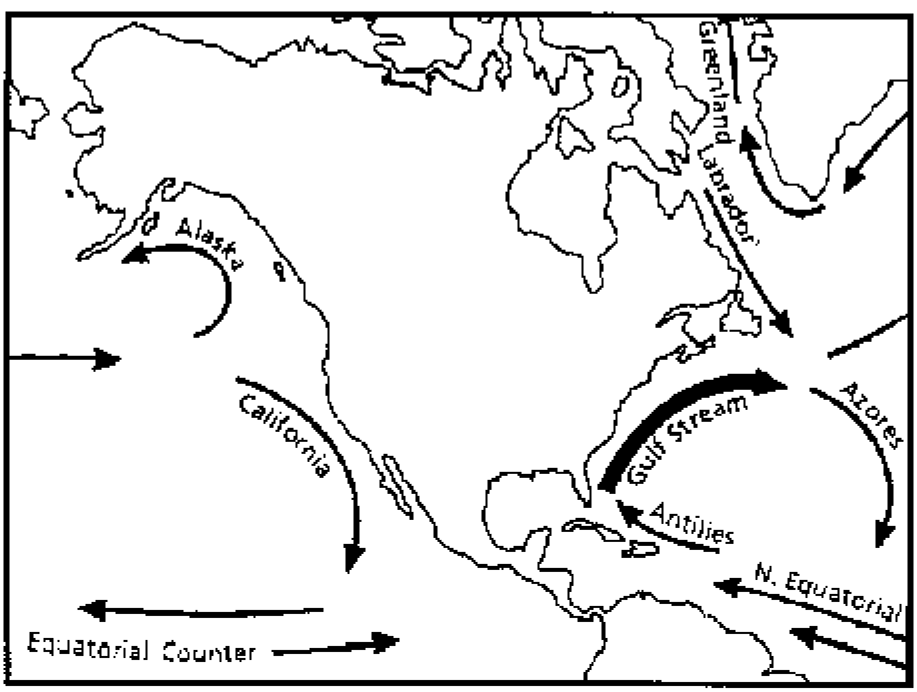

Figure 3.4. Major Pacific and Atlantic Ocean current systems of importance to North America.

Current. Flows along the continental shelf of the Atlantic seaboard are generally to the south; localized conditions result in a counterclockwise flow in the Gulf of Maine and a clockwise circulation pattern on Georges Bank.
In the North Pacific, the North Equatorial Current flows westward, ultimately feeding the northward flowing Kuroshio Current (the Pacific counterpart to the Gulf Stream) off Japan. The eastward flowing North Pacific Current splits off the West Coast of North America and forms the southward flowing California Current (which completes the subtropical gyre) and the northward Alaska Current (which is part of the counterclockwise subpolar gyre in the North Pacific. The California Current is a classical upwelling system with cold, nutrient-rich waters from depth replacing the surface waters which are displaced offshore. By contrast, downwelling is seasonally prevalent in the Alaska Current system. The Alaska Current is strongly affected by buoyancy-driven factors related to precipitation and runoff, as is the Labrador Current in the Atlantic.

These current systems play major roles in the dispersal of marine organisms and in the productivity of marine ecosystems. In the following, the potential effects of climate change on these current-generating mechanisms will the explored. Representation of oceanic features is still in an early phase of development in GCMs. The spatial resolution employed in climate modeling efforts to date has been low relative to the scale of the oceanic structures of interest although some results are now available for the deep ocean circulation. Subsequently, accurate assessments of the potential changes in ocean dynamics will be somewhat tentative until GCMs with finer resolution of ocean processes are developed.

3.2.2 Potential Changes in Wind Driven Processes

Anticipated increases in temperatures at high latitudes should lead to decreased temperature gradients from low to higher latitudes resulting in an overall projected reduction in global wind fields. Wright et al. (1986) have suggested as much as a 10% reduction in the wind strength in the Atlantic. This in turn would lead to a reduction in the flow of the major wind-driven gyres. Accordingly, one might expect a weakening of flow in the Gulf Stream. The formation of Gulf Stream rings and eddies would be diminished at lower flow rates. Warm core rings have been associated with advective loss of marine planktonic organisms from continental shelf waters and therefore a decrease in ring activity may reduce one potential source of loss for the early life stages of commercially important species, resulting in a positive effect. In the Pacific, the strength of the California Current is expected to decrease due to the general decrease in atmospheric circulation as a result of a reduction in the west wind drift (U.S. GLOBEC 1994).

Several major atmospheric circulation patterns have important consequences for climate and ocean dynamics in North America. Low pressure systems over Iceland and southern Greenland and over the Aleutians (and high pressure systems over the Azores and over Siberia) play a dominant role in climate patterns. In the Atlantic, counterclockwise flow of air around the Icelandic low draws cold arctic air over eastern Canada, the Labrador Sea, and Baffin Bay and brings warm moist air to western Europe. Deepening of the low pressure system over Iceland results in an increase in westerly winds, colder winters over eastern Canada and warmer winters over western Europe. The

North Atlantic Oscillation (NAO) Index (the difference in sea-level pressure between Iceland and the Azores) has been used to monitor the changes in this system over a century. Persistent decadal scale changes in this index during winter have been recorded during this period. Since the late 1960's the NAO index has been in a positive phase, indicating colder than normal temperatures over Labrador and Greenland and warmer temperatures over western Europe. Projections for the NAO over the next century based on the Hadley and Canadian climate models, however, show no trend in the index over time; however the Canadian model does suggest substantial changes in the Arctic Oscillation (Fyfe et al. 1999).

Changes in the strength of the Aleutian low pressure system have been linked to regime shifts in the North Pacific (Beamish 1993; Mantua et al. 1997). Intensification of this low pressure system is linked to an increase in wind stress and an increase in surface water temperatures in coastal regions of the Northeast Pacific. These changes have important implications for biological production in these regions which are discussed in detail in section 4.5. The Canadian climate model predicts an increase in the Pacific North American Index (PNA, based on sea-level pressure measurements in the North Pacific) over the next century, particularly after 2050. The Hadley model, however, predicts a generally lower PNA index in the latter part of the next century, although it does produce a strengthening and southward shift of the Aleutian Low by 2090. A climate index based on water temperature patterns over the North Pacific (the Pacific Decadal Oscillation, or PDO Index) is projected to increase in the both the Canadian and Hadley models with a stronger trend in the former.

The second major consideration for wind-driven processes involves intensity of upwelling and downwelling processes. The trade winds drive surface waters away from the west coasts of North and South America and these surface waters are replaced by deeper nutrient rich waters, resulting in high levels of primary productivity in these upwelling regions. Factors affecting wind fields therefore will affect the intensity of upwelling. Bakun (1990) has argued that increased heating over land could exacerbate the differential between land and sea temperatures, leading to increased local winds and therefore increased localized upwelling. In general, heating over land causes increased land/sea temperature gradients during summer months, but the reverse is usually true in the winter. Possible changes in the frequency and intensity of El Niño Southern Oscillation (ENSO) events will also have important consequences for upwelling in the California Current System (Timmerman et al. 1999; see also a review by Meehl et al. 2000). The Canadian model shows a steady decrease in the Southern Oscillation Index (SOI; sea-level pressure difference between Darwin Australia and Tahiti). A lower index favors El Niño conditions and therefore more frequent ENSO events are projected under this model. By contrast, the Hadley model shows no clear trend in ENSO events until a quadrupling of atmospheric carbon dioxide concentrations (Collins 2000).

3.2.3 Potential Changes in Buoyancy-Driven Circulation

Increases in precipitation and runoff can be expected to influence flow strongly in systems such as the Labrador Current (Wright et al. 1986; Frank et al. 1990) and the Alaska Current. With increased runoff, the density of the immediate coastal waters is reduced, increasing the density gradient between inshore and offshore waters. This density differential results in an alongshore flow (to the south on the east coast and to the north on the west coast of North America). Increases in precipitation and runoff in higher latitudes under various climate change scenarios will result in an intensification of the buoyancy-driven component of flow in these systems. Temperature increases and resulting ice melt in high latitudes can be expected to contribute to an intensification in this system. It is expected that the Labrador Current will intensify under the projected changes in rainfall and runoff. Increased flows may lead to increases in turbulent mixing and in eddy formation, resulting in enhanced exchange of nutrients in some regions.

Projections of rainfall patterns in the Atlantic region of the United States differ sharply between the Hadley and Canadian climate models (see section 3.4) with the Hadley model predicting an increase while the Canadian model predicts a decrease. An increase in runoff will result in projected increases in southward flow and transport along the eastern seaboard while the decrease projected by the Canadian model will result in decreased southward transport. The longer-term projections for freshwater delivery along the Gulf Coast generally indicate reductions and if this happens we can expect declines in the westerly coastal flows in the Gulf region. By contrast, the expected increase in precipitation along the West Coast of the conterminous United States could result in enhanced northward transport. Off Alaska, projected increases in precipitation in this region can be expected to strengthen the northward flowing Alaska Current.

3.2.4 Potential Changes in Deep Ocean Circulation

As noted above, warm water from the subtropical gyre in the Atlantic is transported to the north by the Gulf Stream, ultimately feeding the Norwegian, East Greenland and West Greenland currents. As this water cools and increases in density, it sinks and fills the deep ocean basins and is replaced by warmer surface waters from lower latitudes. This thermohaline circulation pattern, illustrated here schematically in Figure 3.5, has been called conveyor-belt circulation because of this distinctive transport pattern. This thermohaline circulation is a major mechanism of redistribution of heat in the oceans with important effects on climate patterns. Other sources of deep water formation based on this mechanism include the Weddell Sea in Antarctic waters.

Increased temperature and/or decreased salinity at high latitude could result in a reduction in the deep-water formation with important consequences for this convective system (Broecker 1997). It is known that during the last glaciation, the conveyer-belt circulation slowed and may have stopped (Broecker 1985; Imbrie et al. 1992, and 1993). The formation of intermediate water in the Labrador Sea is expected to decrease as a result of increased freshwater inflow and decreased winds (Wright et al. 1986). The important role of intermediate water formation in the Labrador Sea for convective flow in the Atlantic has recently been highlighted (Sy et al. 1997).

Projections by the Hadley Centre model suggest that a decline in the strength of the deep water thermohaline circulation by approximately 25% under a scenario of a 2% increase in CO_2 per year up to a quadrupling of current CO_2 levels (Wood et al. 1999). This would lead to a general cooling in Europe with a reduction in transport of warmer waters from lower latitudes (Driscoll and Haug

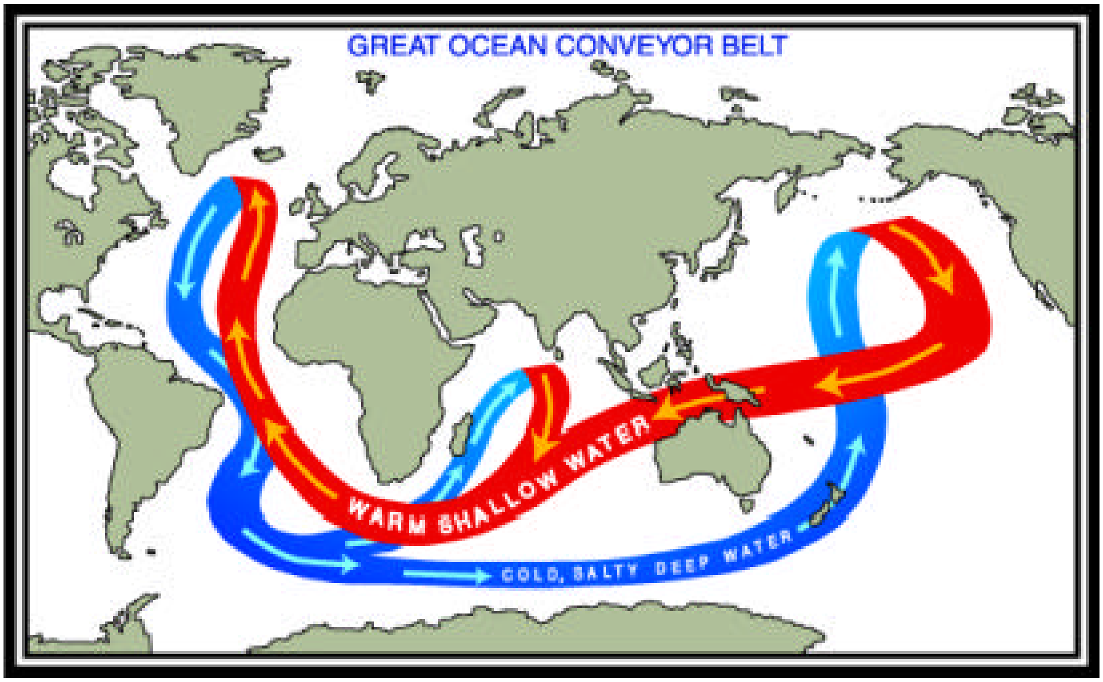

Figure 3.5. The ocean plays a major role in the distribution of the planet's heat through deep sea thermohaline circulation connecting the world's oceans (modified from Broecker 1991). Often referred to as the ocean "conveyor belt", this climate regulating system brings temperate weather to northwestern Europe and could dramatically slow as a result of global warming as it has in the geological past.

1998); however, any such decrease could be offset by greenhouse warming. It should also be noted that the levels of CO_2 increase in this scenario are higher than anticipated under most projections for greenhouse gases. Earlier projections had indicated that change of this magnitude could halt the deep water circulation entirely (Manabe and Stouffer 1993). Sedimentary records do suggest that rapid shutdowns of thermohaline circulation have occurred in extremely short time intervals. Ironically, the result could be further acceleration of global warming trends, as a result of a decrease in the oceanic uptake of carbon dioxide that would likely follow weakening or cessation of thermohaline circulation (Sarmiento and Le Quere 1996).

3.2.5 Changes in Ocean Structure and Dynamics

Changes in temperature, precipitation and wind also have important potential implications for oceanographic features such as stratification, the position of frontal zones, and mixing processes. These factors, which are also covered in Section 3.1, have important implications for issues such as retention and loss of organisms, nutrient regeneration, and production processes in the sea.

Changes in wind-driven vertical mixing can be expected to have several important effects. Changes in the mixed layer depth with changes in wind stress have been implicated in changes in primary production in the Northeast Pacific with associated changes in salmon production (Hare et al. 1999). Wind stress also affects turbulent mixing, which is hypothesized to affect the feeding success of the early life stages of fish. Lasker (1975) suggested that reduced turbulence and calm conditions would enhance survival of anchovy larvae. In contrast, increased levels of turbulence are hypothesized to increase contact rates of fish larvae and their prey. High turbulence levels decrease the probability of successfully capturing prey, however, and prey ingestion rates are therefore highest at intermediate levels of wind stress and turbulence (MacKenzie et al. 1994).

Frontal zones, at the interface between stratified and well-mixed waters, are typically highly productive regions. Important fronts are associated with strong tidal mixing areas, at the break between the continental shelves and the continental slope, upwelling zones, the mouths of estuaries and rivers, certain topographic features (e.g., submarine canyons, islands, etc.). Increased precipitation and runoff has the potential to shift the location of coastal fronts farther offshore while tidal fronts may shift to shallower water (Frank et al. 1990). Such a shift in the tidal fronts at the Georges Bank, for example, would result in a contraction of the well mixed, highly productive zone on the top of the bank. The position of the shelf-break front is expected to shift slightly offshore of the eastern coast of North America with projected strengthening of the Labrador Current (Frank et al. 1990).

Case Study: Scenarios for the Coastal Northeast Pacific Ocean

Both the Canadian and the Hadley models suggest an increase in the intensity of the Aleutian Low in winter (DJF) as a result of climate changes in the next century. The greatest changes are likely to be observed at about 45°N and about 1000 kilometers west of the North American coast for the Canadian model and about 2000 km offshore for the Hadley model. Summer (JJA) wind patterns would be less influenced but the two models disagree as to the sign of the change. The Canadian model predicts a slightly greater high pressure system, with an increase of 1 to 3 mb, while the Hadley model predicts a slight decrease of less than 2 mb except near to the northern boundary of the North Pacific where there would be little change. One can conclude that the winter wind systems would intensify with fewer changes in summer conditions.

The intensification of the Aleutian Low in winter, combined with a weakened subtropical high, could accelerate the cyclonic circulation in the Gulf of Alaska in two ways. First, the winds would drive the surface waters eastward, where they would converge along the coast creating a cross-shelf density gradient. The upper waters would be expected to respond with poleward acceleration on the eastern side of this low pressure region. Second, the impingement of the storm system onto the coastal mountain range will result in heavy rates of precipitation, in a region where precipitation rates may already exceed 8 meters per year (Royer 1982). This uneven distribution of fresh water could enhance the cross-shelf pressure gradients and further accelerate the flow. Thus, there could be an acceleration of the poleward flow along the eastern boundary of the Northeast Pacific. If so, there could be less reversal (equatorward flow) in the California Current and hence more relatively warm, salty water from the subtropical gyre will enter the Gulf of Alaska. Upper layer ocean temperatures would rise, while the low density "lid" on the Northeast Pacific could intensify.

The intensification of this "lid" could decrease the ability of nutrients to enter the upper euphotic zone. Since the primary source of nutrients in the Northeast Pacific is the deep water, vertical mixing is necessary to move them into the upper layers. Thus, the diminished density in the upper layer will inhibit this mixing, especially over the shelf. For the deep waters, an enhanced Aleutian Low will increase the upwelling in the central Gulf of Alaska. This central gulf upwelling will bring nutrient rich water into the euphotic zone, enhancing the primary production there. Biological populations that thrive in the deep ocean might increase their productivity in this scenario, whereas the coastal populations might fare worse.

Progressing from the Gulf of Alaska into the Bering Sea, the Alaska Coastal Current will carry higher temperature, lower salinity water into the Bering Sea. Similar to the Gulf of Alaska, the stratification of the Bering Sea should increase, especially on the shelf. With higher water temperatures, the seasonal sea ice in the Bering Sea should retreat northward. It should appear later and leave earlier each year. With the high temperatures in the coastal region, the nearshore ice should disappear faster than that offshore. However, increased stratification would limit the seasonal heating and cooling to a shallower layer and could enhance the seasonal cycle. If this led to winter cooling in a shallower mixed layer, it is possible that there could be an increase in the ice cover with the climate change. Nevertheless, the increased heat advection will probably dominate over this redistribution of heat in the water column.

The importance of the role of ice cover in the Bering Sea to the biological production there is somewhat uncertain. However, the ice edge retreat in the spring has been shown to enhance the local upwelling (Niebauer 1988). Without the ice or with the ice at a location many kilometers to the north, productivity on the shelf could be reduced in the southern Bering Sea but enhanced in the northern regions. There should be a poleward shift in marine populations not only in response to the retreat of ice cover, but also due to the increases in the water temperature.

If the source of nutrients for the euphotic zone in the Bering Sea is the deep layers, climate change might inhibit nutrient transport into the upper layers on the shelf since vertical mixing would be reduced with increased stratification. On the other hand, an increase in the Aleutian Low strength might increase the deep ocean upwelling and subsequently increase the nutrient supply to shelf break and deeper waters. A coastal convergence driven by these low pressure systems will also enhance the stratification over the shelf. The productivity on the shelf would decrease, probably accompanied by an increase in productivity offshore.

The result is likely to be a shift in the position of marine populations with changes in the ocean temperatures and salinities. Native hunters will have a more difficulty in locating marine mammals because of greater open water, changes in the seasonal timing and shifting location of the populations; and marine mammal populations themselves would likely be affected as well (see section 4.5.4) Native villages near to the coast could be more susceptible to erosion and flooding; a problem which has already been increasing in recent decades (Weller and Anderson 1998). Increased temperature and decreased salinity will increase the sea-level, likely making flooding more frequent and severe. The later advance and earlier retreat of the sea ice will allow storms to increase the sea state above prior levels with the same amount of wind stress, also leading to an overall increase in coastal erosion for many areas.

3.3 HURRICANES AND EXTRATROPICAL STORMS

Hurricanes account for far more insured losses of property than do other hazards such as earthquakes and wild fires. At the time of Hurricane Andrew in 1992, six of the thirteen most-costly "insured" catastrophes in U.S. history were hurricanes – Andrew, Hugo, Iniki, Frederic, Alicia and Betsy. They accounted for 67% of the total "insured" losses, more than three times the losses suffered during earthquakes. However, tropical hurricanes are not the only storm threat to coastal inhabitants and property owners. Extratropical winter storms can cause extensive property damage over huge areas of the U.S. coast. For example, the Halloween ("northeaster") storm of 1991, popularlized as *The Perfect Storm*, caused damage amounting to over $1.5 billion along the Atlantic coast from Cape Cod to Cape Hatteras (Dolan and Davis 1992). During both the 1982-82 and the 1997-98 El Niño, extratropical storms battered California causing an estimated $500 million in damages in the most recent event (Griggs and Brown 1999).

Coastal storm hazards exist because people and infrastructure concentrate along the coasts within range of storm flooding, wave forces, coastal erosion and hurricane force winds. Whereas over the past century loss of life during hurricanes has decreased substantially because of improved tracking and early warning systems, Figure 3.6 illustrates how property losses have increased greatly as the concentration of people and infrastructure along our coasts continues (Herbert et al. 1996; Pielke and Pielke 1997). Therefore, even if storm intensity and frequency remain the same in the future, there will likely be continued acceleration in property losses. Such an acceleration will be amplified should global climate change increase storm activity. However, at present, the relationships between climate change and, for example, hurricane frequency and intensity are unclear.

3.3.1 Historical Trends

Globally, the historical record shows "no discernible trends in tropical cyclone number, intensity, or location" (Henderson-Sellers et al. 1998). However, regional variability can be large. Over the past 30 years intense hurricanes in the Gulf of Mexico decreased in frequency and intensity (Figure 3.7), consistent with trends in the Atlantic Basin (NRC 1998). However this probably reflects decadal scale variability that may be returning, or could in the near future, to a period of higher hurricane frequency (Landsea et al. 1996). In contrast, in the western north Pacific, where hurricanes are called typhoons, storm frequency initially decreased then increased (Chan and Shi 1996).

In the north Atlantic Basin comprehensive historical records of hurricanes date to the 1940's when aircraft observations first became available. These records indicate that hurricane occurrence in the Atlantic Basin has strong annual to decadal variability. For example, the number of hurricanes occurring per year can vary by a factor of three or more for consecutive years. During El Niño years, hurricanes are less prevalent in the Atlantic Basin than during non-El Niño years. Furthermore, during the 25-year period from 1941 to 1965, there were seventeen Category 3 or above hurricanes (winds greater than 111 MPH) landfalling on the U.S. East Coast or peninsular Florida. In contrast, between 1966 and 1990 there were only two. This extreme variability has been associated with

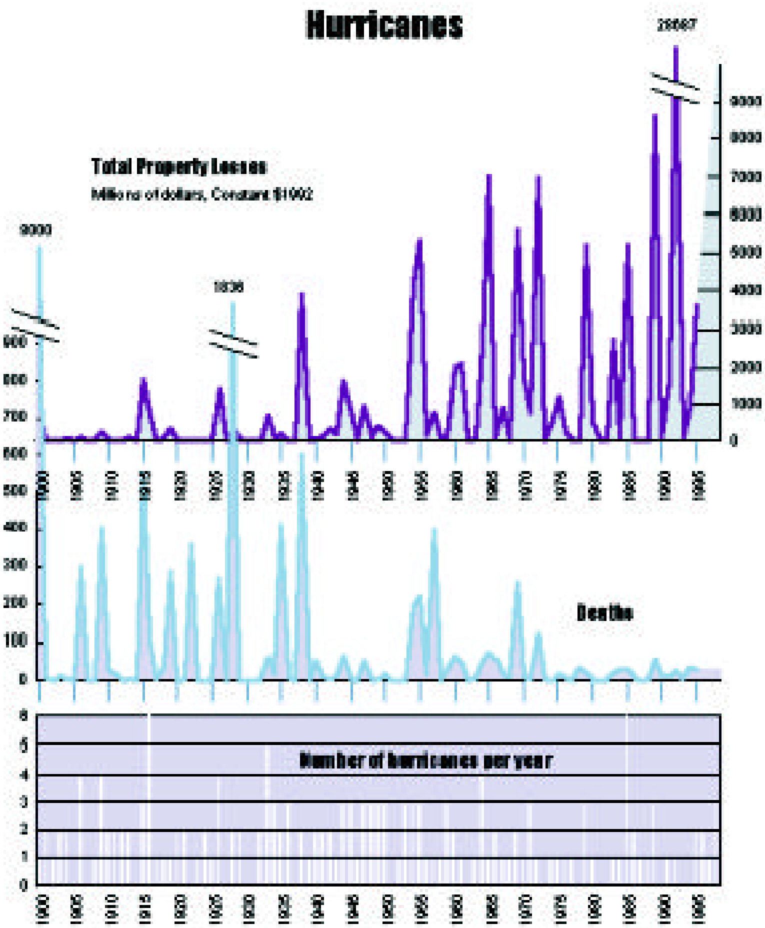

Figure 3.6. Losses of life and property by decade resulting from hurricanes making landfall in the continental U.S. (Source: National Hurricane Center, NOAA).

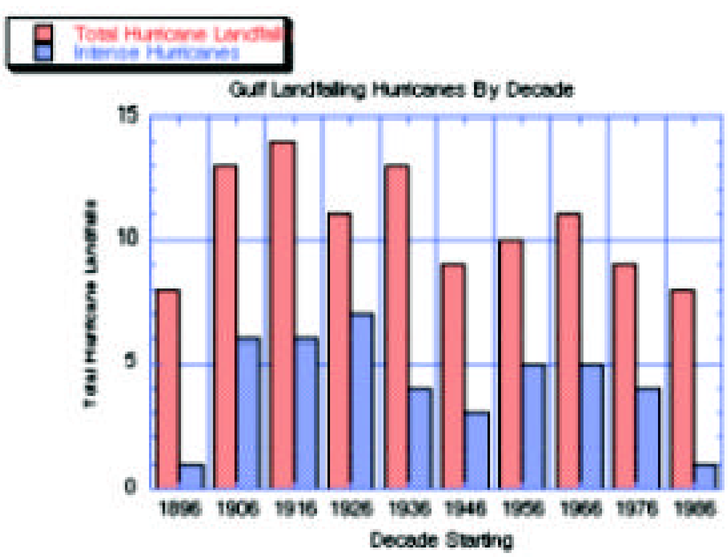

Figure 3.7. The number of hurricanes making landfall on the U.S. coast of the Gulf of Mexico by decade over the past 100 years, showing peaks of activity during the early 20th century and in the 1960s. (Source: Florida State University, Center for Ocean-Atmosphere Prediction).

rainfall in West Africa, where greater rainfall corresponds with a greater number of major hurricanes (Landsea and Gray 1992), although the mechanism is not fully understood. The mid-1990's has seen a recurrence of large numbers of hurricanes in the north Atlantic Basin suggesting a return to a more active hurricane regime (Landsea et al. 1996).

Extratropical storms and hurricanes, when considered together, also have extreme year-to-year and decadal variability. A study of 75 to 85 year-long storm surge records derived from tide gauges at Atlantic City, NJ and Charleston, SC found annual differences in the number of events of 50% and interdecadal variability of 10-20% (Zhang et al. 1997). However, significant long-term trends were not found either in storm frequency or severity. The records included both extratropical storms and hurricanes, but were dominated by more frequent extratropical storms. More importantly, the supposition of storm surges on a rising sea-level (3.9 mm/year at Atlantic City) has resulted in an increase of storm impact over the record length. For example, the number of hours of extreme storm surges per year has increased from less than 200 in the early 1900's to an extreme of over 1200 (more typically 600) hours in the past decade.

3.3.2 Future Trends

Prediction of the future intensity and frequency of tropical cyclones has been limited by the coarse resolution of global climate models. However, some progress has been made in estimating future maximum potential intensities of cyclones based on thermodynamic considerations (Holland 1997). The basic premise of this work is that maximum cyclone intensity is limited by the available energy in the atmosphere and ocean. Such analyses suggest that cyclone intensities will either remain near current levels or increase by 10-20%. However, these projected increases may be overestimated because other factors not included in these analyses, such as ocean spray, tend to limit intensity.

Recently, the relationship between typhoon intensity and climate change was investigated for the northwest Pacific with a regional, high resolution hurricane prediction model (Knutson et al. 1998; Knutson and Tulyea 1999). For a sea-surface warming of 2.2 °C, the simulation yielded storms that were more intense, showing a 5 to 12% increase in wind speed. For a moderate typhoon, these increases in wind speed translate to increases of 11 to 25% in the destructive power of winds. Similar percentage increases would be expected for other factors determining storm impact such as wave height and storm surge. Further, the simulation predicts large increases in rainfall, 28% greater than present.

A review of the linkages between tropical cyclones and climate change concluded that the broad geographic areas where cyclones are generated, and therefore the areas impacted, are not expected to change significantly (Henderson-Sellers et al. 1998). Limited evidence suggests that there will be little change in global frequency of cyclones, although regional and local variability could change significantly depending upon a variety of phenomena (Meehl et al. 2000).

Pacific tropical cyclones generally develop over ocean water that exceeds 28 to 29 °C. During the past 30 years such warm water has generally been limited to the western tropical Pacific, which has been the region of origin of most of the cyclone activity. However, during El Niño, this region extends farther east than usual, posing the cyclone threat to islands farther east. The cyclones normally develop somewhat north or south of the equator and to the west of the date line, and initially move toward the west with the trade winds. They then curve poleward and then finally eastward, threatening islands well off the equator such as Guam, the Marshall Islands, or Hawaii. With global change, this region of warm water is expected to migrate farther toward the east into areas that now experience warm water only during El Niño events. The expected result is a gradual increase in the frequency of tropical cyclones for islands in the central and east-central Pacific, both north and south of the equator. Storm frequencies for the western Pacific may not decrease as they would presently during El Niño events. In fact, they may increase because the SST there will also be increasing. The overall result, then, will be an eastward extension of the tropical region that may normally experience cyclones, especially during the local summer and fall seasons when cyclones are most likely.

For example, recent global climate model investigations have shown that ENSO frequency and intensity may increase with increasing greenhouse gas concentrations. Timmerman et al. (1999), using a GCM with sufficient resolution, found that the tropical Pacific may change to a state similar to present day El Niño conditions. Since fewer hurricanes occur in the Atlantic during El Niño years, this result suggests that hurricanes may decrease in occurrence in the future. During severe El Niño events such as 1982-83 and 1997-98, the jet stream over the north Pacific brought winter storms more to the south causing extensive coastal erosion and flooding in California. Hence, a prolonged El Niño state may decrease the occurrence of hurricanes in the Atlantic, but lead to enhanced coastal impacts by extratropical storms along the West Coast. On the other hand, the results of Timmerman et al. (1999) also suggest stronger interannual variability, with relatively strong cold (La Niña) events becoming more frequent. Although these La Niña events would be superimposed upon a higher mean temperature, this could suggest more interannual variability in Atlantic hurricanes with more intense activity during the stronger cold events.

3.3.3 Implications

Even if storm magnitudes and frequencies of occurrence remain the same, an important impact of future storms, whether tropical or extratropical, may be their superposition on a rising sea-level. As a result of the higher reach of waves on the beaches and barrier islands of the nation’s coast, flooding and erosion damage will be expected to increase (Ruggiero et al. 1996; Sallenger, in press; Heinz Center 2000). Such effects will be particularly exacerbated on coasts with relatively low relief compared to the storm wave runup. However, such effects will not be limited solely to the low relief coasts of the U.S., such as the barrier islands of the southeast. Even the steep terrain of the West Coast is likely to be affected. For example, during both the 1982-82 and the 1997-98 El Niño events, elevated sea-levels of a few tens of centimeters in the Pacific Northwest were sufficient to force wave runup to impact and erode coastal cliffs, causing widespread property losses and damages (Komar 1986; Komar 1998).

3.4 PRECIPITATION AND FRESHWATER RUNOFF

In contrast to a relatively high degree of confidence associated with the increases in global temperature that are associated with global change, the effects upon hydrological cycles are considerably less certain, particularly on regional scales. The scenarios generated by the Canadian and Hadley models in particular are often contradictory as to trend (Felzer and Heard 1999). Generally, the consensus is that under most climate change scenarios, the hydrologic cycle will become more intense (Houghton et al. 1996; Houghton 1997). However altered precipitation patterns may vary greatly on regional scales. The Water Sector of the National Assessment has investigated this issue in detail, and the results of that assessment should be referred to for a comprehensive review.

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

Extreme rainfall events, already demonstrated to have increased over the last century, are likely to become more common, as may droughts and floods (Karl and Knight 1998; Karl et al. 1995). The average precipitation will increase especially at high latitudes, and there are likely to be more periods of high precipitation. There might also be regions where the precipitation will decrease. However, under warmer climatic conditions increased precipitation may not result in a direct increase of freshwater inflow into coastal regions, depending on timing of the precipitation and changes in evapotransporation. Changes in freshwater runoff will also result both from climate-related factors and changes in human population, land-use, and consumption and diversion (Vörösmarty et al. 2000).

In the event that climate change results in increased river flows, more suspended sediments could be transported into the coastal regions, increasing the upper layer turbidity and potentially reducing available light to both plankton and submerged aquatic vegetation. Changes in sediment transport could also alter the amount of sediment available for soil aggradation (accumulation) in wetlands and sands for littoral systems. Increased sediment transport may be beneficial to many coastal areas, providing needed material for accretion to coastal wetlands threatened by sea-level rise, whereas a decrease in sediment transport might concurrently diminish the ability of some wetlands to respond to sea-level rise. On the other hand, other coastal ecosystems may benefit from reduced sediment inputs, which decrease water clarity or result in rapid infilling.

Increased river flows could also increase the flux of nutrients and contaminants into coastal systems, which influence eutrophication and the accumulation of toxins in marine sediments and living resources. Both increased temperatures and decreased densities in the upper layers might also

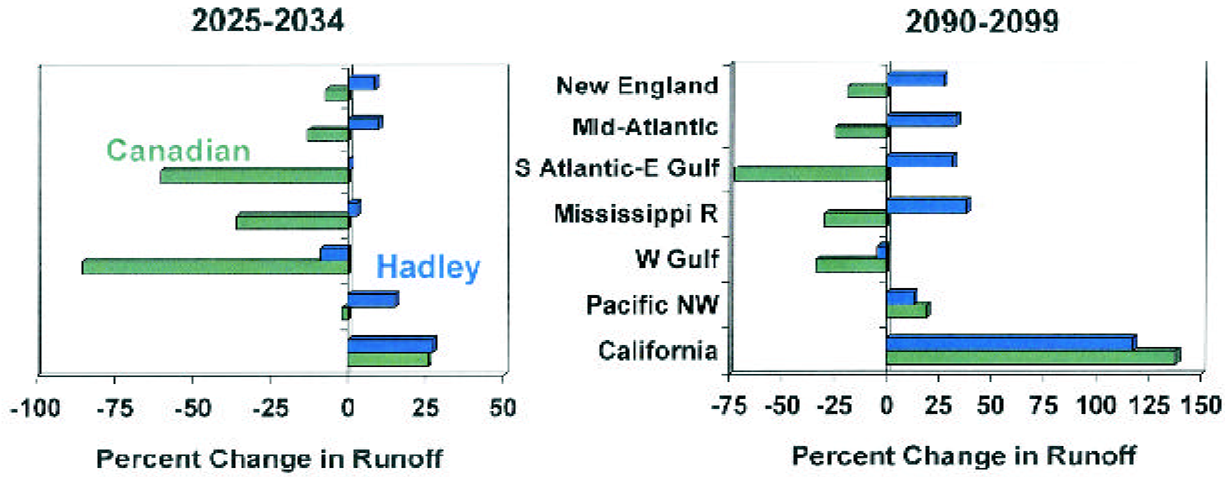

Figure 3.8. Projected changes in average annual runoff for basins draining to coastal regions of the conterminous U.S. estimated from precipitation and temperature projections of the Canadian and Hadley Center GCMs (from Wolock and McCabe, 1999).

reduce the vertical convection enough to prevent oxygenation of the bottom waters, further contributing to anoxic conditions in the near-bottom waters (Justi et al. 1997; Najjar et al. 2000). Decreased freshwater inflows into coastal ecosystems may have the reverse effects to those described above; reducing flushing in estuaries and increasing the salinity of brackish waters.

3.4.1 Changes in Coastal Runoff

Wolock and McCabe (1999) estimated the potential effects of climate change on mean annual runoff for U.S. rivers based on Canadian and Hadley model projections and a simple water balance model (Figure 3.8). They found that estimates based on the two models differed greatly, with the Canadian model often predicting reduced runoff and the Hadley model predicting increased runoff. Runoff aggregated for Atlantic coast drainage basins was projected to increase by 60% for the Hadley model, but decrease by 80% for the Canadian model by the end of the century. Because of these differences and because changes in mean annual runoff in individual hydrologic units were mostly smaller than decade-to-decade variability Wolock and McCabe cautioned that these estimates are uncertain and unreliable. Also, the simple water balance model they used underestimates runoff resulting from highly episodic rainfall in relatively arid areas. Nonetheless, both models projected large increases in precipitation throughout the southwestern U.S., particularly Southern California, where increases in winter precipitation are affected by shifts in the jet stream. These would result in multifold increases in freshwater runoff to the coastal ocean based on Wolock and McCabe's estimates.

For most of the Atlantic seaboard, it is uncertain as to whether there will be enhanced or diminished runoff. For example, the Canadian model suggests decreased precipitation during the winter for the Hudson, Delaware and Chesapeake watersheds, and significantly decreased precipitation during all seasons for the Albemarle-Pamlico watershed. The Canadian model also predicts decreases in precipitation in the summer and fall for the northern watersheds during the middle part of the 21st century. The Hadley Centre model shows no such inter-regional pattern, and generally suggests larger general increases in precipitation throughout the Atlantic seaboard. Hence, the coastal responses are uncertain too. For the Gulf Coast, Wolock and McCabe (1999) suggest, with a few exceptions, diminished freshwater runoff. Decreases of up to 100% are possible in this region, with those associated with the Canadian model being larger than those from the Hadley model. Once again, the Hadley model diverged and indicated that there could be some runoff increases in the 2090-2099 period. With a diminished freshwater influx, the westward flowing coastal current along the Louisiana-Texas coast would likely decrease. The vertical stratification would diminish, making wind mixing more effective. This could reduce the surface temperature since surface heating can be distributed to a greater depth.

For the Pacific coast, both climate model models suggest increases in the runoff, especially in southern California. Results indicate that there will be an increase in the number of storm events entering the U.S. from the Pacific, due to a deepened and southward-shifted Aleutian Low and a southward-shifted jet stream (Felzer and Heard 1999; Felzer 1999; Sousounis 2000). There will be enhanced heating at higher latitudes in the lower troposphere, reducing the meridional temperature gradients leading to fewer storms globally, but the increase latent heat fluxes in the tropics increases the intensity of storm events (Carnell and Senior 1998; Lambert 1995). However, as demonstrated by the increased frequency of Pacific storms, regional patterns will often vary from this global generalization.

Changes in freshwater discharges to the coast are of particular concern in those estuarine environments that have already experienced reductions in flows due to water use and diversion due to human activities. These include such systems as San Francisco Bay (see box), Texas lagoons such as Corpus Christi Bay, Apalachicola Bay, and Florida Bay. These estuaries have already been affected by reduced flows as a result of irrigation, other consumptive water uses, and diversions out of the basins for drainage, flood protection and water supply. While climate models project possible increases in precipitation in the catchment of San Francisco Bay (Wolock and McCabe 1999), thus potentially allowing an increase in flows allowed to the estuary, changes in the timing of precipitation and runoff complicate the matter. Both the Canadian and Hadley models predict decreased precipitation in Texas Gulf region and South Florida (NAST 2000), which would result in decreased runoff (Wolock and McCabe 1999). This plus growth in population and consumptive water uses and saline encroachment due to sea-level rise will likely present a particular challenge to efforts to restore the Everglades and mitigate hypersalinity in Florida Bay.

Case Study: Freshwater Flows to the San Francisco Bay/Delta Estuary

The San Francisco Bay and the Sacramento/San Joaquin Delta region comprise one of the United States' most significant and highly studied estuarine systems. This system has a surface area of nearly 1000 square kilometers (400 square miles), a length of over 100 kilometers (60 miles) and it is the focus of one of the largest population centers in the United States. Like many estuaries, San Francisco Bay supports a complex and delicate variety of ecosystems, while serving as an invaluable resource for the humans who live around it. A significant portion of California's freshwater supply is diverted from the upstream watershed and from the Sacramento/San Joaquin Delta in the upper reaches of the system into the elaborate plumbing system that stores and channels the state's water.

Fishes of high economic importance, as well as hundreds of species of flora and fauna, some of them endangered, depend upon the estuarine ecosystem for their survival. As a balance between the land and ocean environments, the estuary is sensitive to changes in both its upstream watershed and the outside Pacific Ocean. Already, the Delta and the Bay have been stressed by numerous impacts, often relating to human activities. The region has also been subject to numerous ecological insults, including an extraordinary number of invasive species. The Bay and Delta have been described as "the most heavily invaded estuary in the world", with nearly 200 non-native species documented (Cohen and Carlton 1998). In some parts of the estuary, non-native species account for as many as 90% of the species and 97% of the total biomass.

The San Francisco Bay consists of two relatively distinct sub-estuaries, the South Bay and the Central/North Bays. The Bay's total volume of about 6.7 cubic kilometers (1.6 cubic miles; Conomos 1979) equals about one-third of the freshwater runoff that enters the Bay annually, mostly through its northern reach at the confluence of the Sacramento and San Joaquin Rivers. The estuary's sole connection with the open ocean is through the Golden Gate, where relatively freshwater flows seaward near the surface and the more saline waters of the Pacific flow landward through a deep channel. The defining process of the estuarine environment is this mixing of saline ocean water with fresh river water. As sea-level determines the level of the estuary and therefore its horizontal boundaries, the potential for rapid sea-level rise has tremendous implications for the estuary and the humans who depend on it. Freshwater inflow to the estuary, both in terms of its volume as well as its timing, is the other major factor which determines salinity distributions in the Bay/Delta, a factor which is likely be strongly affected by climate change.

Freshwater Inflow

California receives an annual average of nearly 250 cubic kilometers (60 cubic miles) of fresh water in the form of rain and snow. Of this, about 40% ultimately becomes streamflow in the state's river network, most of which culminates at the Delta of the Sacramento and San Joaquin Rivers at the head of the San Francisco Bay. This freshwater supply is highly managed to ensure adequate supplies throughout the year. While most of this water originates in the northern third of California, a substantial portion is collected in reservoirs during the rainy season for later conveyance to the areas of greatest demand in Central and Southern California. Storage capacity in the Sacramento/San Joaquin drainage amounts to approximately 36 cubic kilometers.

The northern reach receives over 98% of San Francisco Bay's freshwater input through the Delta of the Sacramento and San Joaquin Rivers. Runoff from winter storms collects over approximately 150,000 square kilometers (60,000 square miles), an area comprising nearly

40% of the state of California (Conomos 1979). Sacramento River flow is dominated by direct runoff from storms over the western slopes of the northern Sierra, while San Joaquin River flow is primarily due to the melting of accumulated snowpack in the southern Sierra. This leads to a difference in the timing of the peak flow in the two rivers. Since the peak in the Sacramento River flow is associated with direct runoff from storms, it coincides with the winter/spring rainy season (Peterson et al. 1995).

The greater elevations of the southern Sierra mean that much of the precipitation there is retained as snowpack until temperatures rise enough for melting to occur, usually in late spring and early summer. As this water flows through the valley, some is lost to seepage into underground reservoirs, some to evaporation, and a large portion is dammed and used for municipal supplies and irrigation. When the remaining flow reaches the Sacramento/San Joaquin Delta, it is subject to further reductions. The primary diversions are the State Water Project which pumps fresh water from the Delta to supply Southern California with much of its water; the Central Valley Project which supplies water primarily for irrigation; irrigation canals on the Delta islands; and several local canals providing industrial and municipal supplies.

The high freshwater input from the Delta causes a large along-estuary salinity gradient through the North and Central Bays (Conomos 1979). When flows are at their peak, the freshwater signal overrides the up-estuary salt flux and the entire northern reach rapidly becomes fresher. As flows subside, tidal mixing and estuarine circulation begin to dominate, slowly pushing the more saline water up the estuary. This cyclic tug-of-war between saline and fresh conditions engenders a gradation of ecosystem types from marine near the Golden Gate to riparian upstream of the Delta. The actual formation and survival of these ecosystems is influenced and limited by human development around the estuary, in combination with year-to-year variability in the freshwater supply. This can be particularly important for the estuary during the dry season, when controlled releases of stored fresh water are used to flush saltwater from the Delta region and the San Francisco Bay.

Implications of Climate Variability and Change

Variations in the timing and amount of the freshwater supply have significant impact on California and such effects are harbingers of potential effects of longer-term climate change. Excessive rainfall in a short period can overflow reservoirs and cause severe flooding, as in the storms of January 1997. Conversely, insufficient total precipitation during a given rainy season can lead to freshwater shortages later in the year, potentially leading to water rationing, losses of agricultural and hydroelectric power commodities and other statewide impacts. Low freshwater flow due to drought and excessive upstream diversions can lead to unnaturally high salinities in the Bay/Delta estuary, potentially contaminating freshwater supplies and adversely impacting the health of the estuarine ecosystem (Jassby et al. 1995).

Interannual and interdecadal variations are also of strong significance. Multi-year events such as the drought of 1987-1992 have cumulative effects on economies and ecosystems. A multi-year drought or flow abundance can alter salinity, creating conditions unsuitable for existing estuarine ecosystems. Confounding this situation further is the extensive human development around the Bay/Delta which prevents ecosystems from migrating upstream or downstream to more suitable salinity regimes, leading to intensified ecosystem degradation or loss.

The potential implications of global warming for freshwater flows in the Bay/Delta watershed are somewhat uncertain. In particular, it is unclear whether overall water supply will increase or decrease. Several climate models do suggest that precipitation will increase, although much of this increase is likely to occur in intensive precipitation events resulting from winter storms (see section 3.3). It is also unclear what the overall effect of global change on interannual and interdecadal variability may be, although it is clear that increased temperatures would lead to a shift of freshwater flows from spring to winter. This is due to the earlier melting of snowpack under warmer conditions. In fact, this effect has already been observed. A slow rise in winter temperatures since the 1940's has led to earlier snowmelt runoff (Dettinger and Cayan 1995), effectively decreasing the natural storage in the Sierra on an interdecadal time scale. This has partially contributed to an overall rise in Bay/Delta salinities over this period.

If this effect were to strengthen significantly over the next century, the results could be dramatic. Increased winter flows and decreased spring flows would allow contaminants (e.g., pesticides, urban pollutants, etc.) to accumulate more during the longer dry season. When the high winter flows finally arrive, they would flush the system quickly, potentially resulting in a much higher concentration of pollutants which could damage ecosystems and contaminate freshwater supplies. Additionally, the decreased natural storage would make repulsion of saline waters from freshwater pumping sites more difficult, as freshwater supplies during the dry season would be considerably reduced.

Finally, a shift toward earlier flows would result in much fresher salinity distributions in the wet season and much more saline waters in the dry season. This change in the estuarine salinity environments would have significant effects on all estuarine ecosystems, though the details of such changes are as yet poorly understood. Freshwater flows would arrive earlier due to decreased snow accumulation, likely resulting in increased concentrations of harmful contaminants and in a significantly changed seasonal salinity cycle in the estuary. The effects of these changes on estuarine ecosystems are uncertain but are likely to be adverse, further stressing an ecosystem which is already heavily impacted by a wide range of environmental problems (Field et al. 1999). Additionally, the significance of water diversions and the ongoing inability of water managers to fully address the needs for freshwater delivery to the to the Bay remains a major problem that is likely to be further exacerbated by future changes in precipitation patterns and timing.

3.5 SEA-LEVEL CHANGE

Coastal water levels rise and fall on various time scales. Tides resulting from the gravitational attraction of the sun and moon cause water levels to rise and fall daily anywhere from a few centimeters in some estuaries to four meters along the Gulf of Maine. The amplitude of the daily tide fluctuates by about one-third twice each lunar month, according to whether the solar and lunar tides are in phase with each other. Storm surges, winds, currents, rainfall and other factors can also affect water levels on short time scales. These effects are significant because many of the expected impacts associated with sea-level rise are the result of the increase in the baseline sea-level for storm surges and flooding events, rather than direct effects of sea-level rise itself.

Generally, sea-level refers to the average water level over the course of a 20-year period, which is enough time for astronomic and most climatic fluctuations to run through their complete cycles (such as the cycling of Perigean spring tides; see Wood 1986). Over geological time scales however, sea-level has fluctuated greatly. During the Cretaceous Period, over 100 million years ago, sea-level was as much as 350 meters above present levels (Emery and Aubrey 1991), corresponding with a time of rapid seafloor spreading, an ocean between 10 and 15°C warmer than today's, and a warmer atmosphere with little or no landlocked ice. More recently, sea-level has risen and fallen with the 100,000-year glacial-interglacial cycle. During glacial periods, sea-level has been as much as 120 meters (nearly 400 feet) lower than current levels (Fairbanks 1989), whereas during the warmer interglacial periods, sea-level has been as much as 5 to 7 meters (about 20 feet) higher than the present.

On average, global sea-levels have been gradually rising since the conclusion of the last ice age approximately 15,000 years ago; although rates over the last 6,000 years have fluctuated somewhat. During the last 100 years, sea-level rise has occurred at a rate of approximately 1 to 2 millimeter per year, or 10 to 20 centimeters (4 to 8 inches) per century, according to most estimates (Gornitz 1995; IPCC 1996). This refers to the eustatic sea-level, the absolute elevation of the earth's ocean, which has been determined from tidal stations around the globe. However, there are large regional variations due to subsidence, isostatic (glacial) rebound, tectonic uplift, and other factors that contribute to a "relative" sea-level rise which usually differs from the global average. While some long-term tide-gauge records suggest that there may have been a slight increase in the rate of sea-level rise observed over the last century, efforts to verify this (Douglas 1992) have generally been unable to confirm a significant acceleration.

3.5.1 Primary Causes of Sea-level Change

Most of the sea-level change observed over the last several hundred thousand years is accounted for by two major variables; the thermal expansion or contraction of the oceans (steric effects) and the amount of water that is locked up in glaciers and ice sheets. The thermal component results from expansion and contraction of the volume of the ocean associated with changes in mean ocean temperatures; given an equal mass the total volume decreases when ocean temperatures drop, and expands when temperatures increase. Gornitz (1995) reviewed a number of assessments of estimated contributions to sea-level rise, which generally suggested that the majority of sea-level rise anticipated over the next century is likely to result from thermal expansion of the oceans.

The second major variable with regard to current and future sea-level is the contribution to the volume of the oceans from water formerly locked up in glaciers and ice caps. Current major glaciers and ice sheets account for enough mass to raise global sea-level by approximately 80 meters (250 feet), if all were to melt and flow to the sea (Emery and Aubrey 1991). Over the last century, there has been an observed increase in the thinning of glaciers in many parts of the world, including the Alps, many parts of Alaska and many regions in the Andes (IPCC 1996). While this glacial melt has played a role in the sea-level rise observed over the last century (and expected over the next century), the vast majority of landlocked ice is to be found in Antarctic and Greenland ice sheets. Both of these have contributed substantially to observed sea-level rise since the last interglacial (Cuffey and Marshall 2000). It is difficult to estimate the contribution of melting of these ice sheets to sea-level rise over the next century, however recent evidence of thinning of the periphery of the Greenland Ice Sheet suggests it may already be contributing 0.03mm/year (Krabill et al. 2000).

In particular, there is a great deal of concern about the stability of the West Antarctic Ice Sheet (WAIS). This ice sheet, as opposed to most glaciers, other Antarctic ice sheets and the Greenland ice sheet, is not landlocked but rather rests on the continental shelf below sea-level in the Weddell, Bellingshausen and Ross Seas. While the melting of Arctic sea ice will have essentially no impact on global sea-levels, because this ice is already displacing its own mass by floating on the ocean, the grounded ice sheets in Antarctica have the potential to dramatically affect sea-level through melting and/or wasting. Altogether, the WAIS contains enough ice to raise global sea-levels by four to six meters (13 to 20 feet). Concerns for the stability of the WAIS have been raised repeatedly, in part due to the continued disintegration of some smaller ice shelves fringing the Antarctic Peninsula. Oppenheimer (1998) reviewed evidence of global warming and the stability of the WAIS and generally suggested that the probability of mass wasting of the WAIS, followed by a significant increase in sea-level, during the next 100 years was relatively low. However, he also found that the probability of a major rise in sea-level due to melting or wasting of the WAIS was substantially greater after 2100.

Additionally, anthropogenic alteration of hydrological cycles through groundwater mining, water storage, and other processes could also influence future sea-levels. Activities such as groundwater mining, deforestation and water released from the combustion of fossil fuels would have the effect of slightly increasing global sea-level. However the storage of water behind dams and impoundments, and the losses of water due to infiltration beneath impoundments and irrigated croplands, would reduce the total flux of water to the oceans. Gornitz et al. (1997) reviewed recent studies of human-induced alterations of land hydrology and suggested that a preliminary estimate of the net effect of these activities could be sufficient to reduce sea-level rise by 0.8 millimeters per year; or 8 centimeters (3 inches) per century, with a range of 4 to 12 centimeters (1.5 to 5 inches) per century.

Finally, there are significant regional components to sea-level change. The term "relative sea-level rise" refers to the change in sea-level compared with land elevation at a particular location. As Figure 3.9 shows, the rate of relative sea-level change varies considerably along the U.S. coast, largely because of land movements caused by isostatic rebound, subsidence, compaction and settling due to alluvial deposition in deltas, subsidence from extraction of water and petroleum, and tectonic

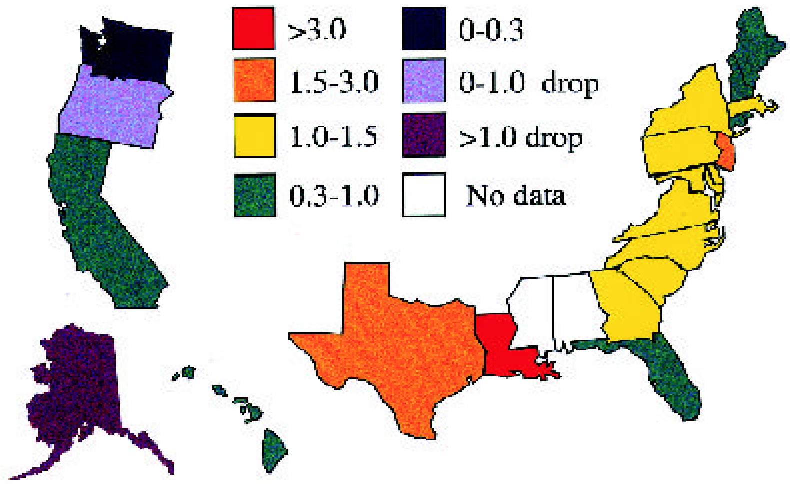

Figure 3.9. Recent average relative sea-level change rates in inches per decade (Titus 1998). These are general trends. Sea-level change rates often vary greatly within states, for example relative sea level rose 1.5 to 2 inches/decade in southern Puget Sound as a result of subsidence and fell at the same rate on the northwest coast of Washington as a result of uplift of the land mass.

factors such as earthquakes. For example, within the U.S., portions of the Gulf Coast are experiencing a relative sea-level rise of 10mm/year, or one meter per century, largely as a result of land sinking relative to the ocean (subsidence). Concurrently, portions of the Washington and Alaska coastlines are experiencing a relative sea-level fall of up to 8 millimeters per year; or 80 centimeters (30 inches) per century, as a result of glacial rebound and tectonic uplift.

Land movements are not, however, the only reason for regional variations in the rate of sea-level rise. Regional climate can also alter sea-levels through changes in local atmospheric pressure and alongshore wind stress, integrated water column density and thermocline depth (Chelton and Davis 1980; Bailey et al. 1995). Variability in short-term average sea-level can also be significant; for example, along the west coast of the Americas relative sea levels may increase during strong El Niño events by as much as 20 to 50 centimeters (7 to 20 inches) over short time periods (Komar and Enfield 1987). Additionally, Ruggiero et al. (1996) found increased short-term sea-levels along the Oregon coastline corresponding with major El Niño events between 1970 and 1995.

3.5.2 Approaches to Generating Sea-level Rise Scenarios

For the last decade, sea-level rise impact assessments have generally followed a convention of considering the impacts of a one-meter rise in sea-level due to global warming, along with similar round numbers such as 30 cm, 50 cm, 60 cm and 2 meters (approximately 1 foot, 18 inches, 3 feet and 6 feet). The general approach has been to analyze the entire range of possibilities, for three reasons. First, as new evidence accumulates, projections of sea-level rise may change; but such changes need not undermine the validity of an impact assessment that had already considered a broader range. Second, the consideration of worst-case scenarios is important for some types of

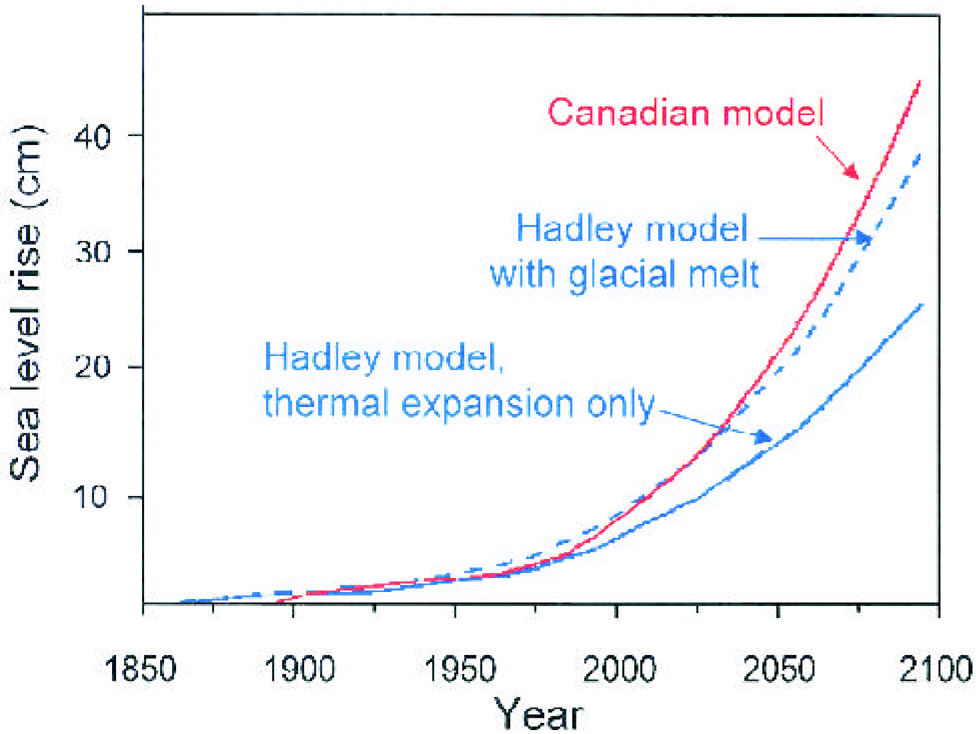

Figure 3.10. Reconstructions (over the past 100 years) and projections (over the next 100 years) of global sea level from the Hadley Climate Centre and Canadian Climate Center General Circulation Models. Hadley model simulations include the effects of glacial melting as well as thermal expansion of the ocean, while the Canadian model considers only thermal expansion.

risk assessment, where events with small probability but high impact may have a great impact on defining the most rational course of action. Finally, most studies suggest that sea-level may continue to rise at an accelerated rate for a few centuries, so the sea may reach a level that is unlikely within 50-100 years during subsequent centuries.

General Circulation Models do provide credible estimates of sea-level rise due to thermal expansion, glacial melt and historic rates of sea-level change, including regional variability in eustatic sea-level resulting from oceanographic and atmospheric conditions. However, these outputs need to be adjusted for regional land movements before effective regional assessments can be performed. Figure 3.10 shows historic and future sea-level rise scenarios for the Canadian and Hadley models between 1900 and 2100. Both models suggest a mean expected sea-level rise of approximately 45 to 51 centimeters (18 to 20 inches) above current levels by the end of the century. Figure 3.11 also shows regional Canadian and Hadley climate model outputs for sea-level change around the year 2090, in which significant differences exist between the East and West coasts due to changes in oceanographic and atmospheric conditions. In general, the Hadley model predicts a greater sea-level rise for the Pacific coast than for the Atlantic and Gulf coasts as a result of altered current and wind patterns. By contrast, the Canadian model predicts a more complex pattern of sea-level rise, but with relatively similar increases along all U.S. coasts.

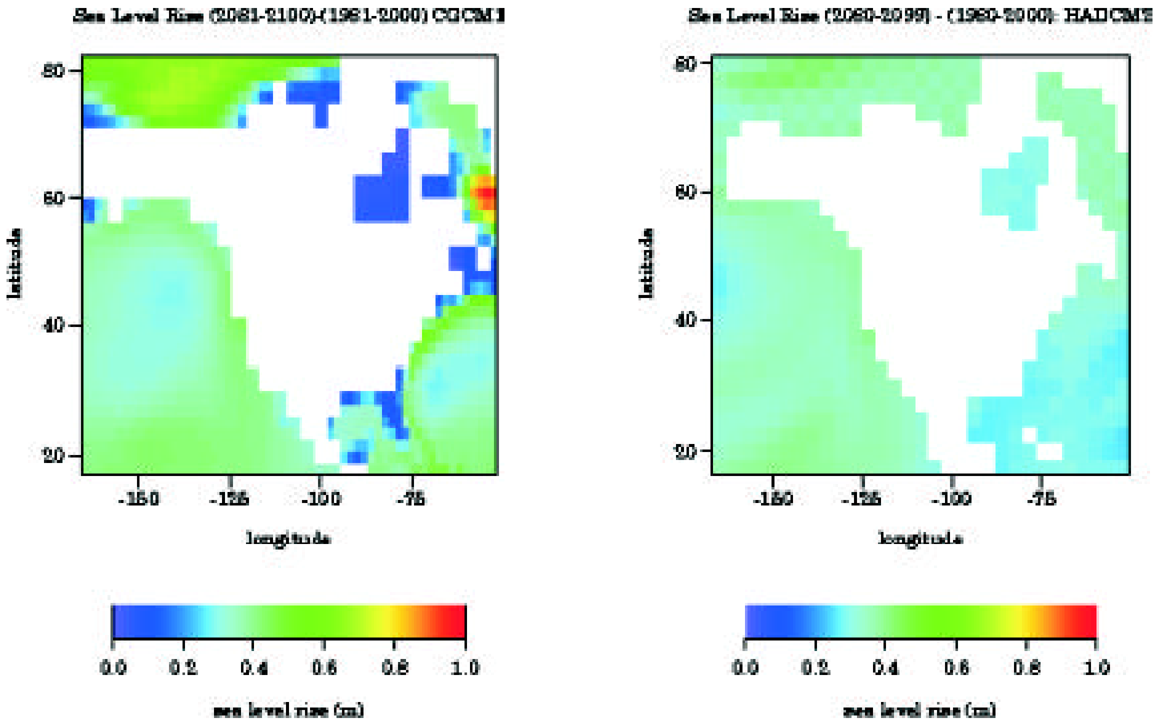

Figure 3.11. Projections of sea-level change (in meters) around North America near the end of the 21st century by the Canadian Climate Center (left) and Hadley Climate Centre (right) models. These do not include the effects of subsidence or uplift on relative sea level, but do indicate that the rise in the level of the ocean will not be uniform because of the effects of currents and winds around the continental margins.

In estimating these projections, the Canadian model is limited to considering only the rise in sea level caused by thermal expansion, while the Hadley model provides output for both thermal expansion alone and thermal expansion as well as contributions from glacial melt (Gregory and Oerlemans 1998). Because of the uncertainty in the response of major ice sheets to future global change, neither of these two models include any consideration of ongoing or potential changes in sea level caused by accumulation or melting of Antarctica and Greenland ice sheets, although some regional assessments, such as the Metropolitan East Coast, have incorporated estimates of glacial and ice sheet melt into their sea-level rise projections. Nor do the regional outputs consider local land movements also described earlier. One approach to addressing regional differences in sea-level change is to obtain the difference between global average relative sea-level rise and regional estimates of sea-level change to estimate local subsidence (e.g., the "residual" of local sea-level change, consisting mainly of geological factors). This subsidence can then be added to the model projection of sea-level rise as predicted by GCM model output (Gornitz, personal communication).

These scenarios are consistent with the Intergovernmental Panel on Climate Change's 1995 estimates (Houghton et al. 1996) that sea-levels would most likely increase by approximately 37 centimeters by 2100. Additionally, most studies conducted since yield similar point estimates of about one foot above current trends over the next century, for a total sea-level rise of approximately

45 to 52 centimeters (18 to 20 inches) above their current level by the year 2100 (Titus and Narayanan 1996; Wigley 1999). It is also generally agreed that sea-level rise will continue to accelerate beyond 2100, as a result of the long time frame necessary for oceans and ice sheets to approach equilibrium. Finally, the *rate* of sea-level rise may be as important as the absolute rise for some key natural processes, such as the ability of wetlands to keep pace with sea-level change. The available studies suggest that the rate of sea-level rise by the year 2100 is unlikely to be substantially greater than the average rate between now and the year 2100, except in the worst case scenario where the rate could be about twice as great.

Case Study: Sea-Level Rise and Migratory Shorebirds

Shorebirds undertake twice yearly migrations that are among the longest known among any animal species. In the Americas, these may involve annual journeys of up to 18,000 miles between their breeding areas in the high arctic and their wintering areas in the southernmost parts of South America. These long-range migrations are energetically costly, thus shorebirds require a series of coastal “staging” sites where they can rest and replenish their fat reserves, the main fuel for long distance migration (Blem 1980; Evans and Davidson 1990). During their stopovers, individuals of some shorebird species may double their weights in a few days to accumulate enough fat to fuel their flight to the next staging site (Myers 1983; Burger and Olla 1984). Such weight gains are only possible at sites where extremely rich food supplies are readily available. Thus, the availability of staging sites with rich and accessible food supplies is a critical factor in a species’ migration schedule and the elimination of any one important site could potentially undermine the feasibility of the entire flyway strategy.

The international conservation importance of two of these sites, Delaware Bay in Delaware and New Jersey, and Bolinas Lagoon in California, is reflected in the fact that they have been declared “Wetlands of International Importance” under the Ramsar Intergovernmental Convention (Smart 1987). San Francisco Bay, California, has also been nominated for Ramsar listing as an internationally important wetland. This reflects not only the importance of these sites for shorebirds, but also the existence of threats to their long-term survival. In the past, shorebird habitat at coastal sites has been lost largely due to reclamation (Evans 1997; Goss-Custard and Moser 1988). More recently, a new threat to shorebird staging sites has been recognized, habitat loss due to sea-level rise caused by global climate change (Ens et al. 1995; Evans 1991; Markham 1996).

Systematic survey data have shown that five sites in the U.S. are extremely important in terms of the numbers of shorebirds that they support. These include San Francisco, Humboldt, and Willapa Bays on the Pacific coast; Bolivar Flats on the Gulf of Mexico coast, and Delaware Bay on the Atlantic coast. Information on the numbers of birds using these sites was obtained from two long-term surveys: the International Shorebird Survey (the East Coast sites) and the Pacific Flyway Project. The current distribution and extent of shorebird intertidal feeding habitat (mud and sand flats) was obtained from the National Wetlands Inventory database. Probabilistic local sea-level rise scenarios for each of these sites were obtained from studies carried out by the USEPA (1995).

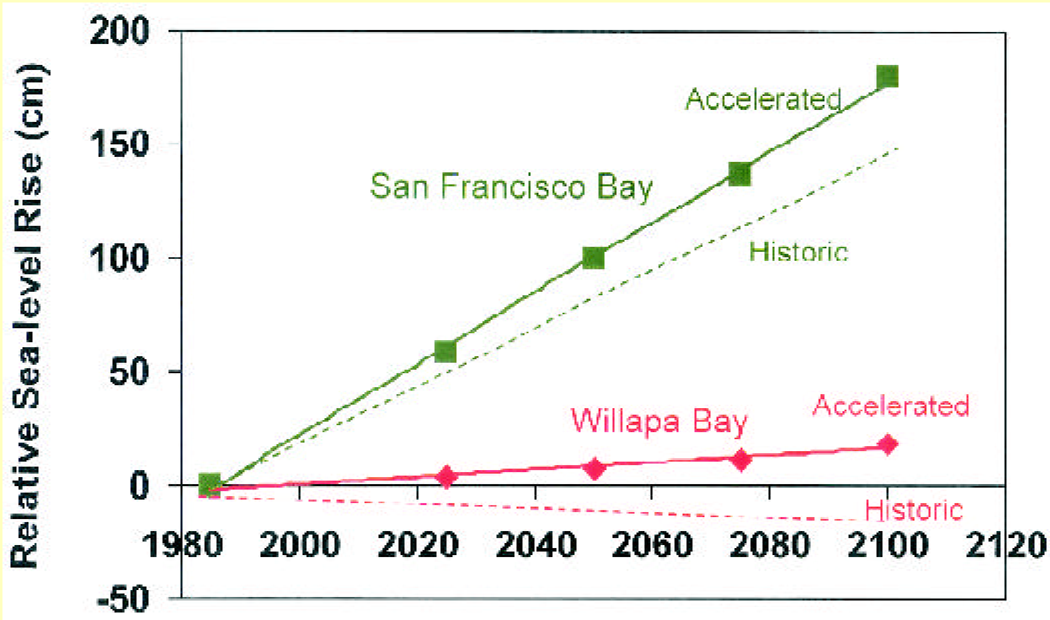

Figure 3.12. Scenarios for the rates and extent of sea-level change for Willapa Bay (A) and South San Francisco Bay (B) based on the Sea Level Affecting Marshes Model (SLAMM4).

The likely effects of three sea-level rise scenarios on the extent of intertidal shorebird habitat at each of the sites were estimated using the most recent (4th) version of the Sea-level Affecting Marshes Model (SLAMM 4). Preliminary results of this study are showing that the extent of habitat loss is likely to vary greatly between sites depending on the sea-level rise scenario, but also on local factors, such as rates of land subsidence or uplift. These patterns are illustrated below by comparing the results from two sites on the Pacific coast; Willapa and South San Francisco Bays. Figures 3.12 shows the rates and extents of relative sea-level change projected for these two sites. The historic scenarios are based on empirical data from tide gauges at the two sites, and do not include any acceleration in sea-level change. The 50% probability scenario is based on a global sea-level rise of 34 cm, a level consistent with those currently projected by the Canadian or Hadley models.

The results generated by the SLAMM model show that under historic rates of local sea-level rise, Willapa Bay is likely to lose very little intertidal flats and to gain a relatively small amount of saltmarsh by the years 2100 and 2200. In contrast, the model indicates that South San Francisco Bay will lose approximately 70% of its tidal flats by 2200. When we factor in the 50% probability scenario, Willapa Bay could lose approximately 30% of its tidal flats by 2200, while South San Francisco Bay could lose virtually all of its mud and sand flats in the next two centuries. The predictions for Willapa Bay and South San Francisco Bay differ so markedly because of local differences in crustal movements and their effects on local sea-level change. At Willapa Bay the land surface is slowly rising due primarily to isostatic rebound. This uplift reduces the potential for inundation of tidal flats. However, at South San Francisco

Bay, the land surface has been subsiding due to depletion of the local aquifer and, perhaps, tectonic movements. The net results of this is that local sea-level rise at South San Francisco Bay has been rapid.

Studies at other sites show that the two sites likely to be most severely affected by sea-level rise are San Francisco Bay and Delaware Bay. While it is difficult to assign likely numerical responses between habitat loss and shorebird populations, the projected extents of habitat loss at these two sites under the 50% probability scenario warrant serious concern. Clearly, under this scenario future sea-level rise will likely have serious effects on the ability of many coastal wetlands to support populations of migratory birds that depend on intertidal feeding habitats. However, important questions remain unanswered, particularly regarding the effects of human responses to sea-level rise. For example, the installation of extensive coastal protection structures with a concomitant reduction in the ability of the coastal site to migrate inland could exacerbate the effects of sea-level rise. Also significant is that the severity of effects will likely vary widely between sites. However, it is not known what effect the virtual removal of one or more important sites on a flyway might have if accompanied with only minor effect on others.

Chapter 4
Impacts to Coastal and Marine Environments

Globally, few environments on the earth are as biologically diverse and productive as those found in coastal areas and ocean margins. Marine ecosystems are currently thought to contain about one-fifth of all known species, although there remain numerous undescribed species and even ecosystems in the deep sea and in polar regions which have scarcely been sampled. Hundreds of new species are described almost annually, from habitats previously poorly or not at all known to science; including hydrothermal vent communities and whale carcasses (NRC 1996a). All but one animal phylum occurs in the marine environment, while only about half of the known phyla occur on land.

As alluded to in the opening of this assessment, most of these systems have already been moderately to severely affected by anthropogenic activities. Changes in the range and abundance of native species as associated with climate change will further intensify the impacts to the function and biodiversity of coastal and marine ecosystems (Reid and Trexler 1992, Mathews-Amos and Berntson 1999). As these system provide substantial goods and services to both human welfare and planetary processes as a whole, their continued ability to function is critical. Natural systems, such as tidal wetlands, can provide flood control, storm protection, and waste recycling and thus have tremendous value when measured economically. However, estimating the effects on such resources are difficult to quantify because they lie outside the traditional market and have only rarely been thoroughly measured. Despite this, Costanza et al. (1997; discussed in section 2.2) have used a number of published studies to summarize the value of earth systems economically. Their work suggests that coastal and marine environments constitute over half of the total value of the natural environments ecological services.

The number and diversity of biogeographic biomes, realms and provinces in the marine and coastal environment is enormous, as many as 21 oceanic and coastal margin realms and 45 coastal provinces have been described (Ray et al. 1992). However we have greatly simplified ecosystem descriptions for the purposes of this assessment. Additionally, we have attempted to be highly inclusive of human settlement and activities in these systems, particularly in the section discussing shorelines and coastal developed areas. Thus, five principal ecosystem types were evaluated for this assessment; shorelines and coastal communities, estuaries, coastal wetlands, coral reefs, and ocean margins/marine fisheries. This breakdown provides some means for understanding what may be the most significant impacts on broad ecological systems, and individual case studies provide specific examples of the complex set of interactions between the effects of climate and human activities.

4.1 SHORELINES AND COASTAL DEVELOPED AREAS

Diverse and complex natural processes continually change shoreline systems (the beach, shoreline, and nearshore) physically, chemically, and biologically, at scales that range from the micro and macroscopic (sand-grains and seconds) to global and long term (sea-level rise). Regional and local characteristics of shoreline systems define the differing interactions and relative importance of these natural processes. Human activity may also add another dimension to change by exacerbating and attenuating, both directly and indirectly, natural processes. Individually, each process is complex but taken collectively, they create an extraordinarily intricate system that constantly attempts to achieve a dynamic balance between force and response.

Coastal erosion is already a widespread problem in the U.S., and to varying degrees all coastal states are subject to hazards relating to erosion somewhere along their coastlines. For example, over the past 50 years in Oahu, Hawaii, a quarter of the beaches have been lost or significantly

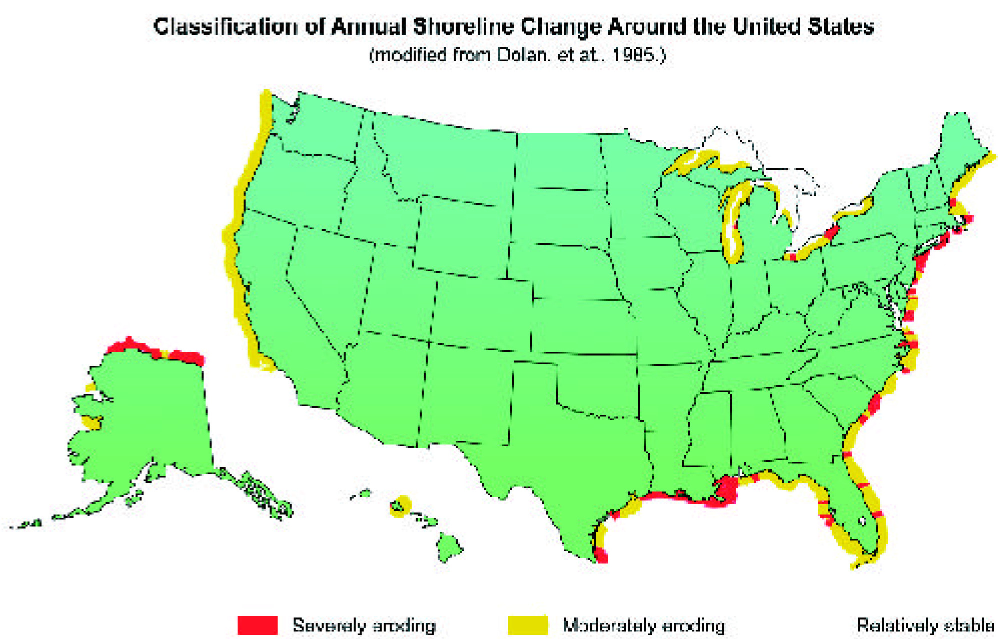

Figure 4.1. Classification of the rate of shoreline erosion throughout the United States (after Dolan et al. 1985).

degraded due to causes that are poorly understood. Generally, the highest-risk areas are those currently experiencing rapid erosion rates and with very low relief, such as the southeastern United States and the Gulf Coast. Figure 4.1 shows some of these areas, although the scale and detail in this figure is extremely coarse and finer scale resolution is necessary for understanding true regional vulnerability.

Sea-level rise is one of the most significant threats to shoreline systems, by increasing the vulnerability of developed shorelines and floodplains through the elevation of the baseline water level for extreme storms and coastal flooding events. However, it is important to recognize that these impacts are largely associated with human settlements and developed areas. In general most unaltered and naturally functioning shorelines are capable of adapting or responding to sea-level rise, storm surges and wave impacts, and other climate related phenomena.
Storms and hurricanes are the most visible and costly direct manifestations of climate to shorelines, and particularly developed areas. As discussed, earlier hurricanes and extratropical storms have resulted in enormous economic impacts extending into billions of dollars in insured losses alone.

Assessing the full costs of such disasters is difficult; recent studies have suggested that in many instances the reported costs of coastal hazards and disasters are significantly under-reported (Heinz Center 2000). This is because such estimates rarely account for the costs to individuals, families and neighborhoods, as well as to natural resources and the environment. As coastal population increases, in some states growth projections are as much as 45 to 50% population growth by 2025 (see section 2.1), the increases will assuredly be accompanied by new property construction. Subsequently, the economic vulnerability of human developments in coastal areas to hurricane and storm activity will continue to rise. This will be independent of, although aggravated by, any climate induced changes in the frequencies or intensities of these events.

4.1.1 Shoreline Processes

Fluids and sediments within shoreline systems are constantly in motion in response to a variety of natural processes. Winds not only move unconsolidated sediments and reshape features along the shoreline, they produce waves that move across the surface of waters until they become unstable over shallow water and steepen and break, dissipating their energy in turbulence and heat. In many areas, waves consistently approach the coast at oblique angles. Even the slightest angle between the land and the breaking waves will create currents that transport sediment along the shore. These “longshore” currents are a primary cause of sand migration along barrier and mainland beaches and are greatly affected by bottom topography (bathymetry). Rivers carry sediment to the coast and commonly build deltas into the open water, though wave action transports some of the material away from the river mouth to other areas. Through this process, sand is added to beaches as natural nourishment. When rivers are damned or where they empty into estuaries, sand generally does not nourish coastal beaches, thus contributing to further erosion.

Storms, hurricanes, typhoons, and similarly extreme atmospheric phenomena along coasts produce high winds which in turn generate large waves and currents. The storms may also produce storm surges that temporarily raise water levels far above normal. For example, Hurricane Camille, one of only two Category 5 hurricanes ever to hit the U.S. in recorded history, induced a storm surge along the Mississippi Coast of as much as 7 meters (24 feet). Although these events are sporadic, they are a primary cause of beach erosion in the U.S. Storm waves eroding the beach usually move much of the nearshore and beach sand seaward, where it may be stored in offshore bars or lost from the active system when deposited in very deep water. Much of the sand stored in bars migrates toward shore during calmer weather, contributing to the natural recovery of the beach. Storms often display seasonal association, with hurricanes and typhoons occurring in the summer and fall and extra-tropical storms occurring predominantly in late fall, winter, and early spring.

Natural processes that change the water level over a long period of time also affect coastal dynamics. Sea-level change is certain to change the nature of the bottom and that affects the shapes of waves as they approach the coast, and thus may produce changes in local and regional scale sediment movement and resulting shoreline morphology. Thus, any climate-induced changes to storm tracks, intensity and duration would be likely to produce significant changes in sediment deposition and erosion patterns.

Tides rise and fall in a matter of hours in response to the gravitational attraction of the moon and sun; exceptionally high (spring) and low (neap) tides occur each month when the sun and moon are aligned. Tides help determine where and when the waves break and where sand is moved from and to. In addition to the daily cycles of tides, many other forces lead to significant changes in water level. Tides are important in determining the ultimate impact of a storm. If a storm hits the coast at high tide, the storm surge is magnified greatly; whereas if a surge hits a coast during low tide the effect may be negligible. The Great Lakes and other enclosed “seas” also experience dramatic water level changes in response to precipitation, snowmelt and evaporation. Local changes in water level also occur when the land either rises or falls relative to the water.

Along tectonically active coasts, such as the earthquake prone West Coast of the U.S., land may rise slowly as much as 4 centimeters (1.5 inches) per century, or may rise or fall dramatically by several meters in episodic earthquakes and land movements. In recently abandoned deltas, such as near the mouth of the Mississippi River, compaction of newly deposited sediment can result in extensive land subsidence of as much as one centimeter per year, or one meter per century. The Earth’s crust in parts of Alaska and the Great Lakes region are now rising due to the retreat of glaciers, which many postulate is the result of global warming. However, most of the nation’s beaches and barrier coasts have already begun responding to natural and possibly climate-induced relative sea-level rise, and often reductions in sediment supply as well. Thus, climate change may result in processes which counterbalance or accentuate each other, and anticipating the impacts that humans will have to face must be based on thorough knowledge and understanding of the interactions between climate forcing and the responses of the earth system.

4.1.2 Potential Impacts of Sea-level Rise

If a one-meter rise in sea level occurs during the next century, the worst-case IPCC scenario, thousands of square kilometers could be lost, particularly in low-lying areas such as the Mississippi delta, where land is also subsiding at approximately one meter per century. Figure 4.2 indicates several estimates of potential land loss for seven regions of the U.S. under several different scenarios, including no change in the current rates of relative sea-level rise, a 50 centimeter (20 inch) increase in sea level, and 1 meter (3 feet) sea level increase over the next century.

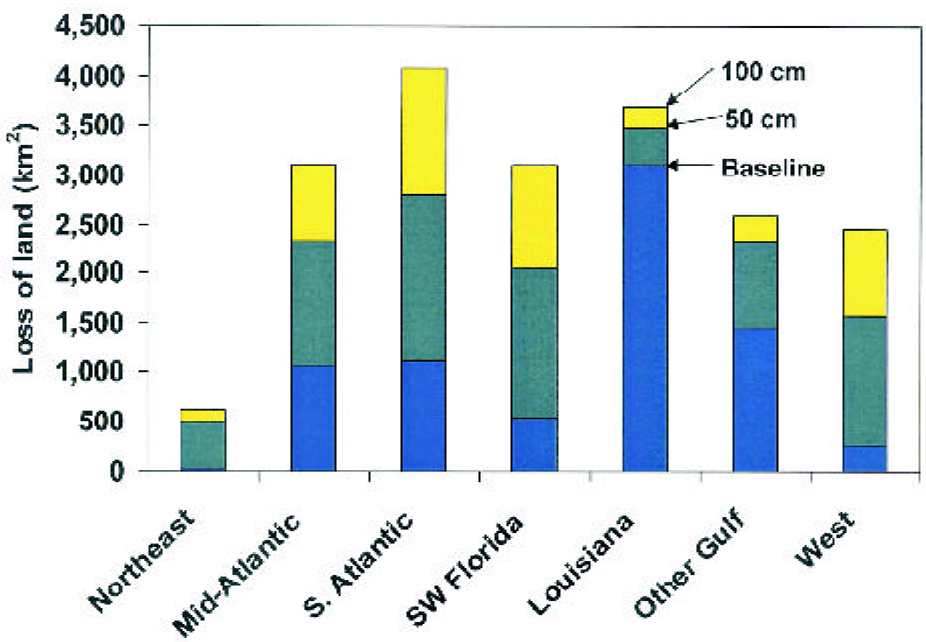

Figure 4.2. Estimated land loss for seven regions of the U.S. without shoreline protection based on projections of current rates (baseline) and sea-level rise of 50 cm and 100 cm over this century (after Titus et al. 1991).

Rising sea level will also, in general, increase storm surge flooding both as a result of the higher mean water level and because of sea-level rise induced erosion of land forms (Zhang et al. 1997; Ruggiero et al. 1996). Some areas will experience dramatic changes, going from no flooding to extensive flooding. Many coastal features, such as levees, seawalls, and naturally occurring sand dunes and ridge lines effectively block storm surges for most storms. Whenever one of these features is overtopped by storm surge from either a hurricane or an extratropical storm, the areas inland will flood. Numerical modeling has shown that large amounts of water can move over such barriers, flooding over the marshland or bay behind the barrier, and sweeping over mainland areas. Furthermore, when beaches and dunes are overtopped, there is a net landward transport of sand contributing to the net erosion of the oceanfront shoreline.

In general, a rise in sea level or changes in storms or storm surges will result in the increased erosion of shores and associated habitat, increased salinity of estuaries and freshwater aquifers, altered tidal ranges in rivers and bays, changes in sediment and nutrient transport, a change in the pattern of chemical and microbiological contamination in coastal areas, and increased coastal flooding. Secondary impacts associated with sea-level rise, such as inundation of waste disposal sites and landfills that will reintroduce toxic materials and increased siltation of subtidal habitats due to shoreline erosion, also pose threats to the health of coastal populations and ecosystems.

Many coastal structures were designed with the 100-year flood as their basis. This flooding level determines the elevations to which federal projects, such as the U.S. Army Corps of Engineers levees that protect New Orleans, are built. This is also the level to which coastal structures must be built to qualify for flood insurance through FEMA's National Flood Insurance Program. If sea level rises, the statistics used to design these structures changes. A 50-year flood may become as severe as (or even more severe than) a 100-year flood before sea-level rise (for a thorough review of risk, return times and flooding events, see Pugh and Maul, 1999). Coastal insurance rates would have to be adjusted to reflect such increased risk (Heinz Center 2000). Furthermore, FEMA estimated that the number of households in the coastal floodplain would increase from 2.7 million to 6.6 million by 2100 (FEMA 1991). This again reiterates the earlier point that the vulnerability of coastal developed areas to natural disasters can be expected to increase in the future, independent of any climate induced changes in risk.

Assessing total economic impacts from sea-level rise on coastal areas and on a national scale is still somewhat speculative. Nevertheless, a recent study (Yohe et al. 1996) has quantified the present economic costs (protection plus abandonment) to coastal structures, again using the extreme 1-meter sea-level rise as a baseline. This analysis estimated costs of as much as $36 billion between 1996 and 2100. However, this number represents market-valued estimates only, which are derived from property-value appreciation, market adaptation, and protection costs. As such, this is an absolute minimum cost estimate, as it does not include the lost ecosystem services value of non-market resources, or the costs to communities resulting from reductions in coastal economic activities such as fishing, tourism and recreation. A comprehensive review of the potential cost of sea-level rise to developed coastlines was recently completed by Neumann et al. (2000); and should be referred to for more comprehensive estimates.

4.1.3 Shoreline Systems of the West Coast

Mainland shoreline systems of the U.S. West Coast border an active tectonic region of fault-bounded crustal blocks with high elevations. Ancient shoreline terraces hundreds of meters above present sea level are evidence of rapid and extensive crustal uplift along the coasts of Southern California. The relatively narrow offshore continental shelf is bordered by deep ocean basins, and in several areas submarine canyons extend almost to the shoreline itself. Eroding headlands and sea cliffs provide much of the sediment to feed adjacent beaches. Rivers too, often fronted by extensive lagoons or bays, have historically provided much of the sediment to the nearshore system. However, extensive damming of streams and rivers for flood control and irrigation has greatly reduced the volume of material reaching the coast. The mainland beaches are relatively steep, producing a narrow zone where the brunt of the forces generated by breaking waves are concentrated.

Climate variability, such as the El Niño Southern Oscillation (ENSO), affect the frequency and intensity of storms impacting this narrow zone, with corresponding cycles of beach and cliff erosion. During the 1982-83 and the 1997-98 El Niño events, impacts were especially severe along shorelines throughout California, Oregon and Washington (Komar 1998; Kaminsky et al. 1998). Good (1994) shows that along the central Oregon coast, a rapid buildup of seawalls and revetments routinely follows the major El Niño events of the last two decades, as coastal property owners attempt to protect their shorelines from increasing erosion. Sea-level rise would certainly allow these patterns of erosion to continue, although the magnitude of change will likely be less than in regions with much more shallow nearshore slopes. Yet, even relatively small rates of erosion can be hazardous when structures have been or are built very close to shorelines.

4.1.4 Barrier Island Systems along the East and Gulf Coasts

The U.S. East and Gulf coasts are rimmed by a series of barrier island/bay systems separating the gently sloping mainland coastal plain from a similarly sloping continental shelf. The waters of the bays or lagoons between the islands and the mainland are mixed with ocean water passing through tidal inlets and freshwater runoff from the mainland. Most rivers cutting through the low-lying coastal plains flow slowly toward the bays and deposit much of their sediment directly into the bays, providing source material for extensive mud flats or marshes. The islands bear the brunt of winter storms and hurricanes prevalent along these coasts, protecting the mainland from the very large waves characteristic of ocean conditions.

However, with a rising sea level, many of these islands “roll over” or move toward the mainland through a process of beach erosion on their seaward flank, overwash of sediment across the island and deposition in the quieter waters of the bay. The rates of such natural barrier island movement depend largely on the rate of sea-level rise, and also on the frequency and severity of storms and hurricanes. Since the slope of these areas is so gentle, a small rise in sea level produces a much larger landward translation of the shoreline than occurs on the steeper West Coast. Human activities can severely impact this natural landward migration. The construction of buildings, roads, and seawalls disrupts overwash, although storms and sea-level rise continue. In response, the beachface and nearshore erode, threatening buildings and narrowing the beach.

Ringing the bays and lagoons of barrier island systems are a variety of salt marshes and other wetlands which provide critical habitat to a variety of aquatic and terrestrial species. In some cases, such as along the coast of Louisiana, broad expanses of wetlands sheltered from storm waves have developed. Such ecosystems are particularly at risk from sea-level rise. Wetlands require a delicate balance of sediment, fresh and salt water and are particularly vulnerable to inundation and erosion as a result of sea-level rise.

Case Study: Economic Impacts of Sea-Level Rise

Climate assessments have attempted to estimate the nationwide impacts of climate change on agriculture, forests, water resources, utilities, human health and many other sectors of society. Nationwide assessments of the potential consequences of sea-level rise to the coastal zone have focused on the extent and magnitude of land loss, the costs to flood insurance and other economic impacts. This case study summarizes the results of a number of these earlier assessments on impacts to U.S. coastlines; another thorough review of sea-level rise impacts to U.S. coasts was recently completed by Neumann et al. (2000).

Estimating Land Loss

Two types of studies have assessed the area of land vulnerable to sea-level rise; those that focus exclusively on land elevations but examine the entire coast and those that focus on smaller study areas but examine the range of processes that contribute to land loss. Schneider and Chen (1980) used printed topographic maps to estimate the amount of land below the 4.5 and 7.5 meter (15 and 25 foot) contours, elevation that roughly represent the potential sea-level rise that would result from a complete disintegration of the West Antarctic Ice Sheet (WAIS). While assessments using elevation and topography data provide some rough indication of vulnerability, actual land loss would also depend on a multitude of additional variables such as sediment supply, coastal erosion rates, tidal ranges, regional variations in relative sea-level change and the types of measures taken by society in response to real or perceived threats from sea-level change.

A 1989 USEPA Report to Congress considered these issues in an analysis of 48 coastal sites evenly spread throughout the contiguous 48 states, representing approximately 10% of the U.S. coastline. The study estimated the potential loss of wet and dry land for three alternative policies of coastal protection; including no protection (retreat), protecting all non-ocean shores with bulkheads, and protecting only those areas developed by 1980 (see also Park et. al. 1989; Titus et al. 1991). This report estimated that a global mean sea-level rise of 50 centimeters (20 inches) would inundate 8,500 to 19,000 square kilometers (3,300 to 7,300 square miles) of dry land if no shores were protected, and 6,000 to 15,000 square kilometers (2,200 to 6,100 square miles) if currently developed areas were protected. The loss of coastal wetlands was estimated at that time to be 17 to 43% of (then) existing wetlands without protection; 20 to 45% if developed areas were protected and 38 to 61% of existing wetlands if all shorelines were protected. Thus, the level of protection was closely coupled with the ultimate consequences to coastal wetlands under the assumptions of those studies; with more protection implying a significantly greater overall loss of coastal wetlands.

Implications for the National Flood Insurance Program

A Report to Congress by the Federal Emergency Management Agency (FEMA) in 1991 also examined the nationwide implications of rising sea level on coastal hazards. The study assessed the potential increase in flooding of coastal areas, and estimated that the total extent of the 100-year floodplain would increase from approximately 50,000 square kilometers (19,500 square miles) in 1990 to over 70,000 square kilometers (27,000 square miles) with a sea-level rise of one meter (approximately 3 feet). The report also concluded that even a 30 centimeter (1 foot) rise in sea level would increase the total area of the 100 year floodplain to nearly 60,000 square kilometers (23,000 square miles).

In this report, FEMA also estimated the projected increase in annual flood insurance premiums for representative properties insured by the National Flood Insurance Program (NFIP). By assuming that current development trends would continue, the study estimated that flood damages would increase by 36 to 58% with an approximately 30 centimeter (1 foot) sea-level rise, and by 102 to 200% for a one meter (3 foot) sea-level rise. Thus, under the assumption that these rates could be considered actuarially sound for most coastal properties, it was then assumed that premiums would rise by roughly the same proportions. However, many other studies have suggested that NFIP premiums were not then and are not now actuarially sound (Heinz Center 2000), a consideration which should be included in any assessment of the potential consequences of increased flooding risk of low-lying coastal areas.

Estimating the Cumulative Costs of Sea-Level Rise

In general, studies that have examined the potential cumulative cost of an approximately 50 centimeter (18 inches) sea-level rise have estimated the total costs to society at between $20 billion and $200 billion by the year 2100, and the cost of a one meter (3 feet) sea-level rise as roughly twice that amount (Yohe 1989; Titus et al. 1991; Yohe et al. 1996). The cost estimates vary widely because studies use a range of assumptions as well as a different means of calculating potential costs; for example Yohe et al. (1996) estimated the costs of sea-level rise based on the assumptions that only those areas which could be economically protected would be protected.

In another study, Yohe (1990) estimated the cost of not holding back the sea, based on the value of developed coastal land and structures that would be likely to be lost as a result of inundation without shoreline protection. This study estimated that the then-current value of land and structures threatened by inundation and erosion from a 50 centimeter sea-level rise would be approximately $130 billion (within a range of $78 to $188 billion). Importantly, this and other studies did not attempt to assess the impact to natural resources resulting from inundation, such as wetland production, flood control, nutrient retention, loss of shoreline habitat and other ecosystem services.

These early studies estimated costs based on the assumption of a uniform national response; which greatly oversimplifies the likely cost of responding to sea-level rise as the least expensive approach would be expected to vary significantly from site to site. By using alternative scenarios, Yohe et al. (1996) were able to estimate costs based on whether or not property owners choose to strategically depreciate their property such that by the time abandonment was necessary the property was worth very little. In an alternative scenario, owners continued to maintain their property and hence the full value of the structure was lost if the property was abandoned. Their results suggested that costs associated to property owners with a one meter rise in sea level by 2100 would be approximately $45 billion if property owners maintained their structures but would be reduced to $36 billion in the “foresight” scenario. The difference thus represents some measure of the potential economic benefits of using market-based adaptation policies in responding to future sea-level change.

Case Study: Adaptation to Sea-level Rise on Long Beach Island, New Jersey

In the last three decades, many of the barrier islands of the U.S. Atlantic and Gulf coasts have been transformed from tranquil fishing villages to thriving recreational centers which may host hundreds of thousands of visitors each weekend. The water that makes these islands desirable, however, also places them at risk. Homes built near the water with oceanfront views are vulnerable to both storms and erosion, and back bays limit people's ability to escape these problems by simply retreating landward. These risks could become more severe with rising sea level.

If human activities do not interfere, and if sand supplies are sufficient, barrier islands generally respond to changes in sea level by washing over landward. Barrier islands are commonly overwashed during storms, effecting a landward migration of the beachfront. When the overwash reaches the back bay, the entire island may migrate landward while maintaining its form. However, where there is limited sand supply and a high rate of relative sea-level rise, there may be an insufficient supply of sand to keep the island above sea level. Under such scenarios, islands may break up and eventually disappear. One example of this was the fate of the Isles Dernier in Louisiana which have decreased in surface area by as much as 77% over the last 100 years (McBride et al. 1989).

Coastal geologists are generally capable of forecasting whether a particular island will break up or wash over, as island disintegration appears to be more frequent in areas with high rates of relative sea-level rise and lower sediment supplies (Penland et al. 1988). For developed islands, however, human activities tend to impede landward island migration. Structures block the landward transport of sand, and after storms transport sand landward, local public works departments may bulldoze sand back onto the beach rather than allowing it to blow or wash to the bay side as necessary for island migration. Thus, islands narrow enough to migrate landward under natural conditions may become narrower even if there is no explicit decision to hold back the ocean or fill part of the bay.

There are four primary options by which developed barrier islands could respond to rising sea level. These include gradual erosion and abandonment, encircling the island with a dike, elevating the beach and low lands in place, and imitating the natural overwash process by engineering a landward retreat. A series of case studies of Long Beach Island (Yohe 1989; Leatherman 1989; Weggel et al. 1989; Titus 1990) examined each of these options and suggested that island raising might be the most likely option for this island, given that current policies are designed to elevate homes, roads, and the beach profile. Similarly, a USEPA (1989) report to Congress assumed that for this and other narrow, densely developed islands, elevating the island in place could be one plausible option. However, such an approach is unlikely to be appropriate for wide or lightly developed islands.

Long Beach Island, 15 miles north of Atlantic City, New Jersey, is 18 miles long, and generally only about two to four blocks wide. Over 95% of the structures are single family houses. The island was mostly developed before 1960, and thus only a few houses are elevated above flood levels. The 1962 Ash Wednesday storm cut an inlet in Harvey Cedars, and destroyed many houses at the south end of the island. Studies of possible options for coping with sea-level change on Long Beach Island involved several estimations. These included the necessary quantities and costs of the sand required for various island raising options; the engineering costs of moving structures, infrastructure and building levee and pumping systems; and the value of the property that would be lost if shores were not protected. The study considered the implications of a rise in relative sea level of nearly 2.5 meters (up to eight feet), including both the initial sand requirements and long-term maintenance, although recent projections of likely sea-level rise rates are considerably lower than this.

Leatherman (1989) and Titus (1990) estimated the amount of sand that might be required for elevating the island and engineering a landward retreat. Most of the sand required for raising the island would be used to nourish the beach. Currently, about 60% of the island is below the 5 foot (NGVD) contour, which is only about 60 centimeters (2 feet) above spring high tide. The studies assumed that after the first 30 centimeters (1 foot) of sea-level rise, low areas would be raised concurrently with sea level. For areas above the 1.5 meter (5 foot) contour, they assumed that fill would be brought in only after the sea had risen by one meter (three feet). The retreat scenario used estimates of the costs of moving homes from the oceanfront as estimated in Weggel et al. (1989). Both of these options involve raising the low bay sides of the island, and the additional sand required to create new land in the retreat scenario approximately balanced the savings from not having to raise oceanside lots vulnerable to erosion.

Figure 4.3 illustrates the total costs of the four options, which include both sand and structure

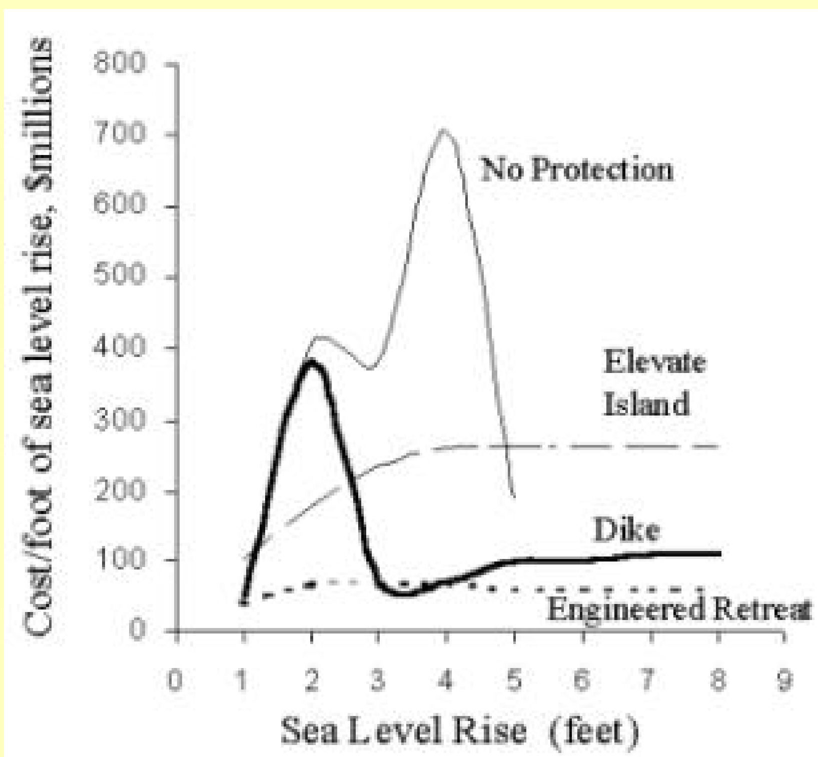

Figure 4.3. Estimated incremental costs of four alternative responses to sea-level rise on Long Beach Island, NJ (Titus 1990).

costs. Both retreat and island raising assumed that half the structures on the bay side would be elevated. The island raising scenario also assumed that half of the oceanside houses would be elevated. The retreat scenario estimated the amount of roads and utilities built on the newly created land as equal to the $20,000 per house moved. Both scenarios assumed no additional cost for rebuilding infrastructure on elevated parts of the island, because water mains and sewers would presumably remain functional although roads and telephone poles would likely be rebuilt anyway. For the protection scenario, in which the island is encircled with a levee, it was estimated that a levee and drainage system could be constructed for $330 million. Although the cumulative costs of a levee system would be somewhat less than the cost of raising the island (at least for a rise greater than one meter), the economics do not seem compelling. From the perspective of financing, a levee would be more difficult to afford than raising the island: A levee would require the community to secure an amount of capital equal to $26,000 per house; while island raising could be implemented gradually for a few hundred dollars per house per year. A levee would almost certainly reduce property values, due to the aesthetic problems of losing waterfront views and ready access to the bay.

The results of these studies suggest that for a rise of two feet or more, the cumulative cost of protection for any of the four options would be less than the value of the property lost without protection. Moreover, comparing cumulative protection costs to lost property understates the economic viability of protection. Because a typical real estate investment has a payback period of a decade, the viability of protection might be better approximated by comparing property values with the protection costs by decade. Over the course of a century, total rental value would generally be about ten times the market value of the property, that is, $20 billion. This suggests that should Long Beach Island be vulnerable to future sea-level change, some form of protection could be considered. These results also suggest that an engineered retreat would cost less, although the institutional problems of moving houses from the ocean front to the bay side would be great, as people's position relative to the water would be altered

The issue of whether to protect or retreat from barrier islands at risk of severe erosion is an ongoing and contentious issue in policy and management arenas (Heinz Center 2000; Pilkey and Dixon 1996). It is clear that coastal development can adversely affect the integrity of natural features and processes in barrier island systems, and compromise the ability of natural systems to function following major storms or erosion events. Thus, there will be no easy solutions to the issues that will challenge those who live on and manage barrier islands as they adapt to future sea-level rise. Management strategies will have to evolve with time as the magnitude and impacts of sea-level rise become more apparent.

4.2 WETLANDS

Understanding the combined effects of climate variability and change on ecosystems is frequently constrained by a lack of existing information on the way in which ecosystem functions are affected by environmental changes. For coastal wetland ecosystems the effects of global climate change can be felt directly through changes in sea-level rise as well as indirectly through alterations in watershed inputs (Boesch et al. 1994; Brinson et al. 1995). Importantly, the response of upland ecosystems to climate change affects the timing and delivery of water and sediment to the coastal zone via interactions among precipitation, storms, landcover, and land use. This critical linkage between coastal and terrestrial ecosystems makes predicting the response of coastal wetlands to climate change more complex and expands the range of factors to be considered. Because of these difficulties, the challenge of predicting the future of coastal wetlands becomes an increasingly significant problem as coastal areas continue to become heavily populated and developed, resulting in both direct and indirect deterioration and destruction of wetlands.

Coastal wetlands are valuable ecosystems. By providing refuge and forage opportunities for wildlife, fishes and invertebrates, marshes and mangroves around the coastal U.S. are the basis of the economic livelihoods of many communities. Shallow ponds and seed producing vegetation provide overwintering habitat for millions of migratory waterfowl, and the structure of trees and forests is vital to songbirds and waders alike. The role of wetlands in absorbing nutrients and reducing loading to the coastal ocean is widely recognized, as is their value for protecting local communities from flooding; either by damping storm surges from the ocean or by providing storage for riverine floodwaters. Thus, coastal wetlands are undoubtedly some of the most valuable ecosystems in the nation (see Section 2.2) and also some of the most threatened. Climate change and variability compound existing stresses from human activities such as dredging and filling for development; navigation or mineral extraction; altered salinity and water quality resulting from activities in the watershed; and the direct pressures of increasing numbers of people living and recreating in the coastal zone.

We present here a discussion of how coastal wetlands (high and low salinity marshes as well as forested wetlands such as mangrove and baldcypress swamps) respond to climate variability and might respond to climate change. Principal variables of concern to coastal wetlands include increased atmospheric temperature and concentrations of carbon dioxide, alterations in river discharge, changes in sediment discharge, increased frequency and intensity of tropical cyclones and accelerated sea-level rise. While direct scientific evidence for responses to individual factors is sometimes available from experimental studies or localized opportunities, understanding of how the various components of climate change interact at the land-sea margin has rarely been directly examined. However, the value of these ecosystems and the demonstrated potential for future changes in climate require us to assess the implications to coastal wetlands in order to develop and implement coping strategies where possible.

4.2.1 Salt Marshes

Salt marshes occur in temperate areas in the lower reaches of estuaries and colonize the upper tidal flats where inundation frequency and duration are low enough to allow plant growth. While saline marshes around much of the United States are dominated by the smooth cordgrass *Spartina alterniflora*; regional variants include *Salicornia virginica* and *Spartina foliosa* in California and southern Oregon, and a more diverse assemblages including *Distichlis spicata*, *Triglochin* spp., and *Plantago maritima* in the Pacific Northwest. In the west, these native halophytes are being supplanted at low tidal elevations by invasive *Spartina alterniflora* which can grow vigorously on open mudflats unavailable to the natives. Salinity typically varies between full strength to half strength (ca. 15psu) ocean salinity, depending on coastal physiography and the level of freshwater inputs to the coastal ocean.

Many plants have adapted to hot and dry conditions through alterations in the way in which they fix carbon in the Calvin cycle; commonly these plants are referred to as C4 plants (a minority of plant species, but including important agricultural plants such as sugarcane and corn), whereas most species are C3 plants. Studies of short-term response of photosynthetic rate to elevated CO_2 indicate that the response will be greater in C3 plants than in C4 plants; indicating how the response of salt marshes depends greatly upon the community composition. Curtis et al. (1989) showed an increase in primary productivity of *Scripus olneyi* (C3) under increased CO_2, but no indication of an increase in the total nitrogen in above-ground biomass. Their findings also showed a dichotomy between C3 and C4 plants in the effect of increased CO_2 on the percentage of nitrogen found in leaf material, as well as to varying conditions of ultraviolet radiation (Van de Staaij et al. 1990). How such changes interact with environmental stresses from salinity and aerobic soil conditions in salt marshes is a subject of ongoing research. Experimental studies of European salt marsh species have shown that the growth reduction associated with increased salinity can be reduced to some extent by CO_2 enrichment (Rozema et al. 1990; Rozema et al. 1991) and other workers have noted increased salt tolerance. Some agricultural species increased water use efficiency under elevated CO_2, suggesting an increased tolerance for drought or salt tolerance. However, if nutrient use efficiency of plants is also affected by enhanced CO_2, these effects may be more difficult to predict.

Increases in salinity of coastal wetlands resulting from decreased freshwater discharge (and subsequent intrusion by more saline offshore waters) may result in decreased productivity of coastal salt marshes, but should not necessarily result in a habitat shift. It is widely documented that *Spartina alterniflora* tolerates a wide range of salinities (Adams 1963; Webb 1983). Similarly, the variation in salinities found by Visser et al. (1998) in marshes dominated by the cordgrass *Spartina patens* was also wide (average salinity 10.4 ± 5.8 ppt), and overlapped with the zone dominated by *Spartina alterniflora* (average 17.5 ± 5.9 ppt) that it seems likely that major changes in salinity would be required to result in a significant change in habitat types in the more saline marshes. Decreases in salinity will likely increase the productivity of salt marsh plants as osmotic stresses are decreased. However, the salinity data of Visser et al. (1998) suggest that decreases in salinity of more than 5 ppt might be required for *Spartina alterniflora* to be replaced by more brackish marsh species.

Salt marshes experience little wind damage from tropical storms and hurricanes but are strongly influenced by storm tides. The severity of storm surge impacts is highly correlated with the speed and path at which the storm approaches the shore. Hurricane Hugo caused little geomorphic change to the salt marsh at North Inlet, SC because it crossed the shore rapidly with little rainfall (Gardner et al. 1991). By contrast, Hurricane Andrew caused widespread damage to coastal marshes in Louisiana because it crossed the shore slowly and at an oblique angle (Guntenspergen et al. 1995).

Storm surges can introduce sediment into the marsh and redistribute sediment as portions of the marsh are eroded (Cahoon et al. 1995; Guntenspergen et al. 1995; Nyman et al. 1995) resulting in substantial sediment accretion and geomorphic changes. Tropical storms are potentially important both in providing a pulse of sediment over a broad geomorphic scale to balance the effects of subsidence, particularly for deltas, and in enhancing coastal marsh survival for areas remote from a sediment source. Despite delivering sediments to the marsh surface, tropical storms and hurricanes are capable of compacting some highly organic and weakened marsh substrates, resulting in a loss of elevation, apparently by the weight and force of the storm tide surges (Cahoon et al. 1995; Cahoon et al. 1998).

Perhaps the most widely examined effect of climate change on coastal salt marshes are their responses to sea-level rise. Salt marsh surfaces are frequently considered to be in an equilibrium relationship with local mean sea level (e.g., Pethick 1981; Allen 1990), and indeed dating of buried salt marsh peats is a frequently used technique for reconstructing past sea-level changes (e.g., Orson et al. 1998). That marsh surface elevation changes to keep pace with sea-level rise is well established; unfortunately researchers are unsure whether the elevation change is driven by sea-level change or whether the space provided by a rising sea level merely allows the increase in elevation to occur. The latter would imply that elevation change is limited by sea-level conditions (see Gehrels and Leatherman 1989; and Reed 1990 for reviews). The projection of salt marsh sustainability under future climate scenarios a complex issue and depends on: the relative importance of organic matter to marsh vertical development (Bricker-Urso et al. 1989); the complexities governing organic matter accumulation during rising sea level (Reed 1995); the importance of subsurface processes in determining surface elevation change (Cahoon et al. 1995); and the role of storm events and hydrologic changes in controlling sediment deposition, soil conditions and plant growth (Cahoon et al. 1995b; Goodbred et al. 1998; Kuhn et al. 1999).

A group of researchers (Working Group on Sea-level Rise and Wetland Systems 1997) identified the rate of sea-level rise as one of the key issues to the ability of marsh systems to cope with climate change. Some answers may be found where subsidence already produces rapid rates of relative sea-level rise (RSLR) for coastal marsh areas. In the Mississippi Deltaic Plain some studies have suggested that marshes cannot keep pace with relative sea-level rise rates approaching 1 centimeter per year (Baumann et al. 1984). Many parts of this system are being rapidly degraded, for a wide range of reasons which are detailed more fully in the following case study (see also Boesch et al. 1994). On the other hand, tide gauge records show these rates of sea-level change have been occurring for decades in some parts of coastal Louisiana, yet vast areas of salt marsh still exist (e.g., Fuller et al. 1995). These marshes are diminishing in area by marginal erosion rather than submergence effects.

This suggests that under optimum conditions of sediment supply, salinity, and water quality, salt marshes may be able to survive rates of sea-level rise as high as 50 centimeters (18 to 20 inches) in 50 years; rates lower than the expected rise in sea level estimated for much of the coastal U.S. over the next 100 years. Local subsidence or hydrologic changes, however, could increase the rise in sea level experienced by individual marshes perhaps exceeding the local

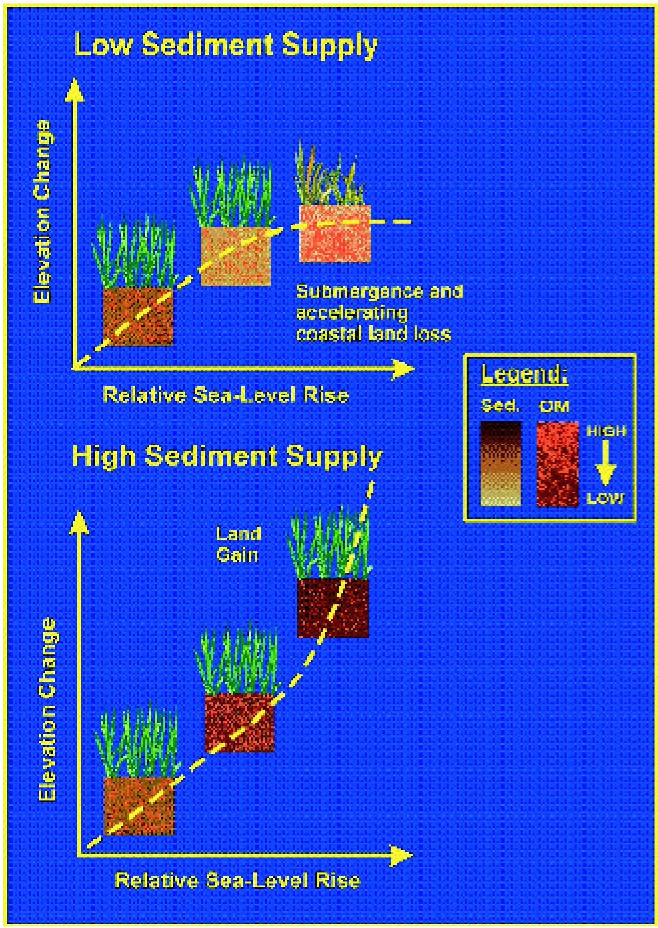

Figure 4.4. How coastal wetlands respond to sea-level rise depends greatly on the supply of sediments with which soils can be accreted sufficiently to allow the surface of the wetland to gain elevation. With high sediment supplies coastal marshes and mangroves can persist even under high rates of relative sea-level rise. (Reed 1999).

threshold of marsh vertical development. Figure 4.4 illustrates this process graphically. For Louisiana, Swenson and Swarzenski (1995) noted that for periods of several years at a time in the late 1960's and early 1970's tide gauges have recorded rates of relative sea-level rise as high as 6 cm per year. Such high rates are considerably greater than global long-term trends in sea level. The cause of these perturbations is unclear and may be associated with peculiar combinations of river discharge and wind patterns. Yet this period does coincide with a period of very high land loss in coastal Louisiana confirming the notion of an upper limit of the rate of sea-level rise beyond which marsh deterioration occurs. Even if thresholds are exceeded only long enough for marsh vegetation to be stressed and die, the consequences for coastal salt marshes are serious.

4.2.2 Low salinity marshes

Inland from salt marshes but still close enough to the coast to experience tidal fluctuations in water level, are wetlands dominated by a variety of grasses and annual and perennial broadleaved aquatic plants. This wetland type is found most commonly in the mid and south Atlantic coasts and in Texas and Louisiana, as well as in upper reaches of estuaries on the West Coast. Species diversity is high and dominant plants may include bulrush, maidencane and wild rice species (such as *Scirpus californicus, Panicum hemitomon* or *Zizania aquatica*). Here the effects of climate change and variability on low salinity marshes will manifest themselves as changes in salinity and flooding regime associated with changes in freshwater delivery to the coastal zone, or with sea-level rise and the physical stresses of storm surges.

Increased salinity penetration, either sustained or pulsed, can dramatically affect low salinity coastal wetlands. Wetland species have developed various adaptations to higher salt concentration, such as mechanisms to extrude salt from their tissues, mechanisms to balance the osmotic potential of the salt with other compounds, and means to secrete salt from their tissues through specially produced salt glands (Mitsch and Gosselink 1993). However the tolerance for salt varies widely among wetland plants, and even plants which usually can tolerate some salinity can be negatively affected by changes in salinity. For example, growth of the cordgrass *Spartina patens*, usually considered a salt tolerant species and found in low marshes in Louisiana at an average salinity of 8.5 psu (Chabreck 1972) was shown to be adversely affected by salt concentrations above about 5 psu in higher march substrates (Pezeshki and DeLaune 1993). Another species (maidencane, *P. hemitomon*) typical of freshwater marshes was able to grow, albeit at a reduced rate, at a salinity of 9 psu for a month in one study (McKee and Mendelssohn 1989), and showed 76% carbon assimilation at 5 psu in another (short-term) study (Pezeshki et al. 1987b). Clearly the magnitude and frequency of salinity pulses introduced into fresher marshes as a result of climate change will determine whether fresher marshes species survive. Gradual changes in salinity, associated with long-term trends of decreased freshwater discharge to coastal areas, will likely result in a transition to more salt tolerant species; however, concurrent changes in salinity patterns that result in decreased plant productivity may impair the ability of marshes to keep pace with sea-level rise.

Increasing marsh surface elevation is fundamental to prevent coastal submergence and thus loss of vegetated wetlands under conditions of sea-level rise (Reed 1995). While the accumulation of inorganic sediments is viewed as critical to the vertical development of substrates of mangrove and salt marsh systems, organic accumulation is more important in typically more peat-based substrates of low salinity marshes. The dependence of low salinity marshes upon the generation of organic material means that their ability to respond to changes in mean sea level is critically related to the ecological thresholds associated with flooding, plant productivity and decomposition of organic material. Blum (1993) has found in Virginia marshes that differences in organic matter accumulation between high and low marshes are due to differences in root production rather than root decomposition. Root production in these marshes appears to be influenced by variations in tidal inundation conditions, suggesting a sensitivity of this contribution to vertical accretion to alterations in flooding regime caused by sea-level rise. If marsh flooding exceeds the ability of marsh plants to build organic soil, or result in soil waterlogging and plant deterioration, then organic coastal marshes will not survive.

In the rapidly subsiding Mississippi Deltaic Plain there are many fresh marsh areas which are subjected to high rates of relative sea-level rise (1 cm per year in many areas). In part, these rates may be due to the development of "flotant" or floating marshes. These are described by Sasser (1994) as "wetlands of emergent vegetation with a mat of live roots and associated dead and decomposing organic material and mineral sediments, that moves vertically as ambient water levels rise and fall." That the mat can move in response to water level variations indicates that plants are unlikely to be stressed by increases in mean sea level alone. Sasser (1994) suggests that the floating marshes of the Mississippi Deltaic Plain probably developed under freshwater conditions removed from riverine sediment inputs. Under certain conditions, floating marshes form when natural "attached" organic marshes are subjected to subsidence or sea-level rise and the buoyant organic mat is subjected to increasing upward tension (O'Neil 1949). The marsh eventually breaks free from its mineral substrate and floats. This adaptation to sea-level rise relies upon buoyancy of the organic mat – a characteristic of marshes with minimal mineral sediment deposition. However, where sulfate is present in marsh soils, some mineral sediment input is required to buffer the development of toxic sulfides. Thus, the development of floating marshes is probably constrained to areas of very low salinity, where sulfide is less of a problem, and low mineral sediment inputs. In these areas, marshes that maintain surface elevation under conditions of sea-level rise may undergo a change in marsh character, from attached to floating.

Even if low salinity marshes with highly organic substrates can survive sea-level rise their long-term sustainability may be reduced because of increased sensitivity to greater storm surge impacts. Among the impacts of 1992's Hurricane Andrew on low salinity marshes were the introduction of large quantities of sediment onto the marsh surface that smothered vegetation, the introduction of salt water into fresh marsh resulting in salt burn, the disruption and erosion of organic marsh substrates, and the distribution of large quantities of wrack onto marsh that killed the underlying vegetation (Guntenspergen et al. 1995). However, plant cover was quickly re-established in all impact types except for scour areas and areas of thick wrack accumulation. Additionally, shifts in species dominance resulted in laterally compressed areas because of increases in elevation (as much as 1 to 2 meters). Elevation decreased continuously to about pre-storm elevations in these areas over the next two years (Cahoon et al. 1995). Any increase in the frequency or magnitude of such storm impacts associated with climate change will reduce the time for recovery from such impacts and threaten the long-term sustainability of these organic substrates.

4.2.3 Mangroves

Mangroves, comprising approximately 60 species of trees and shrubs, are the predominant form of vegetation in the intertidal zone of tropical estuaries, lagoons, and sheltered coastlines. They are largely confined to latitudes between 30 degrees north and south of the equator, with a few notable exceptions that may be explained by the occurrence of warm ocean currents or by the presence of relict populations of more poleward past distributions (Duke 1992). According to one recent estimate, the total area of mangroves in the world is 181,000 square kilometers (Spalding et al. 1997); although only a small fraction of this habitat is found within the states and territories of the United States. In the continental U.S., well-developed mangrove forests are found only in South Florida, although mangrove communities also exist in the Caribbean, Hawaii and throughout territories in the South Pacific. The impacts of climate change and variability on these systems occur via changes in atmospheric conditions such as CO_2 concentrations and temperature, ability to cope with sea-level rise, and structural damage to the forest canopy during storm events.

Increases in air, soil and water temperature may affect the growth and distribution of many coastal forested wetlands. Most mangrove species in tropical regions appear to have maximal shoot growth at around 25°C and maximum rates of photosynthesis at around 28 to 32°C (Clough et al. 1982; Andrews et al. 1992). Therefore, changes in productivity may be relatively minor. Because temperature increases may stimulate productivity of mangroves to a much greater degree at subtropical and temperate latitudes, global increases in air temperature may result in poleward shifts in the distribution of tropical and subtropical species such as mangroves. The limiting factor for at least some species, however, is not mean temperature, but the occurrence of low temperature or freezing events that exceed tolerance limits (McMillan and Sherrod 1986; Snedaker 1995). Better data on the likely changes in such events are needed before poleward shifts can be projected with any degree of certainty, although warmer winter atmospheric temperatures projected by climate models for the southeastern U.S. make northward expansion of the range of mangroves on the Gulf and Atlantic coasts likely. Duke (1992) suggests that a particularly important factor controlling the poleward distribution of mangroves is winter water temperature. He found that mangrove distribution generally matches the 20°C winter isotherm.

Mangrove forests are susceptible to catastrophic wind damage from tropical cyclones; often resulting in mortality and significant changes in forest structure and function (Wanless et al. 1994; Doyle et al. 1995; Baldwin et al. 1995). Recovery following storms can be rapid (Brokaw and Walker 1991; Frangi and Lugo 1991; Roth 1992), but more frequent or intense storms are likely to result in long-term structural and functional changes in forested wetlands. Mangroves in the Caribbean region, for example, may be shorter in stature in the future (Doyle 1999) if storms are more frequent. Snedaker (1995) suggests that more frequent storms in the Caribbean may favor the black mangrove *Avicennia germinans* and the white mangrove *Laguncularia racemosa* over the red mangrove *Rhizophora mangle*, because of the former species' greater capacity to recover following severe structural damage (but see also Doyle 1999). In addition, the death of red mangrove trees has been related to the conversion of forest to mudflat habitat (Wanless et al. 1994) apparently caused by a rapid loss of elevation related to oxidation of mangrove peat (Snedaker 1995; Wanless et al. 1995).

There have been few experimental studies of the effects of enhanced CO_2 concentrations on the growth of mangrove species, and these have focused on the response of mangrove seedlings only under controlled greenhouse conditions. Red mangrove seedlings grown under elevated CO_2 conditions had higher "root to shoot" ratios, relative growth rates, and net assimilation rates, and greater biomass, leaf area, and stem length (Farnsworth et al. 1996; Ball et al. 1997).

Seedlings exposed to elevated CO_2 for one year reached sexual maturity two years earlier than typically occurs under field condition (Farnsworth et al. 1996). The growth of the red mangroves *R. apiculata* and *R. stylos* were enhanced by elevated CO_2 levels, but the response of each species differs along salinity and humidity gradients (Ball et al. 1997). This suggests that current differences in forest structure and productivity along salinity gradients may become greater under a regime of increasing atmospheric CO_2. Both of these studies indicate that mangroves can be flexible in their response to elevated CO_2 and that these findings must be integrated into the impacts of sea-level rise to yield accurate predictions of the effects of local climate change to mangrove ecosystems.

The much greater volume of research on the effects of elevated atmospheric CO_2 on agricultural and upland forest systems and in herbaceous wetlands suggests that some growth enhancement is likely, at least for seedlings, but the long-term impacts on productivity, nutrient cycling, and other ecosystem processes are very uncertain. There appears to be a high potential for significant interactions between atmospheric CO_2 concentrations and plant responses to salinity, temperature, nutrient, and water stress, and Field (1995) recommends long-term assessments of CO_2 effects under conditions where these factors are controlled.

Freshwater inputs can moderate salinity distributions in the coastal zone. Although mangrove forests are ecologically confined to high salinity coastal areas, mangrove productivity increases proportionally with the availability of fresh water (Pool et al. 1977). This response is modulated by reductions in pore water salinity and thus salt stress. The production and accumulation of mangrove peat has been observed to be great in low salinity mangrove impoundments in Florida. If freshwater runoff decreased to the point where mangroves were continually exposed to higher salinities then organic production would be expected to decline (Snedaker 1995). Gas exchange studies (Ball and Farquhar 1984) indicate that net photosynthesis in mangroves decreases as salinity increases. The higher sulfate concentrations of high salinity waters would also facilitate anaerobic decomposition by sulfate reducers and the potential loss of existing mangrove peat. This response may have implications for the survival of mangrove forests under increased sea-level rise, but increased salinity alone is unlikely to result in catastrophic loss of mangrove forests.

The response of mangroves to sea-level rise will vary depending on the forest type, environmental setting, and supply of freshwater and sediment. Mangroves have historically kept pace with sea-level rise through extensive peat production, which depends on an adequate supply of fresh water to maintain root growth, and sediments (Snedaker 1993). Mangroves not only migrate upslope in response to sea-level rise given an adequate sediment supply and room for landward expansion; but they may also expand seaward if sedimentation is rapid (Woodroffe 1992). From a global literature review of ^{14}C dating of mangrove peats, Ellison and Stoddart (1991) concluded there will be a world wide collapse of mangroves when the global rate of SLR exceeds 1.2 mm per year. This was based largely on their perception that mangroves exhibit high fidelity to particular habitats. They 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 sediments from terrigenous sources.

In contrast, Bacon (1994) predicted that there will be a variety of responses for mangroves in the Caribbean, including loss, migration, change in forest structure (see also Snedaker 1995), and expansion, because of the wide range of wetland types and geomorphic settings in which each mangrove species occurs. Similarly, Snedaker et al. (1994) indicates that mangroves in south Florida expanded during a 60 year period when the rate of sea-level rise was 2.3 mm per year. Our understanding of how mangroves will respond to sea-level rise is limited, in part, by a lack of knowledge of short-term accretionary processes in mangrove forests (Woodroffe 1992). Cahoon and Lynch (1997) noted that in a red mangrove forest in southwestern Florida, filamentous turf algae and the dense mangrove root mat bound unconsolidated sediments in place. Hence, both sediment deposition processes and root growth at the soil surface contributed to vertical soil development. They also found that the ability of that mangrove forest to keep pace with sea-level rise was best described by short-term measures of vertical accretion and elevation change than by longer-term measures of vertical accretion by using lead ^{210}Pb dating techniques.

Case Study: Wetland Loss in Coastal Louisiana

Between 1956 and 1990, Louisiana coastal wetlands were lost at rate of 60 to 100 square kilometers (24 to 40 square miles) per year. As approximately 40% of the nation's brackish and freshwater coastal wetlands are found in Louisiana, this constituted as much as 80% of the total loss of these wetlands in the U.S. (Boesch et al. 1994). Unlike wetland loss in other parts of the country, wetlands lost in South Louisiana were generally converted to open water rather than drained and filled for agriculture or other types of development. The remaining 1.4 million hectares (3.5 million acres) of wetlands in South Louisiana provide critical nursery areas for finfishes and crustaceans (particularly shrimp and crabs) that make up the bulk of Louisiana's seafood industry. Additionally, these coastal wetlands serve as important buffers for storm surges, protecting inland residential and commercial infrastructure from severe flooding.

Wetland zonation in the highly structured ecosystem is structured by factors such as tidal influence, soils, elevation, freshwater inflows and energy regimes. Plant communities grade inland from salt marshes near the Gulf shoreline to brackish marshes, freshwater marshes and wooded swamps. These coastal wetlands serve as important buffers for storm tides, thus protecting inland residential and commercial infrastructure from severe flooding. The continued loss of Louisiana's coastal wetlands threatens more than $100 billion in public, private and commercial construction, including the infrastructure that handles over 60% of U.S. oil imports and about 90% of the oil and gas produced in U.S. Outer Continental Shelf. However, the oil and gas industry itself has been directly responsible for a substantial proportion of these losses, as wetlands have declined in response to the combined effects of canal dredging and the fragmentation of wetlands into smaller units which are more vulnerable to the forces of tides, storms and boat wakes.

A combination of anthropogenic and natural factors contribute to the dramatic wetland losses in South Louisiana, where seasonal overbank flooding of the Mississippi River successively created six distinct deltaic land masses over the last 7,000 years. Subsidence has largely attributed to dewatering and compaction of sediments deposited by deltaic processes. Global sea-level rise combines with subsidence to produce rates of relative sea-level rise in Louisiana in excess of 1 cm/yr as measured using tide gauges. In the past, each time the river shifted its course away from an active delta, the abandoned delta began to naturally deteriorate, forming barrier islands and erosional headlands. When people levied the Mississippi River to prevent flooding, the natural processes that build and maintain coastal wetlands were disrupted. Dam construction in the upper parts of the Mississippi River basin since 1950 reduced the amount of sediment transported by the river by about 50%, limiting potential accretion in this sediment-dependent ecosystem.

Other human activities that exacerbate these problems include the dredging of access canals, well sites, and pipeline rights-of-way for oil and gas extraction. By 1994, 523 oil fields had been discovered in Louisiana's coastal zone and 23,477 wells had been drilled. Dredging of navigation channels for other forms of commerce increased tidal exchange in many embayments. Drainage of formerly wetland soils in New Orleans and other population centers accelerated natural sediment compaction, lowering their elevation and increasing their susceptibility to flooding. These changes to natural hydrology alter the balances between sediment deposition, plant growth, organic matter, accumulation and subsidence that have maintained the coastal marshes for thousands of years. The result is that marshes fail to maintain their elevation, gradually becoming waterlogged with plants and soils submerged for longer periods on each tide. Eventually, the plants die and soil integrity is lost allowing rapid erosion of the remaining marsh substrate. Additional stress is placed on fresher marshes and forested wetlands by penetration of saltier water further inland via canals and rapidly expanding coastal bays. Because of the altered hydrology these changes in salinity frequently occur too rapidly for the natural transition to more salt tolerant vegetation to take place and marshes and swamps are converted directly to open water. Once lost, coastal wetlands have proven to be extremely difficult to restore.

Vegetated wetlands characteristically capture sediment from surface waters and produce organic matter that results in vertical accretion of the wetland surface. In some areas of South Louisiana, wetlands accrete material sufficiently to keep pace with current rates of relative sea-level rise. In other areas, subsidence dominates and plant growth is reduced. Thus, if global warming increases the rate of sea-level rise beyond the present average for the Gulf of Mexico, those regions of coastal Louisiana where marshes are currently on the margins of survival will suffer. Critical ecological thresholds will be crossed when flooding and salinity are too great for plant survival and even more extensive land loss will result.

Accelerated sea-level rise that may result from global warming is being considered in efforts to address coastal wetland loss in Louisiana. However, because regional subsidence dominates relative sea-level rise and is expected to do so for many decades, most management attention is being directed to protecting and restoring barrier islands that shield the wetlands from wave attack, managing wetland hydrology, and diverting the flow of river water and sediments into the coastal wetlands. An ambitious plan has been developed by state and federal authorities under the Coastal Wetlands Planning, Protection and Restoration Act to achieve some sustainable condition by 2050 (Louisiana Coastal Wetlands Conservation and Restoration Task Force and Wetlands Conservation and Restoration Authority 1998), however its implementation faces daunting scientific, technical, social and economic challenges. The potential consequences of climate change on these coastal wetlands add but another formidable challenge.

4.2.4 Freshwater Forested Wetlands

Coastal freshwater wetland forests frequently have an extremely diverse flora of trees, shrub and herbs (Conner et al. 1986). In the southeastern United States they can be roughly divided into deepwater swamps dominated by baldcypress (*Taxodium distichum)* and tupelo gum (*Nyssa aquatic*), with a red maple (*Acer rubrum*) and buttonbush (*Cephalanthus occidentalis*) understory; and a seasonally flooded bottomland hardwood forests dominated by several oak species (*Quercus* spp.), green ash (*Fraxinus pennsylvanica* var. *lanceolata*), and other hardwood species. The impacts of climate change and variability on these systems are likely to occur via changes in salinity, ability to cope with sea-level rise, and structural damage to the forest canopy during storm events.

Changes in salinity regime can result from either decreased freshwater discharge to the coastal zone, or from increasing sea level which allows penetration of salt water into previously freshwater areas. The result of changes in salinity regime for the forest community depends on the magnitude, rate and periodicity of salinity increases. Many studies have examined the effects of salinity on baldcypress, and it is apparent that intraspecific variations in plant response need to be understood before the effects of salinity change at the landscape scale can be assessed. Allen et al. (1997) showed that baldcypress seedlings from a variety of coastal and inland swamp locations could tolerate salinities of 2 psu. Higher salinities resulted in reduced leaf biomass with lesser effects on root biomass and stem biomass. However, Myers et al. (1995) did not find groundwater salinity levels of 2.8 psu as limiting cypress seedling growth; and Conner and Askew (1992) note that older seedlings are more able to tolerate pulses of salt water (30 psu) as might be experienced during storm surge flooding of an interior swamp forest. The storm surge caused by Hurricane Hugo flooded some low-lying coastal forests greater than 3 m deep with salt water, and the storm surge carried saline water (> 20psu) along waterways up to several hundred kilometers inland (Blood et al. 1991). Elevated soil salinity levels lingered for months and had adverse affects on tree survival and growth, as well as on nutrient cycling processes (Blood et al. 1991; Williams 1993).

The effect of tropical cyclone activity on forested wetlands can be structural as well as hydrologic. Low salinity and freshwater forested wetlands differ in their susceptibility to tropical storm impacts, with damage to forest types generally greatest to pines, least to swamp, with hardwoods intermediate (Conner 1998). This pattern was generally followed with the effects of Hurricane Andrew in south Florida, where cypress trees located in cypress domes experienced little damage while 85% of the pine trees sampled on hardwood hammocks suffered major stem damage (Slater et al. 1995). Damage to the forests on the hardwood hammocks also led to invasion by exotic species following Hurricane Andrew (Horvitz et al. 1995). In the Atchafalaya River basin in south Louisiana, Hurricane Andrew caused little damage to cypress-tupelo communities but caused significant damage and mortality to bottomland hardwood forests where forest structure and function were altered (Doyle et al. 1995). However, in some areas in the vicinity of Cape Cod, Atlantic white cedar wetlands were more severely affected by blowdowns from Hurricane Bob than adjacent upland forests, a fact attributed to their relatively shallow root systems (Valiela et al. 1998).

Combined effects of climate change and variability on freshwater discharge to the coastal zone and sea-level rise rates will likely result in increased flooding in many coastal swamp systems. Increases in freshwater discharge during floods are unlikely to result in any deleterious effects in freshwater forested wetlands as long as seasonal low-water periods allow for substrate drainage and forest regeneration. Baldcypress regenerates well in swamps where the substrate is moist and where competing species are unable to cope with flooding. Seedlings must experience dry periods long enough to allow growth and survival during future flooding (Conner and Toliver 1990). DeLaune et al. (1987) recognized gradients in seedling survival for both baldcypress and oak species along an elevation gradient in a Louisiana coastal swamp. Increased flooding thus reduces the area of appropriate elevation for seedling survival. Furthermore, Rheinhardt and Hershner (1992) reported that increased saturation of substrate also alters species composition in freshwater swamps. They found ash and black gum (*Fraxinus* spp. and *Nyssa sylvatica*) in wetter areas compared to red maple and sweetgum (*Acer rubrum* and *Liquidambar styraciflua*) within drier swamps of the Virginia coastal plain. Similarly, Conner and Brody (1989) noted a change from bottomland hardwood species to water tupelo and baldcypress in model simulations of the effect of relative sea-level rise on Louisiana forested wetlands.

Regarding the ability of freshwater forested wetlands to survive sea level, Rheinhardt and Hershner (1992) note that freshwater swamps are "precariously positioned" at the upper reaches of tidal penetration and keep pace with sea-level rise by accumulating biomass. An experimental study by Day et al. (1989) showed slow root decomposition in both periodic and frequently flooded study sites containing baldcypress seedlings. This suggests that accumulation of dead organic matter will not be impaired by rising water levels associated with sea-level rise. Connor and Day (1991) found a positive relationship between vertical accretion of swamp soils and flooding duration but also note that accretion was dependent upon the availability of suspended sediments in the flooding waters. Thus the effects of increased flooding from riverine systems associated with climate change might also provide increased sediments that allow swamp systems to keep pace with sea-level rise.

4.2.5 Summary of Climate Impacts

The survival of coastal wetlands under conditions of altered climate really depends primarily on the ability of the plants to adapt and keep up with the rate of change. The biogeomorphic processes which control the wetland landscape may produce gradual changes, e.g, from marsh to mangrove swamp, as long as the environmental thresholds which control plant survival are not crossed. The challenge in predicting coastal wetland response, either the nature of the gradual change, or when and where the thresholds are exceeded, depends upon interactions among the responses to the various climate forcing discussed here. Even when considered individually the various system responses are complex:

Atmospheric Changes: Increased CO_2 and temperatures generally mean increased plant production. The response varies between species however, and will likely change competitive interactions within vegetative communities. The potential decreased growth associated with UV-B, or changes in nutrient allocation and utilization might counter any increases associated with other atmospheric changes.

Freshwater Inputs to Coastal Wetlands: More fresh water is generally beneficial to coastal wetlands, and a decrease may result in salinity stress for some communities. Furthermore, a gradual change does not necessarily result in wetland loss and salt and brackish marshes may replace freshwater marshes and swamps. However, the expected spatial variations in runoff associated with various climate scenarios make generalizations about response impossible; examples of where thresholds for coastal plants may be exceeded are in the western Gulf of Mexico where already limited freshwater inputs are expected to decrease dramatically in the future.

Sediment Delivery to Coastal Areas: For coastal wetlands that already face gradual sea-level rise, increased sediment delivery increases sustainability by providing for vertical accumulation of substrate. Dramatic sediment delivery events could increase elevation sufficiently to convert wetlands to areas of upland vegetation, but unless the net effect is greater than the cumulative effects of sea-level rise, episodic sedimentation should be seen as part of dynamic equilibrium, balancing long-term sea-level rise.

Storms: The resilience of coastal wetlands to storm effects varies with salinity. Fresher systems are more susceptible to saline incursions during storms while the structure of some mangrove species reduces their vulnerability to wind damage. The long-term effect of storms on coastal wetlands depends upon the recovery time and the return interval of the storms. Climate induced changes in frequency, if not intensity, of storm impact may therefore result in irreversible damage to forested systems or fragile organic substrates. For minerogenic salt marsh soils, however, storms can provide inputs of sediment essential to vertical sustainability.

Sea-Level Rise: The effects of sea-level rise, at least at the rates currently projected by GCM scenarios, are unlikely to have a catastrophic impact of coastal wetlands in themselves before the middle of the next century; but when combined with subsidence and other environmental changes, the consequences may be severe. Human alterations to coastal landscapes in the last several centuries have been dramatic. The human development of interior wetland margins can prevent or hinder the natural landward migration of wetlands that are susceptible to sea-level rise. Furthermore, groundwater withdrawals may exacerbate the effects of sea-level rise and produce subsidence stress independent of climate change. In terrestrial and fluvial systems, dams and levees placed to enhance navigation or water supply and prevent flooding lead to the reduction of sediment and freshwater supply to coastal areas, limiting the natural ability of wetlands to cope with rising sea level.

It is important to recognize that these various responses may interact in ways that are difficult to predict, and that these factors and their interactions may result in a host of indirect effects on coastal wetlands, such as changes in patterns of herbivory or the effects of invasive species. Most mangrove and freshwater forested wetland plant species are many millions of years old (Duke 1995). Thus they have survived through numerous and very large-scale changes in climate and sea level; including glacial-interglacial periods associated with changes in sea level of 100 or more meters (Woodroffe 1990). Survival under such circumstances generally depended on the ability to migrate, rather than on the persistence of individual wetlands. Individual wetlands today can either accumulate vertically to maintain their position in the coastal zone or migrate as in the past. Studies show that both can occur, where conditions are favorable.

However, in today's human-dominated environment shoreline developments and other types of barriers will limit options for migration. Vertical, rather than lateral, adjustment is therefore the key to wetland survival. Control of river discharge and capture of sediments by dams alter the flux and deposition of sediments that, in the geologic, or even historic, past may have ensured wetland sustainability through vertical accumulation of substrate.

Case Study: South Florida Regional Ecosystems

The South Florida regional ecosystem includes upland, wetland, freshwater, estuarine, and coastal ecosystems all closely linked by surface and groundwater hydrology. A large and very rapidly growing human population is perched on a very narrow strip of land along the coast. This population is highly dependent on the health of the environment for its economic base; especially tourism, recreational fishing and agriculture. The proximity of the Everglades National Park, Biscayne National Park, and the Florida Keys National Marine Sanctuary illustrates the high value society places on this unique environment. The coral reef and fish communities in particular are extensive and provide major sources of recreational fishing and diving.

The historical (pre-drainage) South Florida landscape was a hydrologically interconnected mosaic of habitats, including freshwater marshes, hardwood tree hammocks, cypress swamps, pinelands, mangrove swamps, freshwater lakes and streams, estuarine lagoons and coral reefs (Harshberger 1914; Davis 1943; Craighead 1971; Duever et al. 1986; Gunderson 1994; Davis et al. 1994; DeAngelis 1994). Fresh water flows as a shallow sheet across the gently sloping landscape below Lake Okeechobee, through the tangled mangrove forests to the estuaries and out to the coral reef tract. Fresh water flow is the unifying force and sustaining element of the system. Wading birds, alligators, sawgrass plains, mangroves, and tropical hardwood hammocks are among its most recognizable features. However, the essence of the Everglades is the abundance and diversity of species that once lived among the diverse range of habitats spanning vast open spaces.

This landscape derived from a unique combination of climate, soil, substrate, and topography (Obeysekera et al. in press) and a unique mixture of tropical, temperate, and endemic plant species. Episodic events, such as fires, freezes, floods, droughts and hurricanes, controlled the structure of the landscape. Fires were associated with the dry season and dry years, and even very small elevational differences led to totally different responses to the natural fires. For example, the shallow (1 meter deep) moat surrounding hardwood hammocks, that themselves were only a meter or so higher than the surrounding sawgrass plains, protected the hammocks from fire. This allowed hardwood trees to reach ages measured in decades and even centuries within an expansive matrix of sawgrass that burned on cycles of a few years (Robertson 1962; Gunderson and Snyder 1994).

Currently nearly 5 million people live in urban centers within a few kilometers of this former ecological paradise, and the population of Florida as a whole continues to grow at a rate of almost one million people per decade. Water, once the critical characteristic of the natural system, has become the most limiting resource. The lack of adequate quantities and timely distribution of clean water to coincide with the system's natural cycles has reduced the Everglades to a degraded remnant of its former self, which continues to decline. The natural variability of surface water has been altered dramatically, so that now in very wet years, massive amounts of freshwater are discharged directly "to tide" (meaning discharged through canals and pumps into a few coastal estuaries). However, the historical sheetflows of water that used to flow into other parts of the coast, especially Florida Bay, have now been substantially reduced, occasionally resulting in hypersaline conditions. The human-dominated nature of the hydrological and, therefore, ecological systems of the region will fundamentally affect their ability, or lack of ability, to adapt to climate change over the next century. These ecosystems will be influenced by potential changes in air and sea surface temperatures, the frequency of episodic freeze events, altered precipitation patterns, the frequency of droughts and associated fires, impacts of hurricanes and tropical storms, and changes in the rate of sea-level rise.

Temperature Changes

The Canadian and Hadley models, as well as most other GCMs, strongly suggest that there will be increases in global mean annual atmospheric temperatures, with greater increases expected in higher latitudes and for nighttime values. Outputs for regions on the scale of South Florida are less certain, particularly because of its dominant maritime influence (Miami is one of the very few cities in all of the United States that has never experienced a 100° F temperature reading). However, elevated mean annual temperatures for South Florida may not be as consequential as elsewhere; both because these increases may be smaller and because the ecosystems of the region are already largely adapted to warm tropical conditions. Analyses by Harris and Cropper (1992) using the Holdridge life-zone model indicate little migration of habitats in South Florida, although the northern limits of the tropical and subtropical habitats would migrate up the Florida peninsula. However, South Florida is already ripe with exotic species that have invaded from more tropical areas, and there is a serious concern that climate change might favor these highly opportunistic species to the disadvantage of native species, (Malcolm and Markham 1997).

Changes in the frequency of episodic freeze events is another possibility. One might expect that climate change would reduce the frequency of such events, although there is little confidence that such a prediction can be asserted based on GCM results. For example, during the 1980's, which to that point was the warmest decade in U.S. history, there was a series of severe freezes in Florida. Many areas that for decades had been prime citrus production regions had their crops completely wiped out, and citrus production moved significantly farther south. The distribution of citrus is an excellent surrogate for the latitudinal distribution of frost sensitive coastal species, especially mangroves. However, if there were to be a reduced frequency of freezing events across Florida, then over time the coastal red mangrove communities might shift farther to the north of Tampa Bay and Cape Canaveral. However, a reduced frequency of freezes would not be expected to cause a major impact on other coastal ecosystems of the region.

Changes in sea surface temperatures (SSTs) in South Florida may result from climate change. Presently, summer sea surface temperatures occur that are near the maxima of many marine species (Vicente et al. 1993; Milliman 1993). Thus, the marine ecosystem impacts are likely to be most associated with transient elevations of SSTs. Since many coral species live near the upper limits of their thermal tolerance, they are particularly at risk of elevated temperature episodes (see section 4.4.3). Recently, a series of such events caused extensive coral bleaching in the Florida Keys and elsewhere, including the Caribbean and the Eastern Pacific (Williams et al. 1987; Glynn and de Weerdt 1991, Milliman 1993). Clearly, if there were a significant increase in such events, there could be severe impacts on the coral reefs of the region, particularly if the frequency of incidences increased to the point at which natural recovery mechanisms were precluded. Additionally, elevated temperatures and changes in precipitation often coincide, such that nearshore marine organisms must often cope with greatest fluctuations in salinity when already near their limits of thermal tolerance (Moore 1972).

It is less clear that elevated SSTs would have directly adverse affects upon seagrass or wetland communities of the region. Literature on this issue was developed in the early 1970's when the Turkey Point nuclear power plant was being considered for siting on the southern coast of Biscayne Bay. The concern was that thermal pollution might send many coastal species over the top of their temperature tolerances. Roessler and Tabb (1974) noted that mean summer temperatures in Biscayne Bay are about 31°C, with maxima near 33°C. Studies on thermal gradients indicated that maximal temperatures tolerated by fauna were in the range of 32 to 33°C, at which about 50% of the species were excluded, and 37 to 38°C, at which 75% of the species were excluded (Roessler and Tabb 1974). However, experience in Biscayne Bay since the nuclear power plant became operational have shown an absence of significant thermal effects on the ecology of the Bay, suggesting the ecosystem has accommodated any additional thermal load near the facility.

Other more subtle effects may occur from elevated water temperatures in South Florida. For example, there is evidence that the gender of sea turtles is determined by ambient temperatures at critical stages in embryonic development, with elevated temperatures leading to a preponderance of females (Mrosovsky and Yntema 1980; Mrosovsky and Provancha 1992). There is also particular concern for individual animal species that are already stressed and have greatly reduced ranges, such as the manatee, Cape Sable sparrow and Florida panther. Additional stress resulting from higher temperatures could put those populations at increased risk for extirpation or extinction (Harris and Cropper 1992).

In very shallow water, such as some areas of Florida Bay or in canals and lagoons, high surface temperatures can lead to anoxia, potentially causing massive die-offs of fish and invertebrate species. Elevated surface temperatures could be expected to interact with elevated salinity conditions, for example in areas of northeast Florida Bay low freshwater inputs led to hypersalinity conditions and possibly to the seagrass die-off of the late 1980's and early 1990's (Robblee et al. 1991). At a larger scale, there has been speculation that climate induced changes in ocean temperatures might alter circulation patterns in the Gulf of Mexico and Caribbean (Gallegos et al. 1993). As South Florida lies at a critical intersection of the Loop Current and the Gulf Stream, the interactions of these major circulation systems are key controlling factors in the distribution, recruitment, and survivability of coastal marine fish and invertebrate communities (Lee et al. 1992; Lee and Williams 1999). While this is highly speculative at this point, there could be major implications for all of coastal South Florida were circulation to be altered.

Precipitation

As discussed previously, the intra and interannual variability of precipitation has been a major shaping force on the South Florida landscape. It is unclear how mean annual precipitation would change in South Florida; the Canadian model suggests a decrease in winter, but increase in summer for an overall annual increase in precipitation, while the Hadley model suggests an increase in winter, decrease in summer, and annual decrease in total precipitation. Thus it is necessary to consider the effects of either an increase or a decrease in regional precipitation as well projected increases in evapotransporation in assessment of the effects on surface and groundwater availability. Moreover, the massive flood control system that has been engineered for the region has significantly altered the consequences of variations in precipitation on the surface water resources of the region.

A critical aspect of precipitation changes would be increases in the incidence of drought conditions through delayed onset of the wet season, particularly over several succeeding years. While the occasional drought year was historically an important positive event ecologically, as discussed above, too frequent or too extensive droughts may be detrimental to South Florida ecosystems. If there were significant increases in drought intensity or frequency, then the competition for water resources for human uses would intensify, perhaps further reducing freshwater availability to natural wetland and coastal ecosystems. This would lead to increased salinity in Florida Bay and release of high saline waters through the passes of the Florida Keys potentially adversely affecting coral reefs offshore.

A major and virtually inevitable consequence of increased frequency or intensity of droughts is the increased incidence of fires. Many of the ecosystems of South Florida are fire-adapted and thus require periodic fires, especially the upland pineland community and the sawgrass plains of the Everglades. However, almost all of the original pinelands of South Florida have been altered or destroyed to allow for human habitation. As a result, only small remnants remain, making them vulnerable to other stressors. In addition, habitat fragmentation and fire suppression policies can allow build up of fuel loads, thereby increasing the risk of more intense, catastrophic fires. Major fires can bypass the natural barriers that protect hardwood hammocks and mangroves from fires. These ecosystems are greatly disturbed by fire, and recovery can take decades or longer. Thus, if climate change causes decreasing precipitation and an increased frequency of drought, one potential major adverse consequence would be increased risk to coastal mangrove ecosystems and hardwood hammocks from fire. This, in turn, would make these ecosystems more vulnerable to exotic species invasions. For example malaluca, Brazilian pepper and other species that threaten wetlands are also well-adapted to fire events and may have advantages over some native species, which would in turn make them more capable of converting some native wetlands to uplands and further crowding endemic species.

Tropical storms and hurricanes

South Florida historically experienced hurricanes roughly once per decade, but some projections are that climate variability or change might result in changes in the frequency or intensity of tropical storms and hurricanes (see discussion section 3.3). Hurricanes can alter the plant communities; for example Hurricane Donna in 1960 destroyed mangrove forests north of Cape Sable that had numerous century old trees. Additionally, much of the remnant pine forest near Florida City was eliminated by insect invasion following physical abrasion of the tree trunks from flying debris from Hurricane Andrew. Hurricane Andrew also caused considerable damage, albeit quite locally, to coral reefs, especially in interaction with subsequent tropical and winter storms (Lirman 1997). In many cases following hurricanes, exotic and opportunistic species take over large areas, such as the tremendous expansion of the range of *Casurina* (Australian pine) caused by Hurricane Donna, and the replacement of very large, old hardwood trees, such as mahogany, in hammocks by vines and other opportunists.

Thus, with more hurricanes there might be increased local damage to mangrove forests, transient increases of sediment and organic load to coastal waters, increased physical damage to coral reefs, and increased physical disturbance to pinelands. Although the ecosystems of the region have generally adapted to hurricanes over evolutionary time, the anthropogenic habitat alteration of the region has put many ecosystem types at greater risk. The pineland ecosystem is the most obvious example. The most important ecological effects of hurricanes and tropical storms, however, may be indirect. One critical factor involves how society responds to extreme climate events. As noted, the draining of the Everglades was in large part a direct response to loss of human life and property from hurricanes in the 1920's and 1940's (Light and Dineen 1994; Solecki et al. in press). We can only speculate how society might respond to future perceived risks to human life and property, and how that might adversely affect the ecosystems of the region. Clearly however, concern for human welfare has been one of the most important driving forces this century, in many instances causing the degradation of the South Florida regional environment.

Sea-Level Rise

A critical issue with regard to sea-level rise is the extent to which accelerated sea-level rise scenarios might already be partially represented in the current rapid sea-level rise rate observed in South Florida. If the projected global sea-level rise exceeds the rate observed for the past seven decades, then highly significant and possibly devastating coastal effects can be expected. The mangrove-dominated transition zone between marine bays and the freshwater wetlands of the Everglades would be particularly affected (see section 4.2.3) as the coastal fringe and islands succumb to rising waters not counter-balanced by soil accretion. Additionally, brackish waters would intrude farther into heretofore freshwater wetlands, causing an inland migration of the estuarine transition zone, particularly if the fresh water available to the Everglades is also reduced by climate changes and competing uses. Unlike coastal wetlands elsewhere, inorganic sediments to accrete wetland soils in South Florida are produced in situ by biological processes that precipitate calcium carbonate; rivers do not deliver sands and silts to the coast. Little consideration has yet been given in management plans to strategies that might enhance the rate of accumulation of calcareous sediments in these wetlands. Shoreline erosion, loss of wetland fringe and inland migration of the estuarine transition would conspire to result in loss of important habitats (Hendry 1993). Moreover, the extensive coastal development of South Florida would squeeze many species into vanishingly small habitat spaces, with high risk to vulnerable populations such as Key deer, American crocodile, and perhaps sea turtles (Harris and Cropper 1992).

In remaining patches of natural coastline, especially along the coast of the Everglades National Park, many islands and fringe mangrove communities would likely be lost. Saltwater intrusion would occur into surface and ground water systems and freshwater marshes, wetlands, and sloughs would become saline. Reduced habitat could also adversely affect neotropical migratory birds and butterflies using coastal South Florida habitats (Harris and Cropper 1992).

Summary

The natural South Florida regional ecosystem was largely defined by a number of geological and climate variables; including extremely low-relief topography; large influxes of water that slowly moved across a highly oligotrophic (nutrient poor) landscape; and high variability in rainfall within and across years. Located at the northern limits of tropical and subtropical species and communities; the region supported a complex mosaic of terrestrial, wetland, and coastal ecosystems intimately coupled by the regional hydrology. But currently South Florida is also home to 5 million people, with a net growth rate of about 800,000 people per decade, and hosts additional tens of millions of visitors annually (Solecki et al. in press). The region has been tremendously modified by one of the world's most extensive water management systems, primarily to provide water and flood protection for urban and agricultural use (U.S. COE 1994).

Habitat alteration due to human development is pervasive, and whole classes of ecosystems have already been lost (Davis et al. 1994). As a result, the ecosystems of South Florida at present are not considered sustainable (Harwell et al. 1996). In response to this widely recognized environmental problem, an unprecedented process is underway for ecological restoration in South Florida. These include a federal-state-tribal governmental task force that coordinates planning and research; a Florida Governor's Commission for a Sustainable South Florida established to develop environmental and societal goals for the region; a proposed $7.8 billion plan for restructuring the water management system and acquisition of large tracks of land for water storage and nutrient removal (Governor's Commission 1995; U.S. COE 1998, see also Harwell 1998 for an overview). It remains to be seen if this process will succeed in the face of continuing development and population pressures, much less under the additional stress of global climate change.

4.3 ESTUARIES

Estuaries have been described as the most valuable of all ecosystems on earth in terms of their services in support of human societies (Costanza et al. 1997). Many aspects of climate change are likely to influence the functioning of estuaries. These include changes in freshwater runoff, temperature changes, alterations in salinity, and sea-level rise (Kennedy 1990; Peterson et al. 1995; Moore et al. 1997; Najjar et al. 2000). Differences in the response of estuaries to climate is expected among regions, based on regional differences in the response of the upstream terrestrial systems to climate change.

Estuaries vary widely in terms of their geomorphology and bathymetry, relative size of the watershed, physical circulation patterns, and water residence times, and each of these can affect the response to climate change. With regard to bathymetry, estuaries can be shallow or deep, narrow or wide, and they can have sills or not. Some estuaries such as the Hudson River estuary or even the Chesapeake Bay have very large areas of watershed compared to the surface area of the estuary itself. For other estuaries such as Narragansett Bay the ratio of watershed area to estuary area is quite small. The physical circulation of an estuary is controlled by the balance between tides and riverine influences as these interplay with bathymetry.

Generally, four different types of estuarine circulation are distinguished (Postma 1980). These include; salt wedge circulation, where tidal influence is small relative to riverine inputs of freshwater (the Southwest Pass of the Mississippi is an example); partially mixed circulation, where both tidal and riverine influences are important (Chesapeake Bay and the Hudson River estuary are examples); well-mixed estuaries where tidal energy is a more important factor than freshwater inputs from rivers (Narragansett Bay is an example); and hypersaline estuaries, where evaporation exceeds freshwater inputs, resulting in a reverse density flow with less saline coastal waters (Laguna Madre in Texas is an example). Water residence times may vary from less than one day to several years, and even within a given type of classification of estuary, residence times and circulation patterns may vary widely. For example, both Chesapeake Bay and the Hudson River estuary are drowned river valleys, with fairly large watersheds and partially mixed circulation. However, the Hudson has a much smaller surface area and a water residence time of a few days or less while the water residence time in Chesapeake Bay is more than a year.

4.3.1 Effects of Temperature Changes on Estuaries

Overall, the greatest effects of climate change on estuaries are likely to result from increased temperatures and from changes in the physical mixing characteristics, which are affected by changes in freshwater runoff, sea-level rise, and tides. For temperature, we can expect to see large regional differences in the physical drivers. For instance, deep nearshore waters along the Pacific coast will be influenced more by ocean temperatures, while shallow, semi-enclosed waters of many East and Gulf Coast estuaries will be affected more by local air temperatures, as these are influenced by continental weather processes.

The Canadian and Hadley Centre models both predict warmer mean air temperatures in all seasons in the vicinity of Atlantic and Gulf Coast estuaries, but the Canadian model predicts more rapid and greater warming (Doherty and Mearns 1999). The Canadian model predicts mean air temperatures in the Mid-Atlantic coastal regions to increase by 1-2°C over all seasons by 2030, 2-4°C by 2060 and 4-7°C by 2090 (Fisher et al. 2000). These predictions are fairly uniform over the seasons and from New York to North Carolina, although winter warming is slightly less and summer-fall warming is slightly higher to the south. These mean temperature differences must, of course, be superimposed over the current means. Furthermore, some assumptions must be applied to predict the effects of changing air temperature on water temperature.

Water temperatures in estuaries and enclosed bays are to varying degrees influenced by the temperature of the coastal ocean, which in interchanged by tidal action. However, estuarine water temperatures are also greatly influenced by air temperatures on both seasonal and interannual scales. Consequently, the warmer air temperatures projected by climate models would certainly result in warmer estuarine temperatures, particularly along Atlantic and Gulf coasts where estuaries tend be shallower and with restricted exchange to the ocean. This effect is expected to be greater in winter and on the timing of fall and spring temperature changes, because evaporative cooling tends to moderate heating during the warm summer months. This would have numerous potential consequences, the most straightforward of which are latitudinal shifts in species distribution. Populations of species near the southern ends of their distribution, the soft clam *Mya arenaria* in the Chesapeake Bay, for example, may be eliminated in some estuaries because they are unable to survive the warmer winter conditions (Najjar et al. 2000). Other species may extend their range northward and become abundant where they were previously seldom if ever found. Changing temperature regimes may also open the door for the establishment of populations of nonindigenous species introduced by ballast water or other human vectors that were previously unable to survive because of low winter temperatures (Carlton 2000).

Temperature and the timing of seasonal changes in temperature affect other important physical, chemical and biological processes in ways that are complex and difficult to forecast. Seasonal warming and cooling and the temperature differences between surface and bottom waters affect circulation, stratification, plankton production, seasonal oxygen depletion and the survival and growth of larvae. The solubility of oxygen in water decreases with increasing temperature, while warmer temperatures increase oxygen consumption through respiration. For both of these reasons, the warming of estuaries during summer will aggravate the problems of hypoxia (low oxygen status) and anoxia (oxygen free water) that already plague many estuaries.

Case Study: Mid-Atlantic Estuaries

Mid-Atlantic coastal environments are characterized by large estuaries formed as drowned river valleys such as the Hudson-Raritan, Delaware, Chesapeake and Pamlico-Albemarle estuaries. These are often interspersed with coastal lagoons, formed behind barrier islands. Collectively, the large coastal plain estuaries in the Mid-Atlantic region represent the most extensive estuarine environments in the United States. They harbor significant living marine resources during all or part of their life stages. In addition, several of the nation most important ports, New York City, Philadelphia, Baltimore and Hampton Roads, are located in these large estuaries.

Most Mid-Atlantic estuaries are in a degraded environmental condition, but are currently receiving substantial societal commitments for their restoration through pollution reduction, habitat rehabilitation and more sustainable use of living resources. A particular focus of these restoration efforts in the Mid-Atlantic region is the reduction of nutrient over-enrichment, or eutrophication, from point discharges and diffuse sources throughout the watersheds draining into the estuaries. These estuarine ecosystems are also affected in numerous ways by climate variability and change, as they influence water temperature, tidal and longer-term variations in sea level, storms and extreme weather events, and inputs of fresh water and other materials from the land. These driving factors are themselves not independent and their effects on the estuaries are also highly interactive.

Temperature

The annual temperature range experienced in more southerly Mid-Atlantic estuaries is among the widest in the world, ranging from near 0°C to near 30°C, as a result of continental climate regime. The increased temperatures throughout the year projected during the next century will, in general result in a narrowing of the annual water temperature range, particularly in the

Chesapeake and Albemarle-Pamlico systems. This is because warmer winter temperatures will result in less seasonal cooling while the warming effect of higher summer temperatures will be moderated by evaporative cooling. In other words, summer water temperatures may be slightly higher, but winter lows should be considerably warmer. In addition the warmer spring and fall temperatures will probably affect the timing of seasonal temperature transitions, which affect a number of ecologically important processes.

The Mid-Atlantic coastal zone is a transitional biogeographic region, and an altered temperature regime could affect the species that occur in these estuaries. For example, species that are near their southern limits, such as the soft clam *Mya arenaria,* may no longer survive or be prolific in the Chesapeake Bay, whereas warm temperate species found in estuaries in the Carolinas (e.g., commercially important penaeid shrimp or, possibly, the toxic dinoflagellate *Pfiesteria piscicida*) could become more common (Najjar et al. 2000). The introduction of alien species into Mid-Atlantic estuaries from shipping and other means is subject of growing concern. Dozens of species of marine plants and animals may have already been introduced into Chesapeake Bay. Somewhat warmer and less seasonally variable temperatures in these estuaries may allow other nonindigenous species inadvertently introduced by ballast water discharges to establish populations under these more benign conditions.

Sea-level Rise

Most attention to the effects of climate change on coastal environments has focused on global rates of sea-level rise (see section 3.6). However, the regional effects of sea-level rise must be considered in the context of vertical movements of the land surface due to tectonic processes and subsidence and short-to-intermediate scale variations in climate that affect coastal water levels. Because of the combined effects of global sea-level rise and regional land subsidence, the relative rate of rise throughout many parts of the Chesapeake Bay has been about 3.3 mm per year over the past 60 years. This has caused shoreline erosion and inundation of low-lying islands and salt marshes in the bay. By simple extrapolation of past trends, and ignoring any influences of global warming, we would infer an additional rise of 33 centimeters (1 foot) in the bay by the end of the coming century. Ongoing local trends in the bay must be added to these effects, suggesting that through much of the Chesapeake Bay the rate of relative rise will be at least doubled by 2100.

These relative rises in sea level will cause inundation of tidal wetlands (the landward retreat of which will be restricted by steps taken by land owners to prevent the loss of fastlands), shoreline erosion, and further loss of islands and other tidewater lands. The depth and volume of the estuary would also be expected to increase, although those effects would be partially offset by sedimentation due to increased shoreline erosion and changes in the erosion potential of the estuary bottom. Increased depth and volume could result in intrusions of higher salinity up the estuary and its tributaries, with concomitant biological changes and increased potential for salinization of ground water. However, the future salinity distribution in Mid-Atlantic estuaries will also be affected by changes in the freshwater runoff as discussed below.

Storms and Freshwater Inflow

Although some scientists have predicted that global warming may increase the frequency and severity of hurricanes and tropical storms, the recent consensus of climate modelers is that such projections remain uncertain (see section 3.3). However some predict that, because of compression of the latitudinal gradients in ocean temperatures, extratropical storms could increase in intensity, although they may decrease in frequency. Notably, it is these such storms, specifically the "northeasters", large low pressure systems tracking west to east across the coast, that have the largest and most destructive impact in the Mid-Atlantic region. These storms, most common in autumn and winter, often bring strong and prolonged onshore (northeasterly) winds combined with high precipitation and waves to the region. Among the most notorious of such storms was the "Halloween storm" of October 1991, which had major effects on the Delmarva coast and the Bay (and was vividly chronicled in *The Perfect Storm*).

Potential increases in precipitation in the watershed and runoff of freshwater into the Mid-Atlantic estuaries could have profound consequences on efforts to restore and manage these ecosystems. Large floods, such as those associated with Tropical Storm Agnes in 1972, have major effects on these estuaries that last for many years or even decades. Moreover, average annual precipitation has increased by over 20% in the Susquehanna River basin, the largest river basin in the Mid-Atlantic region, over the past 100 years (Karl and Knight 1998). For the Chesapeake Bay as a whole, seasonal high flow records were set in 1996 and 1998.

For the Hudson-Delaware-Chesapeake mean increases in winter-spring precipitation of 0.5 to 1 mm/day are projected by both the Canadian and Hadley Centre models for the 2060 and 2090 periods, suggesting as much as a 30% increase in precipitation. An increase in winter-spring precipitation that increased freshwater inflow by 30% could raise the average flow to the levels seen in these estuaries previously only in high-flow years. This would deliver more nutrients, making the management goal of reducing nutrient inputs more difficult and more of a moving target (Najjar et al. 2000). On the other hand, even if there is no change in summer-fall precipitation, increased evapotransporation may reduce soil moisture, increasing demand on water resources for irrigation and growing populations, and reducing summer-fall flows into these estuaries. Thus changes in freshwater delivery in either direction will have the potential to cause a range of both positive and negative impacts throughout the region.

Mitigation and Coping

The multiple environmental changes in Mid-Atlantic estuaries potentially induced by climate change will interact in complex ways that are difficult to predict. For example, efforts to reduce eutrophication may have to contend with sea-level rise, which will threaten the purifying tidal wetlands, change the flushing and circulation in the estuaries and may lead to greater shoreline erosion that releases nutrients, increases turbidity, and silts bottom habitats. Additionally, increased winter-spring discharges may deliver more nutrients and increase the density stratification causing hypoxia. Warmer temperatures may also affect stratification and rates of plankton production and nutrient regeneration.

With few exceptions, these potential consequences of climate change are not being considered yet in long-term estuarine and coastal zone management in the region. Although the consequences of sea-level rise on zoning setbacks, flood risks, shoreline erosion, and infrastructure (roads, bridges, docks, sewerage, etc.) are being considered in some parts of the Mid-Atlantic region, these factors are generally not considered in a systematic fashion. Moreover, the broader ramifications of changes in temperature, freshwater discharges, and storms, in addition to sea level, are scarcely considered in integrated coastal and estuarine management.

Some mitigation strategies may be appropriate to consider before the consequences are fully manifest. For example, water use and management policies could anticipate changes in the amount and seasonal distribution of water availability – and the needs of the estuaries in water storage allocation. Improved land use practices, such as more efficient nutrient management practices in agriculture and more extensive restoration of riparian zones and wetlands, may be required to meet nutrient reduction goals in seasonally wetter, more “leaky” watersheds. Additionally, newly developing approaches to reduce the risk of introduction of nonindigenous species by ballast water treatment might particularly target points of origin likely to pose greater risks in the future. Climate change will also bring alterations to Mid-Atlantic estuaries about which little can be done. Better understanding of these alterations is needed to inform coping strategies, ranging from shoreline zoning setbacks to multi-species fisheries management.

4.3.2 Another Global Change: Nutrient Over-Enrichment

Climate change is only one aspect of human-accelerated global environmental change, particularly for estuaries. Perhaps even more than its current influence on greenhouse gases in the atmosphere, human activity has altered the biological availability of nitrogen throughout the biosphere (Vitousek et al. 1997). This is of immense consequences for estuaries, as eutrophication may be the largest threat to the integrity of ecological functioning in estuaries. Eutrophication has been defined concisely as an increase in the rate of supply of organic matter into an ecosystem due to either flux from external sources or production within the system through biological processes which are stimulated by nutrient addition (Nixon 1995). Generally, nutrients stimulate excessive algal production, sometimes including blooms of harmful algal species, which in turn may lead to an increase in the decomposition of organic matter by bacteria and other organisms. This decomposition consumes oxygen, and when the rate of oxygen consumption exceeds its replenishment hypoxic (low oxygen) or anoxic (no oxygen) conditions may result (Vitousek et al. 1997; NRC 2000).

The effects of eutrophication in estuaries include higher rates of primary productivity, greater phytoplankton biomass with a concomitant decrease in water clarity, growth in anoxic and hypoxic waters, more frequent and longer lasting blooms of harmful algae, degradation of seagrass beds and corals, and alteration of ecological structure among phytoplankton, zooplankton, and the benthic community (Jørgensen and Richardson 1996; NRC 2000). Fishery resources can be lost both through direct fish kills from low oxygen events and through subtle alteration of the food web towards structures that are less conducive for producing fish. Overall biotic diversity is also decreased (NRC 1996a). Eutrophication is probably the biggest pollution problem in the coastal waters of the United States (NRC 1993; NRC 2000). Over half of the estuaries in the United States have at least some symptoms indicating moderate to high states of eutrophication (Bricker et al. 1999).

Most nitrogen on earth is present as molecular N_2 in the atmosphere, and prior to human acceleration of the nitrogen cycle, this nitrogen was made available to plants only through bacterial nitrogen fixation and fixation by lightning. Human activity has greatly accelerated this rate of conversion of N_2 to plant-available forms through production of inorganic fertilizer, combustion of fossil fuel, and management of nitrogen-fixing agricultural crops (such as soybeans). This rate of fixation by human activity increased globally 2- to 3-fold between 1960 and 1990 and continues to grow (Galloway et al. 1995; NRC 2000). As a result, since the 1960s the world has changed from one in which natural nitrogen fixation by bacteria was the dominant process to a situation where human-controlled processes are at least as important in making nitrogen available on land (Vitousek et al. 1997; Cleveland et al. 1999; NRC 2000). The rate of change is particularly rapid for fertilizer; especially as half of the inorganic nitrogen fertilizer that has ever been used on earth has been used in the last 15 years (NRC 2000).

The alteration of the global nitrogen cycle has not been uniform, and some regions have seen tremendous changes while other regions have seen little change (Howarth et al. 1996). These variations are caused by differences in intensity of agriculture and fossil fuel use. Generally, the increase in nitrogen delivery to estuaries is directly proportional to the increase in nitrogen mobilization by human activity in the watersheds of the estuaries (Howarth et al. 1996; Jaworski et al. 1997; Howarth 1998). For example, human activity has increased the nitrogen flux down the Mississippi River to the Gulf of Mexico by some 4-fold and has probably increased nitrogen fluxes to the estuaries of the northeastern United States by some 6- to 8-fold on average (Boynton et al. 1995; Howarth 1998). Much of this increase has occurred since 1960, and much of it has been in the form of readily available nitrate (Jaworski et al. 1997; Goolsby et al. 1999; NRC 2000).

In the United States, both the use of inorganic nitrogen fertilizer and the release of nitrogen pollution to the atmosphere from fossil fuel combustion have stabilized somewhat over the last decade or two. Globally, both of these sources continue to increase as a result of growth in the developing world (NRC 2000). However, rates of fertilizer application per area of arable land are now becoming quite high in some developing nations such as China. This suggests that future growth in agricultural production in developing nations may not continue to support the rate of population growth, and that over the next few decades we might expect to see rapid growth in agriculture in the United States to augment the food needs of the developing world. It seems likely, therefore, that the use of nitrogen fertilizer in the United States will again grow rapidly in the future, with major implications for estuarine eutrophication.

4.3.3 The Susceptibility of Estuaries to Eutrophication

Estuaries vary greatly in their susceptibility to eutrophication, and the same input of nutrients to two estuaries may lead to much greater eutrophication in one than in the other (Bricker et al. 1999). Many factors contribute to this variation in the susceptibility to eutrophication, including both biological and physical parameters (NRC 2000). Climate change will have a major influence on many of these factors and is therefore likely to alter the susceptibility of estuaries to eutrophication. For instance, the abundance of benthic suspension feeders such as various species of mussels, clams and oysters can affect eutrophication in estuaries (Alpine and Cloern 1992; Meeuwig et al. 1998; NRC 2000), and these organisms may change in abundance in response to temperature increases. The physical mixing regime and water residence time are also critical in determining the sensitivity of estuaries to eutrophication (Malone 1977; Cloern et al. 1983; Moore et al. 1997; NRC 2000; Howarth et al. in press), and these will be altered by climate change as well. Given our current state of knowledge, it is difficult to generalize as to the direction of response, but it seems likely that some estuaries will become more susceptible to eutrophication while others become less susceptible.

Physical circulation patterns influence eutrophication in estuaries in many ways, with perhaps the greatest factors relating to water residence time and to stratification. The water residence time varies greatly among estuaries, from less than a day for many estuaries up to 1-2 years for Long Island Sound and perhaps a few decades for the Baltic Sea. Water residence time can affect eutrophication both through its influence on diluting nutrient inputs (Bricker et al. 1999) and through its interaction with phytoplankton growth rates (Malone 1977; Cloern et al. 1983; Howarth et al. in press). Even at their fastest growth rates, phytoplankton populations are only able to double once or twice per day. Consequently, in estuaries where the water residence time is less than a day, phytoplankton are advected (exported) from the system as fast as they can grow, making the estuary relatively non-susceptible to eutrophication. For example, an increase in primary productivity and eutrophication of the Hudson River estuary between the 1970's and the 1990's has been attributed in part to an increase in water residence time during some summers as a result of lower freshwater runoff from the watershed (Howarth et al. in press). During the wet summers of the 1970's, water residence times in the surface waters of the Hudson were less than a day. However, low freshwater runoff during the summers of 1995 and 1997 increased water residence times in the estuary to several days, resulting in 10-fold greater rates of phytoplankton production.

The extent of vertical stratification can also be important in determining the susceptibility of an estuary to eutrophication. In many estuaries with deeper water columns, phytoplankton production is limited by light availability. An increase in stratification can lessen light limitation by keeping phytoplankton buoyed higher in the photic zone (Malone 1977; Cloern 1991, 1996; Howarth et al. in press). Conversely, a decrease in vertical stratification can increase light limitation and make an estuary less susceptible to eutrophication.

Generally, a decrease in freshwater runoff into any estuary will increase the water residence time and decrease the extent of vertical stratification, and increased freshwater runoff will decrease the

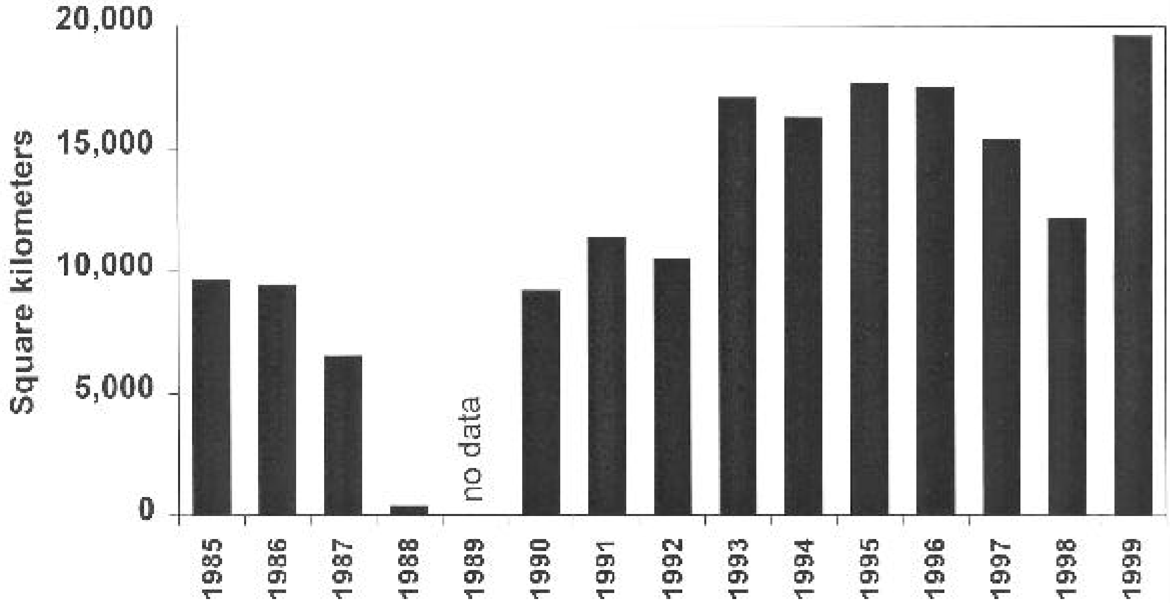

Figure 4.5. Areal extent of mid-summer hypoxia of bottom waters of the Northern Gulf of Mexico continental shelf between 1985 and 1999 (no data collected in 1989). The extent of hypoxia in a given year is greatly influenced by the volume of freshwater discharge and associated nutrient loadings from the Mississippi River Basin (CENR, 2000).

water residence time and increase vertical stratification (Moore et al. 1997). Whether these changes make an estuary more or less susceptible to eutrophication depends upon whether stratification or water residence time is more important in any given system. A change in the water residence time may not matter to eutrophication if the residence time is significantly longer than phytoplankton doubling times, as is true for Chesapeake Bay and Long Island Sound. However, in an estuary where residence time is on the order of days or less, such as the Hudson estuary, a change in freshwater inputs will have a major effect on the susceptibility to eutrophication. Also, while increased runoff leads to increased stratification in most partially mixed estuaries, this is not true for all estuaries. For example, the Hudson estuary becomes less stratified as freshwater runoff increases (Howarth et al. in press). Thus, in the Hudson, decreased runoff increases the susceptibility of the estuary to eutrophication both due to longer water residence times and to greater stratification.

Freshwater runoff will also affect the delivery of sediment and nutrients to an estuary (Moore et al. 1997). The increased sediment input that accompanies greater runoff can increase light limitation and lessen eutrophication. On the other hand, greater nutrient inputs from greater freshwater runoff will tend to increase eutrophication. For the Atlantic coast, the Hadley model predicts increased precipitation while the Canadian model predicts decreased precipitation (Felzer and Heard 1999). The Canadian model predicts decreased precipitation for the Gulf coast and both models suggest increased precipitation for the West coast and for Alaska. In determining how an estuary will respond to such changes, the seasonality of runoff must be considered in addition to annual mean changes. Inputs of sediment and nutrient are often driven largely by spring flood events, but summertime runoff is critical in its influence on physical circulation within the estuary. Given this variation in projected climate change, as well as the expected variation in response to water residence times, stratification, and inputs of sediment and nutrient among estuaries, the response of to climate change will likely need to be determined individually for each estuary.

Case Study: Hypoxia and Climate in the Gulf of Mexico

Every year, melting snow and rainfall wash nutrients such as nitrogen and phosphorus into North America's largest river, the Mississippi. Many of these nutrients eventually enter the Gulf of Mexico and contribute to a vast region of oxygen-starved ocean bottom stretching along the Louisiana and Texas coasts. The phenomenon is known as hypoxia, but has been dubbed the "dead zone" in the popular press, due to the absence of fish and shrimp in hypoxic waters (Malakoff 1999). The hypoxic zone in the Gulf is currently thought to be the third largest in the world, and the total areal extent of the low oxygen conditions, shown in Figure 4.5, has increased substantially since the floods of 1993. Although the impacts to the highly valuable Gulf fisheries have proved difficult to quantify, hypoxia has been shown to impact species abundance and diversity in the Gulf, and may threaten the future health of Gulf fisheries.

This area of low to no oxygen results from a combination of natural and human-influenced factors that stretch across nearly half of the conterminous United States, in a region that contains some of the world's most productive, and valuable, croplands. The vast majority of research suggests that this hypoxia is primarily caused by excess nutrients delivered to coastal waters from the Mississippi-Atchafalaya River System (CAST 1999; CENR 2000). Past experiences in other coastal systems throughout the world suggest that in the face of worsening hypoxic conditions, commercially and ecologically important species may decline precipitously (Caddy 1993; Diaz and Rosenberg 1995). While some efforts to address the problem of hypoxia are taking place, potential alterations in the hydrological cycle related to the global climate may pose additional barriers to the success of recovery efforts in the region.

The Mississippi River Basin (henceforth, the Basin) is the third largest drainage basin (in area) in the world, after the Amazon and the Congo, and drains about 41% of the conterminous United States. Over half of the total land area in the Basin is devoted to cropland, and another 21% is primarily rangeland. Agriculture in the Basin is an approximately $100 billion per year industry, and the region produces the majority of the corn, soybeans, wheat, cattle and hogs in the United States.

In the Basin, as well as elsewhere in the world, the use of industrial nitrogen fertilizers has increased dramatically in the last five decades. Since 1950, the annual input of nitrogen into the land area in the Basin has increased by 7-fold, and fixation of nitrogen by leguminous crops (such as soybeans) has increased by approximately 50%. Additional changes have also resulted in increasing nitrogen loads, including greater cultivation of nitrogen-fixing legume crops, the mobilization of nitrogen from biomass burning, land conversion, wetland drainage, and industrial and automobile sources. Subsequently, over the last four decades the amount of nitrogen delivered by the River has increased approximately 3-fold (Goolsby et al. 1999).

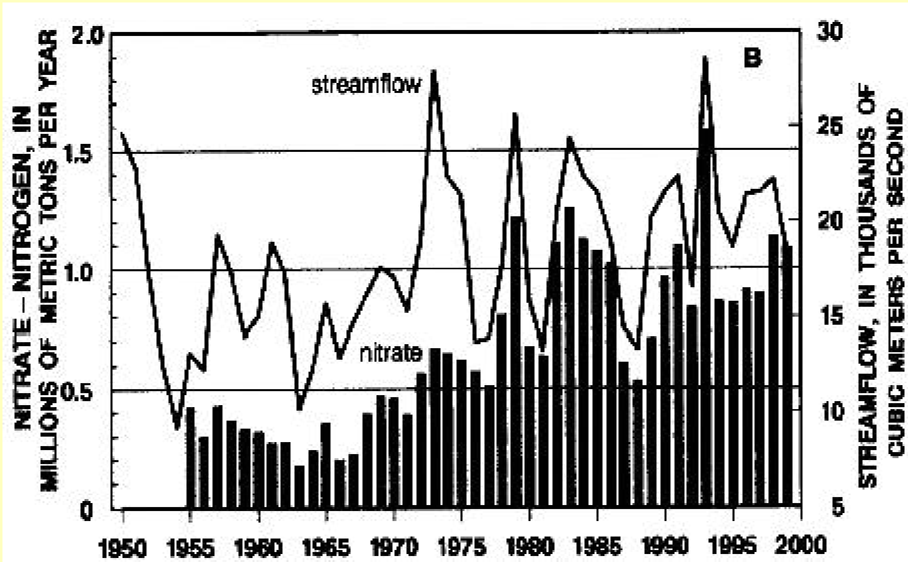

Figure 4.6. Annual flux of nitrate from the Mississippi River Basin to the Gulf of Mexico, 1955-1999, and mean annual streamflow, 1950-1999 (Goolsby 2000).

Since 1980, the mean annual flux of nitrogen to coastal waters has been approximately 1.6 million metric tons per year.

During this same time period however, there has been significant variability in precipitation and streamflow throughout the Basin, which has also shown to be strongly correlated with nitrate flux to the Gulf. Over the last 30 years precipitation nationwide has increased, averaging about 10% more than in the previous 70 years (Karl and Knight 1998), and in many regions within the Basin annual precipitation increased by as much as 20% over this same time period. U.S. Geological Survey data also suggest that streamflow has increased, flows were approximately 30% higher during the period from 1980 to 1996 than between 1955 and 1970 (Goolsby et al. 1999).

Perhaps more significant has been a perceived increase in inter-annual variability and the increase in extreme precipitation events. Over the last 100 years the climate of the United States has demonstrated large decadal scale fluctuations in climate extremes, with a particularly noticeable increase in climate extremes in the U.S. occurring since 1976. Researchers looking at climate data in the upper Midwest have documented an increase of 20% in the number of extreme 1-day rainfall events, in addition to a statistically significant increase in total annual rainfall (Karl and Knight 1998).

The effects of variability on the delivery of nitrogen to the Gulf may be magnified by land use practices. Research suggests that nitrate levels tend to build up in soils during dry years, largely as a result of reduced uptake of soil nutrients by crops (which corresponds with lower crop yields during dry years). As fertilizer application rates are rarely reduced during such periods, nitrate tends to build up in the soil, and during subsequent periods of heavy precipitation this nitrate tends to be flushed into streams at much larger rates than usual. Thus, wet years which follow dry years tend to produce the largest fluxes of nitrate from the Basin to the Gulf.

The period from 1976 to the present has also seen a perceived increase in the frequency and intensity of El Niño events (Trenberth and Hoar 1996). These events initiate major atmospheric circulation anomalies across North America, resulting in impacts to weather and precipitation patterns. Subsequently, the total discharge of the Mississippi River appears to have been more variable since 1980 than in previous decades, and this variability has been shown to be strongly correlated with nitrate flux, as shown in Figure 4.6. Two events, the drought of 1988 and the flood of 1993, help illustrate the linkage between climate, precipitation, and hypoxia in the Mississippi River system.

A common feature of both of these events is that they were extreme local manifestations of persistent anomalous conditions in the atmosphere throughout North America. In 1988, the strongest La Niña event in the past 20 years was underway in the tropical Pacific; this event disrupted atmospheric heating patterns in the tropics through a shift in the location and intensity of the intertropical convergence zone. This subsequently triggered circulation anomalies that are thought to be responsible for the drought (Trenbearth and Guillemot 1996). Survey data indicate that only an extremely small amount of hypoxic waters developed in the Gulf during 1988, concurrent with a 52-year low in the flow of the Mississippi River (Rabalais et al. 1999).

By contrast, the 1993 floods were associated with an anomalous weather pattern across the whole country, which occurred in part as a result of an unusually long "extended" El Niño event (Trenberth and Guillemot 1996; Bell and Janowiak 1995). During the spring and summer of 1993, extremely heavy precipitation fell throughout the Basin, following above average precipitation the previous summer, fall and winter. This resulted in record-high river levels and subsequent flooding throughout Iowa, Missouri and Illinois; followed by the failure of as many as 1000 levees in the Upper Mississippi and Missouri River basins. Damage estimates for that flood were in the range of $15 to 20 billion.

Both the increase in discharge and the increase in nutrient flux during the 1993 flood were very clearly related to the development of massive hypoxic water formation (Dowgiallo 1994). The total nitrogen flux in the river was the greatest ever recorded during this event, and the areal extent of the hypoxic zone in 1993 was twice as large as the 1985-1992 summer average (Rabalais et al. 1999). Since this period, the size of the hypoxic zone has not returned to the pre-1993 average, suggesting that the system may have crossed a threshold during this event.

Future Scenarios

Generally, most climate models agree that future warming is extremely likely to result in a "more vigorous" hydrological cycle, although projected increases in evaporation and evapo-transpiration may ameliorate some the projected changes in runoff and streamflow. Precipitation over the United States is projected to increase on average, with more interannual variability in many regions. However, the Canadian Centre model and the British Hadley Centre model, give significantly different predictions of potential changes in precipitation throughout the Mississippi Basin. In general, the Hadley model predicts much wetter conditions that the Canadian model, with slight increases in streamflow by 2030 and a substantial increase in all months by 2090. The Canadian model actually predicts a decrease in spring flows in the Southeast for both 2030 and 2090, although decreases are not expected throughout the entire Mississippi Basin (Wolock and McCabe 1999).

If average precipitation and runoff does increase, the most likely effect would be greater surface runoff and subsurface drainage of water containing nitrates which, if unaccompanied by measures to reduce nitrogen flux, could worsen the problem of hypoxia in the Gulf of Mexico. An increase in average precipitation would also suggest an increase in precipitation extremes; in other words wet years would be wetter than they have been in the past. Thus the most significant impacts to this region may be changes in the frequency and intensity of riverflow extremes, particularly flooding events.

Modeling by Justi et al. (1997) suggests that increase in bottom water hypoxia is another plausible and likely scenario in the Gulf Coast region. Increasing freshwater discharges to the Gulf would be expected to result in increased nutrient loads, lower surface salinities, higher surface water temperatures, and increased vertical stratification of coastal waters. All of these contribute to conditions suitable for the generation of high primary productivity and subsequent bottom water hypoxia. By calibrating a physical-biological box model of the coastal ecosystem, and using runoff simulations for a doubled CO_2 climate scenario, simulations suggested a 30 to 60% decline in the availability of oxygen in coastal bottom waters during the summertime when the current area of hypoxia is generally greatest (Justi et al. 1997). While their model did not generate scenarios of future changes in the extent of hypoxia, the results suggest that absent other effects, the hypoxic zone would likely increase substantially.

Fortunately, some of the options which have been proposed for addressing the problem of hypoxia in the Gulf might also be useful for mitigating carbon dioxide emissions which are contributing to global change. Research suggests that one of the most effective means to reducing nitrogen and other nutrient loads to the Gulf is to create and restore strategically placed wetlands and riparian zones in locations where they can intercept agricultural drainage and thus optimize nitrogen removal through plant uptake and denitrification. Mitsch et al. (1999) estimated that a program to create or restore 5 to 13 million acres of wetlands could result in a reduction of 20 to 50% of the nitrogen load to the Gulf of Mexico if such wetlands and riparian zones were strategically placed. Not only would the restoration of these wetlands contribute to the reduction of nitrogen loading and subsequent hypoxia to the Gulf of Mexico, but wetlands could act as an important sink for carbon dioxide. Additional local benefits would include improvements in stream and river water quality and drinking water protection, enhanced terrestrial wildlife in river corridors, and increased flood protection from the use of backwaters and diversions for nitrogen removal.

The principal future concern with climate and hypoxia in the Gulf of Mexico is that the future flux of nitrogen to the Gulf will respond quickly and dramatically to changes in precipitation patterns and timing. In the short term, it may also be that climate and precipitation trends will have a greater influence on the spatial and temporal extent of hypoxia than efforts to control both point and non-point source nutrient inputs. This is due in part to the significant time lag expected between the implementation of efforts to reduce nitrogen flux and any observed reduction in nitrogen flux in the system. However, in the long term the problem of excessive nutrient flux will have to be addressed, and mitigation of hypoxia will be dependent upon controlling and intercepting nitrogen inputs from the Basin to the river and ultimately to the Gulf. While the means to accomplish this goal may not be easy, they could be accompanied by numerous ancillary benefits to both the people and the ecological systems throughout both the Mississippi River Basin and the Gulf of Mexico.

4.4 CORAL REEF ECOSYSTEMS

Although coral reefs may seem exotic to many residents of the inland or northern U.S., these ecosystems play a major role in the environment and economies of two states, Florida and Hawaii, and are especially important for U.S. territories in both the Caribbean and the Pacific. Thus, the U.S. actually has responsibility and stewardship for as much as 6,800 square kilometers of coral reef habitat. Where these reef communities exist they often play major roles in both defining the environment and providing resources upon which humans depend, both consciously and implicitly (Wilkinson and Buddemeier 1994). Because many developing nation populations inhabit the same tropical and subtropical coastal zones that are home to most of the world's reefs, the demise or deterioration of reef communities would have profound social, political, and economic implications for the world, as well as serious economic and social consequences for the U.S.

The importance of coral reef ecosystems and their responses to environmental change goes beyond the immediate and obvious issues such as coastal protection, tourism, and fisheries. It is widely recognized that reef and related communities are one of the largest storehouses of marine biodiversity, with untapped resources of genetic and biochemical materials, and of scientific knowledge. Further, the living reef communities are not isolated dots on a map, but part of an interacting mosaic of oceanic and terrestrial habitats and communities, and many of the organisms and processes found on reefs are important in a much wider sphere of related environments. In many important ways, the condition and responses of coral reef communities can be seen as diagnostic of the condition of the world's low-latitude coastal oceans; a truly global signal as well as a resource. This section attempts to address the broader implications of climate change and variability on coral reef ecosystems on a global scale because they are also relevant to the waters of the U.S.

4.4.1 Coral Reef Communities and Organisms

In spite of being combined under a single ecosystem label, coral reefs are diverse entities; for example, Caribbean and Indo-Pacific reefs have essentially no species in common and there are systematic differences in their environments. Dealing with this diversity of subjects is further complicated by lack of terminological consistency among popular usage and the various scientific disciplines (Buddemeier and Smith 1999). Although some general functional and structural similarities can be identified across the spectrum of things that are loosely called "coral reefs", few if any of the organisms found in reef communities are found elsewhere, and there are no practical consensus on the minimum requirements for designation as a reef community. Scale and origin are also issues; a modern atoll may contain only very limited areas of "reef communities", yet the entire structure (including islands, lagoon sediments, etc.) owes its existence to the reef. Thus, different definitions produce major differences in the area, communities, or habitats designated as "coral reef" (Spalding and Grenfell 1997).

Reef communities are subject to interacting marine, terrestrial, and atmospheric influences that operate over a wide range of spatial and temporal scales. These influences range from well-characterized and predictable, through qualitatively understood but quantitatively uncertain, to probabilistic. Because of larval recruitment and other transport mechanisms (Sammarco 1994) the spatial scales of the populations that may contribute to the maintenance of a given reef community can be tens to hundreds of km on relatively short (decadal) time scales and thousands of km over longer periods (Karlson and Cornell 1999). Similarly, the intrinsic time scales of reef systems and organisms tend to be long by human standards, longer-lived organisms may survive for decades to centuries, and many reef communities turn over on decadal time scales (Done 1999). This accounts for much of the difficulty in distinguishing between the effects of environmental variability and the actual or possible effects of baseline trends.

Understanding of the present condition, and especially present problems of reefs has improved greatly in the recent past, but is generally lacking in long-term perspective. Projections of impacts that focus on propagation of quantitative uncertainties are useful in understanding the boundaries of our knowledge and some of our options, but they can obscure the fundamental logic that says that reef communities that are known to be deteriorating and that will certainly be subject to continuing and increasing levels of stress are unlikely to survive. Unfortunately, that characterization can be applied to many of the nation's reefs.

The complexity of community responses and interactions (and of human communication about these topics) highlights a theme inherent in this assessment process, the importance of viewing coastal systems and processes as an integrated whole rather than as a collection of independent components. In the long term, our ability to understand and manage reef environments is as dependent on issues related to estuaries, shorelines, and fisheries as it is to specialized knowledge of specific reef communities or processes.

4.4.2 Environmental Correlates, Stresses, Stress Sources and Delivery Pathways

The limiting values of environmental parameters that define suitable reef community habitat have been identified through a combination of experiment and empirical observation (Smith and Buddemeier 1992). The critical primary parameters include temperature, calcium carbonate

Table 4.1. Classification matrix for stress-inducing variables.

Scale (G = global, R= regional, L = local); Pathway: (P = primary route of stress delivery, S = secondary); Interactions with other variables; and relationship to climatic or direct human influences.

	Changing Variable	Scale	Atmos-spheric	Hydro-graphic	Hydro-logic	Interaction with variable #	Climate Factor	Human Influence
1	CO_2	G (R)	P	S			Indirect	Direct
2	Temperature	G R	P	S		4,8	Direct	
3	Sea-level	G R L		P		7,12	Direct	Indirect
4	Light (PAR)	R (G, L)	P	S	S		Indirect	Indirect
5	Ocean Currents	R G		P	(S)		Indirect	
6	Storms/waves	R L	P			7,3	Direct	
7	UV	R G	P	S		2	Indirect	Indirect
8	Fresh water	L R		S	P	9,12,6	Direct	Direct
9	Nutrients	L R (?G?)	(S)	S	P	11	Indirect	Direct
10	Toxics	L R (?G?)			P			Direct
11	Turbidity	L R		S	P	4,8,9,10,11		Indirect
12	Sedimentation	L		S	P	9,11,13	Indirect	Direct
13	Resource use-physical	L (R)			(assoc)		Direct	
14	Resource use-biological	L R			(assoc)		Direct	

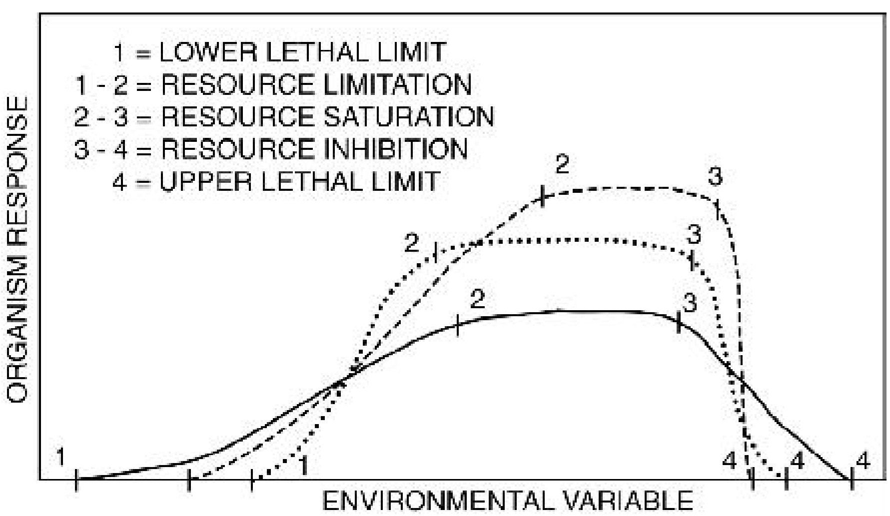

Figure 4.7. Organism responses to changing conditions or resources, plotted on arbitrarily normalized axes. Note that the upper and lower lethal limits and the maximum response in the “saturation” range are all controlled by different variables. (Buddemeier and Smith 1999).

saturation state (Gattuso et al. 1999; Kleypas et al. 1999a; Kleypas et al. 1999b), salinity, and light. The type and rate of sedimentation is also important, as are nutrient levels and the physical energy regime (waves, currents, storms). In addition to natural variations and change, some of these parameters are also modified by human activity, and there are unique anthropogenic stresses on reef systems. These include physical destruction, selective harvesting or overfishing and contamination with toxic materials (Wilkinson and Buddemeier 1994).

Table 4.1 is an updated summary of potential individual stressors and the pathways of stress delivery developed by Smith and Buddemeier (1992); the scale terminology follows Buddemeier and Hopley (1988). The atmospheric and hydrographic (oceanographic) pathways are valid for all reefs, but the hydrologic pathway is primarily relevant to reefs close to larger land masses. Since many anthropogenic effects are also related to proximity of human populations, there are relationships among the hydrologic pathway, direct anthropogenic stresses, and the local to regional scale.

These environmental conditions and stresses may interact in complex and synergistic fashions. A response to a single environmental variable may be depicted in the form often used for resource responses, as there are upper and lower lethal limits, ranges of limitation and inhibition, and a saturation interval (or optimal response range). Figure 4.7 illustrates a suite of idealized response curves to these stressors. With the horizontal axis as a normalized index of environmental suitability, multiple parameters may control organism (or community) responses, with each playing a dominant role under a different range of conditions.

An illustration of both stress interactions and the problem of predictions across different time scales is provided by the combination of acute and chronic stresses (Hughes and Connell 1999; Kinsey 1988). Coral reef communities are generally regarded as stress-adapted, and have been frequently cited as supporting the Intermediate Disturbance Hypothesis, with disturbance playing a key role in sustaining their overall high biodiversity (Connell 1997). This implies that reef communities destroyed or damaged by acute episodic events will generally recover if the environment remains generally favorable. On the other hand, reef organisms and communities may persist under suboptimal conditions for a protracted period in the absence of acute stresses. This is particularly the case if the chronic stress affects primarily competitive fitness, reproduction, or recruitment, as the reef community may appear healthy and flourishing even to professional scientists. However, once a chronically stressed reef is acutely damaged, recovery is very unlikely (Hughes 1994). This is an important issue, since any increase in human activities will tend to increase chronic stresses such as nutrient loading and overfishing, while climate-related acute stresses such as high-temperature episodes are also likely to increase as a result of global change.

Viewed in a geological context, corals and their communities appear to be survivors; their evolutionary history goes back over 200 million years to a time period that includes major environmental changes and extinction events (Veron 1995). Since their origins, reefs have waxed and waned in abundance and character, but have survived a very wide range of conditions and natural stresses. Why then is there such great concern at present? There are two answers, both relating to human society. One is that the present combination of stresses is without natural precedent. Completely unique chemical challenges by globally distributed synthetic molecules are combining with widespread physical disruption and a sustained rate of climate change greatly accelerated by human activity. Reef organisms appear to have good adaptive or acclimative mechanisms (Buddemeier et al. 1997; Gates and Edmunds 1999). However, they have not evolved with or been tested by the challenges of the sort now being presented; for example, it appears likely that the chemical and physical characteristics of the late 21st century may be more akin to

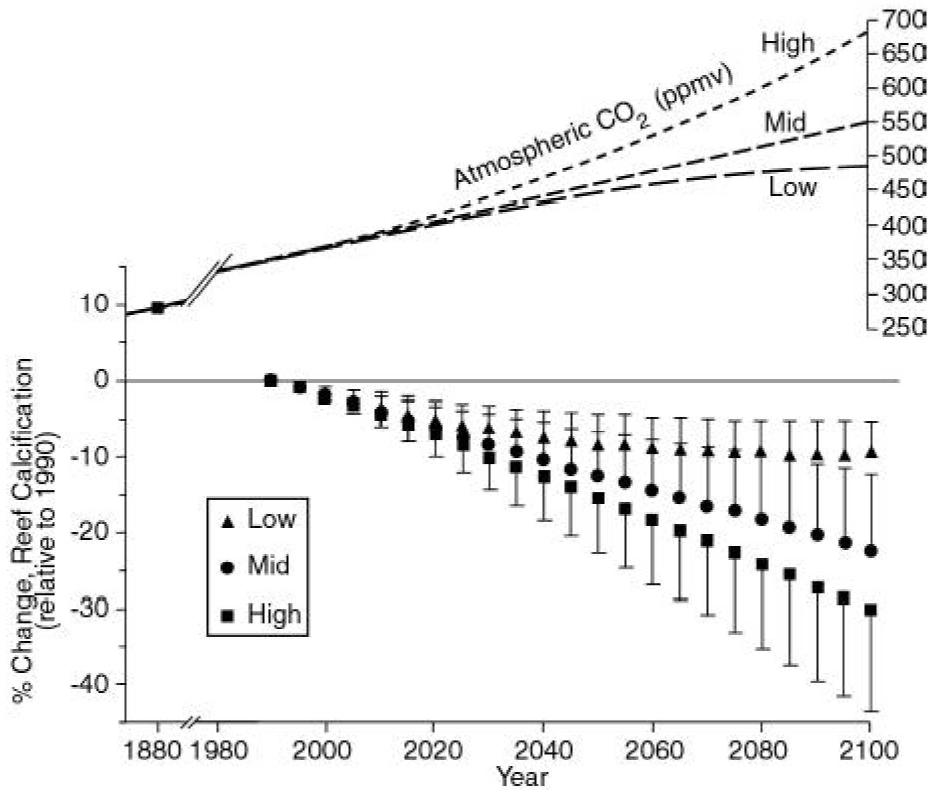

Figure 4.8. Effects of increasing CO_2 on coral calcification rates. Increasing levels of atmospheric CO_2. Houghton et al. (1996) are projected to decrease carbonate ion concentrations in seawater, likely resulting the calcification rates of many reef-building species (Gattuso et al. 1999).

the early Eocene than to any conditions experienced during the past 60 million years of Cenozoic reef development (Opdyke and Buddemeier submitted). The other reason is that from the standpoint of human benefit, long-term survival of the genetic basis for a resource is of little short-term practical benefit if the resource itself, be it a fishery, a living breakwater or a tourist attraction, is gone. The difference between global extinction and local extirpation is vast and important, but rather academic to communities who might have lost "their" reef.

Many anthropogenic stresses that might at first be assumed to be strictly local can have a strong regional effect, through two different mechanisms. Hydrologic and hydrographic processes can reflect distant environmental changes, as in the well-documented case of hypoxia near the mouth of the Mississippi River, a response to cumulative urban and agricultural activities over a continental watershed extending for thousands of miles. Also, the fact that populations of many reef species depend on recruitment of long-lived larvae from distant sources means that a seemingly local episode of reef destruction may eliminate the source population of an important species for a large area. The needs for effective management and regulation transcend jurisdictional boundaries in many cases.

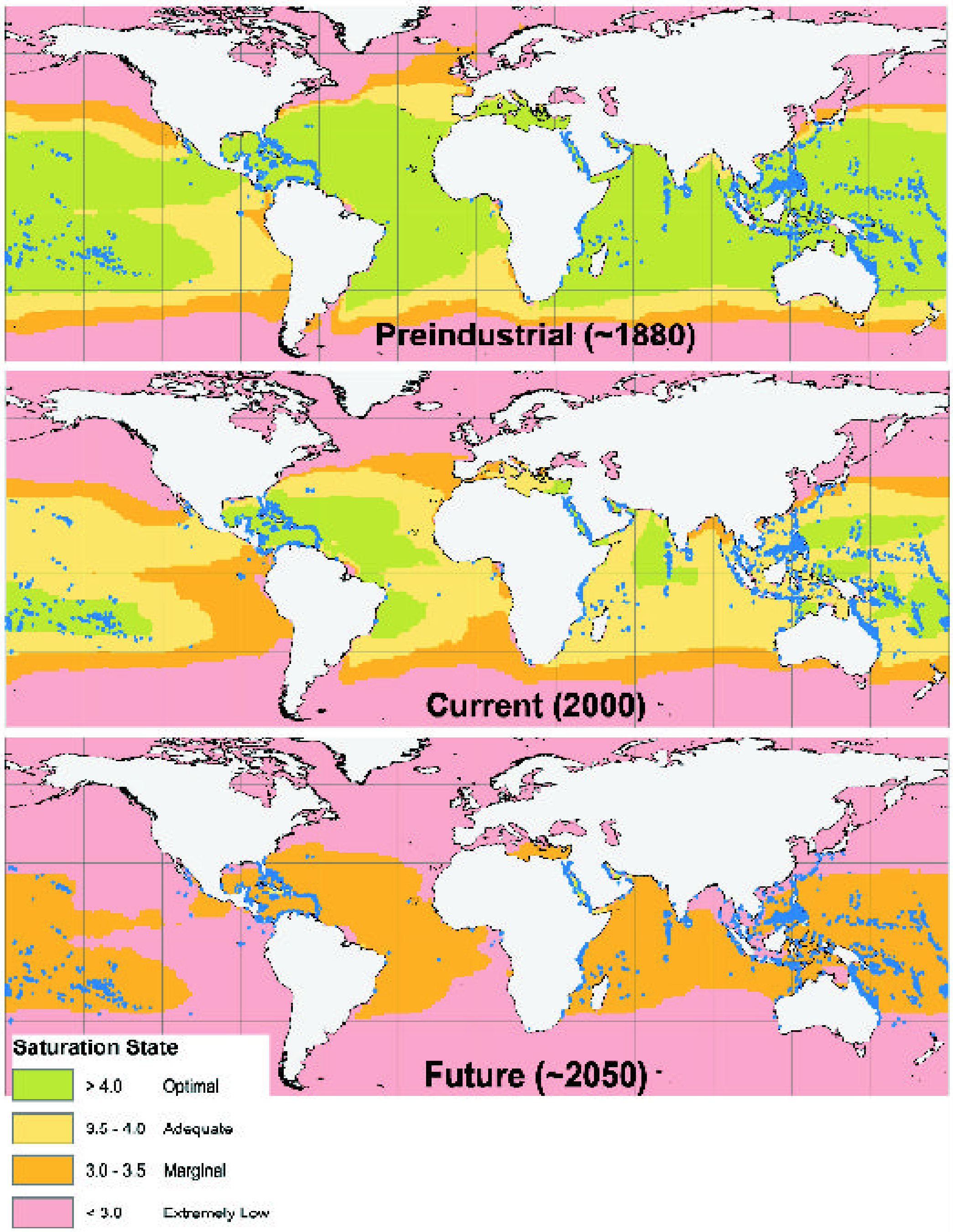

Figure 4.9. Maps of aragonite saturation state distribution based on the model results of Kleypas et al. (1999a). Locations of present reefs and reef communities are shown (www.cgiar.org/iclarm/resprg/reefbase/frameg/). Classification intervals for saturation effects on reef systems are derived from Kleypas et al. (1999b).

4.4.3 Impacts of Globally Consistent Changes

Variables in this category include CO_2 concentrations (atmospheric and surface ocean), temperature, and eustatic sea level. All are projected to increase monotonically on a global scale over the coming century. This does not mean that changes will be uniform; there will certainly be local and regional variations, especially in temperature and local relative sea-level patterns. However, their consistency justifies common discussion before proceeding to local and regional assessment issues.

Atmospheric CO_2

Although it had been posited earlier, only recently have experimental evidence and empirical observations been developed to demonstrate that the calcification rates of reef organisms are sensitive to the mineral saturation state of the ambient water, and that the saturation state is reduced as a result of equilibration with rising atmospheric concentrations of CO_2. The mechanism for this impact is that carbon dioxide acts as an acid when dissolved in seawater, causing seawater to be less alkaline. A drop in alkalinity subsequently decreases the saturation state, or the amount of calcium carbonate (aragonite) which can be dissolved in seawater (and is subsequently available to marine organisms). This, in turn, decreases the calcification rates of reef-building corals and coraline algae. Although the database is still scanty, both organism and mesocosm experiments suggest that reef calcification rates may decline by 17 to 35% by the year 2100, as shown in Figure 4.8. Additionally, this research suggests that roughly a third of that decrease may already have occurred (Gattuso et al. 1999; Kleypas et al. 1999a).

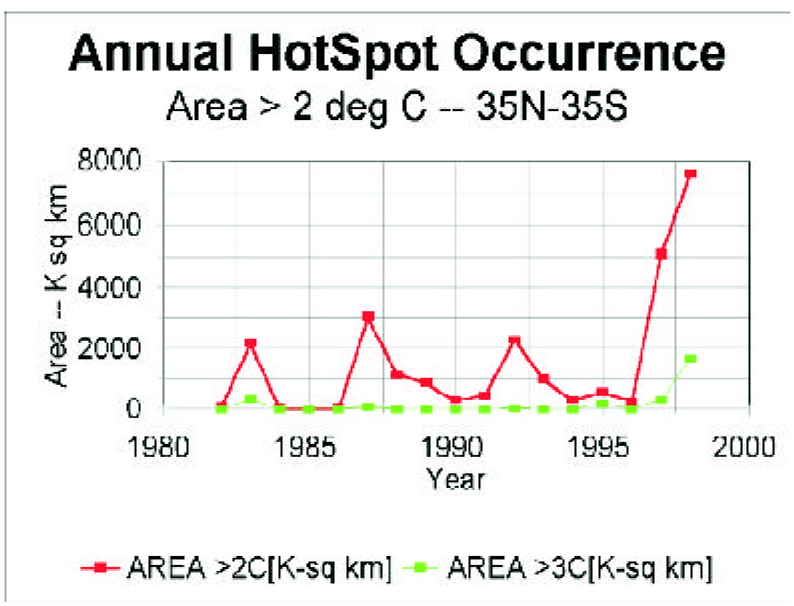

Figure 4.10. Annual areal extent of unusually warm (>2°C over usual high temperatures) sea surface temperatures in tropical seas. Widespread and severe coral bleaching has been associated with periods of unusually warm temperatures, often associated with El Niño conditions (Strong et al. 2000).

These effects are shown Figure 4.9, which presents maps of preindustrial, present and projected future surface ocean aragonite saturation states, derived from the model results of Kleypas et al. (1999a,b). These maps depict the location of present-day reefs and reef communities, which are used to assess desirable levels of saturation state for coral reef maintenance.

If expressed as reduced skeletal density, a lowered calcification rate will increase vulnerability to physical damage, bioerosion, and some forms of predation. If it results in reduced extension (growth) rates, the reduction will impair the abilities of calcifying organisms to compete for space, both in terms of substrate dominance and with respect to harvesting particulate food and incident light. This is a major impact on the overall fitness of communities and organisms subject to other stresses. Additionally, the effects of increasing atmospheric carbon dioxide on the concentration of carbonate ions is greatest at the margins of coral distributions, due to the fact that carbon dioxide is more soluble in cooler waters. Thus, these effects will be most severe at higher latitudes, such that coral reefs at the margins of their distribution probably will not expand their ranges as might otherwise be predicted by some ocean warming scenarios.

Temperature

Seasurface temperatures might be expected to rise by some 1 to 3°C over the coming century, with a non-uniform distribution of increases (see Section 3.1; also Pittock 1999). The rate of increase is likely to be of the same magnitude as, but probably somewhat greater than, the warming trend of the past several decades. Events in recent decades have already culminated in widespread reef stress caused by coral bleaching, the disruption of the coral-algal symbiosis, associated with recent high-temperature episodes.

The increase in mean temperature may be considered a net neutral change, disadvantageous to reefs on the high side of the temperature optima, but potentially advantageous to those on the low temperature margins; which include many of the U.S. reefs. However, this effect is overwhelmed by the negative impacts of increasing frequency and magnitude of high temperature events, which have resulted in the widespread and damaging bleaching episodes of the past two decades. How great will this effect be? The answer depends on the scenario adopted. If the high-frequency SST variation of the past 20 years continues and is superimposed on a general warming trend the acceleration of bleaching occurrence would result an expanding degradation and near-complete destruction in many areas. Figure 4.10 demonstrates the apparent increasing trend of equatorial ocean hotspots, which have been associated with coral bleaching and die-offs, over the last 20 years. Treating the extreme variations as a random phenomenon suggests a possibility of greater intervals between extreme events, and there may be some theoretical basis for that expectation (Kerr 1999). However, in no case does this translate to a return to previous conditions. The question is whether the next damaging temperature episode will occur in a few years, or in a few decades.

Table 4.2. Anthropogenic stresses on coral reef systems and scale of their effects (R, regional; L, local).

Category	*Activity*	*Primary Agents*	*Source scale*	*Effect scale*
1 Land Use	a. Agriculture	Nutrients, biocides, sediment, hydrologic alteration	R, L	R, L
	b. Land clearance	Sediment, hydrologic alteration, nutrients	R, L	L, R
	c. Urbanization	Hydrologic alteration, nutrients, toxics, sediments, category 2 activities		
2 Coastal Modification	a. Construction	Sediment, hydrologic/hydrographic alteration	L	L, R
	b. Dredging	Sediment, hydrographic alteration, destruction	L	L, R
	c. Landfill	Sediment, hydrographic alteration, destruction	L	L, R
	d. Quarrying	Destruction, sediment, hydrographic alteration	L	L
3 Harvest	a. Fisheries	Trophic ecosystem disruptions	L, R	R, L
	b. Collection	Trophic ecosystem disruptions, destruction, extirpation	L, R	L, R
	c. Incidental damage	Destruction, extirpation	L, R	L, R
4 Tourism	Multiple	Potentially 1bc, 2abc, 3abc	L, R	R, L

Sea-level Change

As discussed in Section 3.5, eustatic sea level is expected to rise by more or less 1.6m over this century. This rate, like temperature, is similar to but somewhat greater than that observed in the recent past. However, the direct effects, assessed at a global scale, are likely to be somewhat positive for near-sea-level reefs, many of which have developed large areas that are sea level limited due to the protracted Holocene still-stand. Sea-level rise may open up reef flats and other areas for colonization, in locales where there is a ready source of suitable substrate for coral colonization. Increasing sea level will be a disadvantage for extremely marginal deeper reefs; those near the bottom of the depth range of viability which typically calcify or accumulate very slowly.

Sea-level rise may have indirect negative effects locally if increasing coastal erosion mobilizes sediments that are subsequently deposited on nearshore reef areas or coral communities. Issues relating to erosion and sedimentation interact strongly with land use and management practices, and predictions must be based on detailed local assessments that include projected human activities.

4.4.4 Impacts of Local and Regional Changes

Many of the known or anticipated environmental changes due to climate change are local or regional manifestations that cannot be described in global terms. Among these are ocean circulation patterns, storm frequency and intensity and precipitation patterns. To the extent that regional model predictions are available, these can be addressed for specific areas; however, some useful generalizations are possible.

Ocean circulation will be primarily relevant to the longer-range transport of propagules and pathogens. Significant changes are likely to be detrimental to existing reefs that depend on upstream sources for recruitment, but there is possible advantage if predators or pathogens are an important component of the recruits. Storm frequency and intensity is projected to increase by some (Pittock 1999), or to shift their geographic pattern; although this is by no means certain. An increase in storm incidence or intensity would be of little significance in an ideal natural setting, but when imposed on reefs already damaged and under multiple chronic stresses, it represents a serious additional threat. Finally, precipitation and runoff are expected to increase in many (but not all) areas; where this does occur it will likely result in decreased salinity and increased sediment, both of which will result in additional stress to reefs that are close to larger land masses.

Other locally and regionally important variables may have natural climatic components or modifiers, but are primarily dominated by human activities. Freshwater effects and nutrient and sediment loading are all heavily dependent on land use and watershed modification; all have been increasing in general as have fishing pressure, recreational activities, ship groundings, anchor damage and other direct impacts on reef communities. In view of predictions of continued population growth and economic development, most of these can be expected to continue to increase. Of these variables, sediment and freshwater stresses will be most important relatively close to the coastlines of substantial land masses (large islands or continents), where there is reason for suspicion that nutrient loading may affect the larger coastal zone and marginal seas (Jickells 1998; Moffat 1998). Anthropogenic stresses tend to correlate with human population (density, proximity and economic status), and are thus likely to increase in the absence of specific and effective protective measures.

Table 4.2 summarizes the major categories of human activities that are recognized as having deleterious effects on reef ecosystems and habitats on a wide-spread basis. Not all of the activities are strictly coastal; however, in many areas there is accelerating pressure from coastal zone activities because of the disproportionately high population densities and rates of development and population increase in the coastal zone. These interact with and reinforce the negative effects of climate variability and climate change and global environmental alteration, some of which represent the cumulative effects of human activities at the global scale.

The sequence of classification proceeds from activities in which reefs are commonly not considered at all (land use), through those in which reef systems are incidental considerations (coastal modification) or are substrates or sources for the resource of interest. The final category, tourism, is used here to subsume essentially all recreational and aesthetic values for which identity as a coral reef system is central. Tourism exemplifies the dilemma of balancing economic yield against the poorly quantified, but very real, synergistic effects of multiple stresses. Increases in land-based development and population, as well as increases in extractive activities and the wear and tear associated with high levels of visitation, can cumulatively destroy the critical resource even though the levels of any individual stress, considered alone, can be argued to be within tolerable limits. This is an issue any time multiple stresses coincide.

4.4.5 Symptoms and Conditions

The proliferation of concerns and observations about coral reef conditions has led to an explosion of information that has outpaced traditional publication practices. A number of recent, electronically disseminated reports address reef conditions and factors affecting them (including: Miller and Crosby 1998; U.S. Department of State 1999; Jameson et al. 1995; Hoegh-Guldberg 1999; Wilkinson 1998). The interpretive tenor of these reports ranges from relatively optimistic to direly pessimistic, but they approach consensus in recognizing that many (some say most) reefs are showing signs of human impacts, a significant number of reefs are already destroyed or seriously

Table 4.3. Classes of U.S. coral reefs by region (Veron, 1995).

L = Land (reefs sufficiently close to a continent or large island coast so that terrigenous effects are likely to be significant); O = Oceanic (outer shelf, atolls, or small island reefs, oceanic reefs or banks).

Eastern Pacific Subtropical:	(L) Hawaiian islands; (O) Hawaiian chain, Midway, Wake atolls
Eastern Pacific Tropical:	(O) Johnston Atoll, Palmyra Atoll, Jarvis Island, Kingman Reef
Central Pacific Tropical:	(L) American Samoa (high islands), Howland and Baker Is., Guam, N. Marianas (some); (O) Swains Reef, Rose Island, N. Marianas (some)
Western Atlantic Subtropical:	(L) Florida (incl. Keys), (O) Dry Tortugas, Flower Garden banks
Western Atlantic Tropical:	(L) Puerto Rico, U.S. Virgin Islands.

degraded, and that the potential for continued or increased stress is high. Because of a natural focus on readily observable signs of stress, two themes (or symptoms) are called out for particular attention.

The term “bleaching” is commonly applied to the loss of some or all of a coral colony’s algal symbionts. Although it occurs to some degree in healthy corals in natural settings, it is also a general stress response that can result in mortality (Brown 1997). Reports of extensive and damaging bleaching events have been increasing since the early 1980s. Many of the most wide-spread and severe episodes of bleaching have been associated with periods of unusually warm temperatures associated with clear, calm weather, resulting in combined temperature-irradiation stress. These are often but not always associated with El Niño conditions; the most widespread and devastating occurrence was in 1998, when areas of the Indo-Pacific that had not previously experienced major bleaching suffered severe damage (Berkelmans and Oliver 1999; Wilkinson et al. 1999; Strong et al. 2000). While the relationship between El Niño conditions to general global warming is still under discussion (Kerr 1999), the existence of a global warming trend is well-demonstrated, and can be expected to result in increased frequencies and magnitudes of high-temperature events.

Another of the more disturbing and poorly understood features of the recent decline in reefs and corals has been the increased frequency, virulence, and variety of lethal epizootics among reef corals (Harvell et al. 1999). Population explosions of predatory macro-organisms (such as the Crown of Thorns starfish) have been an issue in the Indo-Pacific for several decades, but within the past decade there has been a sharp rise in reports of diseases caused by bacterial, fungal, and/ or viral agents, especially in the Caribbean and Florida (Harvell et al. 1999; Done 1999). The large-scale coral loss and community shifts associated with these diseases seem to be unprecedented in Holocene and Late Pleistocene time (Aronson et al. 1998; Greenstein et al. 1998). The introduction of new pathogens into the marine environment, the alteration of environmental conditions to favor the propagation of existing disease-producing agents, and the general debilitation of coral "health" that makes them more vulnerable to infection all appear to play a role in this phenomenon. Although the relative importance of these factors is not yet known, the extent and novelty of the epizootic phenomenon clearly implicates significant environmental change at the regional or global scale, and offers little basis to expect that conditions will improve.

4.4.6 U.S. Reefs: Characteristics, Vulnerability and Future Prospects

Table 4.3 summarizes the biogeographic regions and relationships to land masses of U.S. reef locations. Pacific subtropical regions are commonly marginal with respect to temperature, seasonality, and saturation state, and tend to have lower biodiversity. Biodiversity and proximity to other reef systems are lower in the eastern than in the central and western Pacific. U.S. Pacific reefs vary in their relationship to storm zones, equatorial upwelling, and El Niño effects, and include no shelf reefs. In the western Atlantic, all U.S. reefs are within the hurricane zone, and all subtropical reefs are continental shelf reefs. Overall, one of the most important distinctions is the question of "land" vs. "ocean" status, as proximity to major land masses generally corresponds to greater human exploitation or environmental impacts. This in turn indicates greater vulnerability to the suite of environmental stresses related to the hydrologic pathway.

Additionally, U.S. reefs are described, and their conditions assessed, by Miller and Crosby (1998), Reefcheck (http://www.ust.hk/~webrc/ReefCheck/reef.html) and the Global Coral Reef Monitoring Network (http://coral.aoml.noaa.gov/gcrmn/gcrmn.html). One of the most telling conclusions to be drawn from the assessments of Miller and Crosby is that almost all of the reefs identified as being in reasonably good condition are remote and isolated from human populations. The degraded reefs have typically suffered from some combination of natural and anthropogenic stresses, but the variable that sets them apart as a class is the intensity of human use and environmental alteration. This reinforces the notion that corals and reef communities have considerable adaptive and acclimative ability to deal with the effects of natural change and variability, but that the novel combination of those stresses with qualitatively different anthropogenic stresses has pushed many reef ecosystems or regions across a critical threshold. These observations further highlight the dilemma that it is precisely those reefs that are most used and most economically valued that are at the greatest risk and most difficult to save.

4.4.7 Projected Future Changes

The calculus of coral reef system stress in the 21st century is straightforward. Human populations, especially coastal populations, will continue to rise; pressures for economic development will not abate; and atmospheric concentrations of CO_2 (and presumably other greenhouse gases as well) will continue to increase. This means that anthropogenic alterations of the hydrologic and nutrient fluxes will continue, that the earth's radiant energy balance will continue to change, that the surface ocean will become less supersaturated with respect to carbonate minerals, and that, in all probability, the global climate will warm and the hydrologic cycle accelerate. The U.S. is not exempt from these generalizations; global CO_2 projections (and their effects on calcification) will be felt everywhere. Population projections presented in section 2.1 indicate that coastal counties in Hawaii and south Florida will experience population increases of 20 to 50% over the next 25 years.

These changes all imply additional stresses on coral reef systems, either global or episodically local. Many of these stresses will interact synergistically. On average, the environment is becoming less hospitable to reefs, with the effect most pronounced in reefs in close proximity to human populations. There will be a great deal of variation around the overall trend, but averaged over space and time, it seems clear that the observed trend of reef degradation will continue, and probably accelerate. This is exemplified by the projected changes in aragonite saturation state (Figure 4.9), which suggest that conditions for calcifying reef organisms will become systematically more suboptimal of the coming decades — an effect almost certain to reduce there resilience in the face of other increasing stresses.

This does not mean that all reefs are doomed, but the implication is strong that many of the reefs about which people care (from the standpoint of use for various purposes) are poor candidates for survival. The prospect are sufficiently bleak that they raise the question of whether some reefs should be "written off" and environmental protection and restoration programs focused elsewhere. This approach may appear rational if coral reef ecosystems are somehow separable from the larger suite of interacting coastal environments, but they are not. Where reef communities are important ecosystems they provide characteristics and interactions that are linked to other communities and features of the environment. Some of their key functions cannot be provided by any other ecosystem, and their health is not an isolated problem but a symptom of the condition of the coastal (or oceanic) environment.

Synergy of stresses and the response time scales involved make integrated management essential but difficult. The range of reef types and locations, continuum between reef and non-reef habitats, and competitive succession as a mechanism of community failure all point to the need for broadly based, integrative management, conservation, and research. Given trends already in motion, some of the more marginal reef systems will almost certainly continue to deteriorate, making allocation of resources an important policy issue.

Case Study: Kaneohe Bay, Oahu, Hawaii

The coral reef system of Kaneohe Bay represents one of the best-documented examples of reef response to, and recovery from, anthropogenic stress (Miller and Crosby 1998; Smith et al. 1981). The Bay is a relatively enclosed feature on the seaward side of a collapsed volcanic caldera, a feature that serves to funnel freshwater discharge toward the bay, which results in coral kills when high rainfall and low tide coincide. Urbanization of the watershed over the last half-century further modified the hydrology and increased point- and non-point-source pollution loads, resulting in massive algal blooms and coral loss in the early 1970s. In 1978-79 the local sewage discharge was redirected from the Bay to a deep-water outfall, and the coral communities recovered rapidly over the subsequent decade. Throughout the 1990's there has been an ongoing debate about whether the reef communities have recovered, stabilized, or are being subject to renewed or increasing levels of stress.

Hawaiian reefs are generally regarded as marginal, having relatively low biodiversity and carbonate accumulation rates. However, they are by no means at the extremes of reef occurrence in the Northeast Pacific; the Hawaiian chain extends to Midway and Kure Islands, which support coral communities at considerably higher latitudes. The analysis by Kleypas et al. (1999a) would suggest that corals in Hawaii may already be experiencing reduced calcification rates as a result of increasing atmospheric carbon dioxide and subsequent decreasing oceanic saturation states for calcium carbonate (see section 4.4.3). This also implies that stress from this source is essentially certain in the future.

Bleaching has occurred in Hawaii, although not at catastrophic levels, and it is reasonable to assume that this source of coral stress will continue, if not intensify, as climate warms. It appears unlikely that wave and storm-surge damage will see a major increase, but the expected intensification of the hydrologic cycle may lead to more and larger rainfall events; a known stressor of Kaneohe Bay reefs in the past. Population, urbanization, and marine resource use are expected to continue as well, which will probably exacerbate hydrologic problems and increase non-point-source pollution loads. The geomorphic and geographic setting is such that it would be extremely difficult to ameliorate the terrigenous and anthropogenic forces acting on the Kaneohe Bay ecosystem.

The coral reefs and communities of Kaneohe Bay may thus be expected to experience an increased frequency and intensity of acute stress episodes (salinity and temperature excursions) operating against a backdrop of increased chronic stress (reduced calcification potential, resource use and pollution loading), with "natural" global factors and local anthropogenic forces combining in both categories. As pointed out by Hughes and Connell (1999), the detailed trajectory of the system will depend on the exact sequence and history of events and conditions. However, unless the projections are very wrong or there is something surprisingly resilient about these reef communities, the general expectation is clearly that Kaneohe Bay coral reef communities will undergo significant decline in the coming decades.

4.5 OCEAN MARGINS AND FISHERY RESOURCES

Changes in climate will have important effects in ocean margin ecosystems through expected changes in the distribution and abundance of marine organisms and in fundamental changes in the production characteristics of these systems. Alterations in temperature, precipitation, wind fields, and sea level can all be expected to affect oceanographic conditions in the ocean margins with direct ramifications for marine life in these areas. Physiological effects of temperature and salinity changes can also be expected with important consequences for growth and mortality of marine species.

Projected changes in the marine environment also have important implications for fisheries resources. Marine commercial and recreational fisheries support a multibillion dollar industry in the United States (see section 2.2). In particular, the development of the Alaska pollock fishery has resulted in substantial increases in total landings over the last decade. In addition to this economic value, marine fisheries hold a significant social and cultural significance in many coastal communities. The possible effects range from shifts in distribution that may result in changes in availability of key resource species to changes in vital rates, including survival, growth, and maturity with direct implications for overall levels of abundance and, ultimately, fishery yields.

Impacts to marine ecosystems and fisheries associated with El Niño events illustrate the extent to which climate and fisheries can interact. For example, the high sea surface temperatures and anomalous conditions associated with the 1997-98 El Niño had a tremendous impact on marine resources off of California and the Pacific Northwest. Landings of market squid, California's largest fishery by volume and second largest in value, fell from over 110,000 metric tons in the 1996-97 season to less than 1000 metric tons during the 1997-98 El Niño season. Among the many other events associated with this El Niño were high sea lion pup mortalities in California, poor reproductive success in seabirds off of Oregon and Washington and catches of warm-water marlin off of the Washington coast. Even farther north were rare coccolithophore blooms, massive seabird die-offs along the Aleutian Islands and poor salmon returns in Alaska's Bristol Bay sockeye salmon fishery (Macklin 1999).

4.5.1 Effects of Temperature Changes

Changes in temperature can have important impacts on marine organisms including altered distribution patterns, changes in physiological state of individuals, alterations in food web structure, and the incidence of disease. Selected examples of each are given below.

Distribution

Poleward shifts in distribution of marine populations can be expected with increasing water temperatures (Frank et al. 1990; Murowski 1993). Such changes in species composition in intertidal communities at long-studies locations along the California coast have already been documented

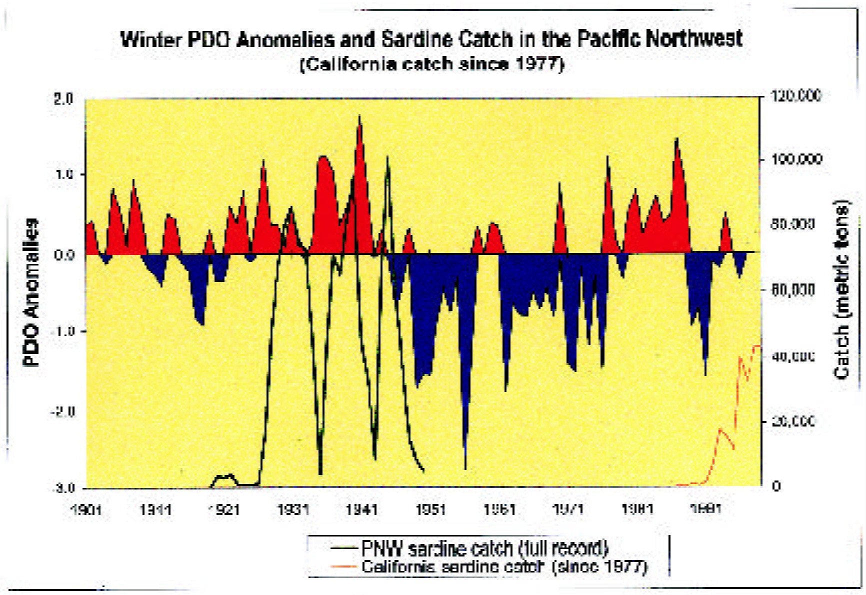

Figure 4.11. The Pacific Decadal Oscillation (PDO) index (five-year moving average) and landings of California sardine in British Columbia, Oregon and Washington (PNW) between 1900 and 1960 and California from 1977.

(Sagarin et al. 1999). Species temperature preferences and overall habitat requirements (for example substrate type, prey and predator abundances, etc.) will determine the extent of potential distributional shifts. Frank et al. (1990) indicate that certain fish species at the southern extent of their range off the east coast of North America can be expected to shift their distribution to the north with important overall consequences for ecosystem structure in this region. Cod, American plaice, haddock, Atlantic halibut, redfish and yellowtail flounder would all be expected to experience some poleward displacement from their southerly limits in the Gulf of Maine and off New England under increasing water temperatures.

An expansion of species commonly occurring in the Mid-Atlantic region, such as butterfish and menhaden into the Gulf of Maine, can also be expected. Colton (1972) notes that for some species, the habitat requirements related to spawning and nursery areas can constrain the response to changes in the thermal environment thus limiting the possibility of adjustment. Loss of populations or subpopulations with shifts in temperature under these constraints is therefore possible.

Hobrook et al. (1997) documented changes in the assemblage structure of temperate reef fishes coincident with a shift in temperature regimes off California in 1976-77. Here, an increase in temperature was associated with a shift in dominance by southern species, a decrease in species richness, and an overall decrease in abundance. Looking towards future changes, Welch et al. (1998) concluded that projected changes in water temperatures in the North Pacific may result in a virtual elimination of suitable thermal habitat for sockeye salmon (see Pacific Salmon case study). Important impacts on changes in the thermal habitat on steelhead trout have also been documented (Welch et al. 1998b). Kruse (1998) noted that marked increases in water temperatures during 1997-98 apparently affected runs of salmon in western Alaska, resulting in sharp declines in numbers of fish returning to home streams and river systems.

Changes in sardine and anchovy populations also appear to be linked to changes in temperature on a global basis (Lluch-Belda et al. 1992). The California sardine fishery developed in the early decades of this century and landings rapidly increased during the 1930's. By the early 1950's however, the fishery had collapsed under increasingly intense fishing pressure and broad scale changes in environmental conditions (Radovich 1982). The decline in the fishery coincided with significant changes in environmental conditions, and a sharp decrease in the recently described Pacific Decadal Oscillation (PDO) index (Figure 4.11). Following a subsequent shift to a positive phase in the PDO after 1976, and significant warming of average sea surface temperatures in the California Current the California sardine population began to show some signs of recovery. Due to a small initial population, the total biomass remained relatively low until about 1990; however over the last decade the sardine population has undergone a tremendous resurgence. Current estimates of biomass range well over 1 million metric tons (Barnes et al. 1997), and sardines are again migrating northwards as far as Vancouver Island in the warm summer months (Hargreaves et al. 1994). Similarly, the commercial fishery has begun to revive; quotas have been as high as 100,000 metric tons in recent years and sardines have again been the target of a growing fishery in Monterey Bay.

In addition to latitudinal shifts in distribution, shifts in the relative distribution with respect to depth and distance from shore may occur. Collectively these changes in distribution with respect to latitude or depth will affect the availability of fish and invertebrate species to regional fisheries, in some instances changing the community structure and the character of these fisheries. Adaptation to these changes will include alteration in the species mix harvested in different areas and possible changes in fishing areas. Changes in management strategies and in allowable exploitation levels will be required under persistent shifts in environmental conditions and the productivity of exploited resources.

Food Web Dynamics

Temperature changes that affect the relative timing of the production cycles of predators and their food sources may also affect their growth and survival rates if a mismatch occurs between the timing of the seasonal primary production cycle and the spawning cycle of fish and invertebrates. The primary production cycle is principally controlled by day length and nutrient availability; however, the spawning periods of fish and other species may be controlled by temperature levels. Temperature changes may also result in regional changes in the species composition of phytoplankton and zooplankton species, affecting the availability and suitability of prey for higher trophic level species, including those of commercial importance. Murawski (1993) reported that substantial shifts in the distribution of small pelagic fishes such as herring and mackerel off the East Coast of the United States can be expected based on observed temperature-dependent distribution patterns. These species provide an important forage base for many piscivorous (fish eating) fishes, marine mammals and sea birds; strongly suggesting that temperature changes may have secondary effects on trophic interactions and the relative distribution of prey and predators.

Physiological Considerations

Temperature is a dominant controlling factor in the physiology of most ectothermic (cold blooded) marine organisms. Growth rates of fishes and invertebrates are strongly linked to ambient temperature. Growth rates during the early life stages often play an important role in vulnerability to predation with faster growth rates resulting in more rapid passage through smaller sizes classes at greatest risk of predation. For example, Marshall and Frank (1999) documented a positive relationship between growth of haddock and recruitment success. Brander (1995) found a similar effect for cod, where growth rate was found to be positively related to temperature. The growth at later stages can affect the overall reproductive output because fecundity is often a direct function of size.

For most species, we assume that an optimum temperature range exists (Jobling 1996), affecting growth and metabolism. Increases in temperature toward the optimum for these species can be expected to result in enhanced growth, survival, and reproductive output. However, further temperature increases beyond the optimum range will result in adverse impacts on vital rates. For example, Cox and Hinch (1997) showed that high, sub-optimal temperatures are related to reduced growth rates in Fraser River sockeye salmon, presumably due to increased metabolic demand or changes in food availability. Size at maturity was found to be lower in warm water periods.

The potential effects of changes in temperature may be particularly severe for sessile species that exhibit little mobility at one or more stages of the life cycle. Many commercially important invertebrate species (particularly shellfish) could be so affected. Dramatic effects on corals as a result of the loss of symbiotic algae at high temperatures (coral bleaching) are documented in section 4.4 and would presumably lead to changes in productivity of fish species in such regions.

Disease and Harmful Algal Blooms

A weakening in the immune system of individuals stressed by higher than optimal temperatures has been linked to epidemics in marine populations. Outbreaks of diseases of marine organisms concurrent with changes in temperature levels have been documented in a number of instances (HEED 1998). For example, diseases affecting sea urchins have been documented under unusually warm water temperatures in both tropical and temperate waters. Changes in the abundance of sea urchins have subsequently been associated with impacts to marine ecosystems, as the grazing pressure by urchins on benthic algae was altered with cascading effects throughout the system.

The northward extension of the shellfish diseases, such as the oyster pathogens *Minchinia nelsoni* and *Perkinsus marinus*, has been linked to increases in temperature levels. It has also postulated that epidemics in seabird populations and disease-related marine mammal strandings were also related to ENSO events and associated warm water temperatures (Harvell et al. 1999).

Harmful algal blooms have been associated with ENSO events and increased water temperatures (Hallegraeff 1993). The prevalence and intensity or red and brown tides appears to have increased over the last several decades (Anderson 1995). Increased water temperature and decreased vertical mixing of the water column can contribute to the growth of toxic algae and changes in the level of toxicity of algal species can occur with changes in nutrients.

4.5.2 Sea Ice and Arctic Ecosystems

Increases in temperature will result in melting of sea ice in polar and subpolar regions with direct effects on the input of freshwater into these systems, and on the convective processes which are critically important to primary production in Arctic systems. It is increasingly recognized that the underside of sea ice is an important substrate for ice algae, which supports an active biological community (Wheeler et al. 1996). Perhaps more importantly, ice edges have been demonstrated to be highly productive regions where interactions between physical and biological processes encourage substantial phytoplankton blooms and subsequently support zooplankton and arctic cod production (Niebauer 1991). The migrations of belugas, narwhals and harp seals to ice edge regions have all been linked to bursts in the productivity and subsequent abundance of Arctic cod in these areas during summer plankton blooms.

Although it is unclear exactly how a reduction in sea ice will affect the productivity of important prey species such as arctic cod, it has been speculated that a sufficient reduction in ice edge extent would have deleterious consequences for marine mammal species which depend upon these systems (Tynan and Demaster 1997). Climate induced regional changes in the flux of organic material from ice or water-column production to benthic communities might also affect the distribution and reproductive success of benthic feeding marine mammals such as gray whales, walruses, and bearded seals (Tynan and Demaster 1997). Declines in many of these populations could in turn lead to a reduction in the availability of prey for top level predators such as polar bears and orcas.

In addition to potential changes in the productivity of ice edge regions, the loss of sea ice would have additional direct consequences through the loss in critical habitat for marine mammals and seabirds that use ice shelves and flows as platforms for daily activities such as reproduction, pupping, resting, molting and migration. Walrus in particular are especially vulnerable to changes in sea ice extent, as floating ice provides walrus 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) and would presumably be greatly affected by a reduction of sea-ice extent poleward. Because polar bears require ice as a solid substrate for hunting ringed seals and other prey, Stirling (1997) predicted that some of the first observable impacts of climate warming will occur in the southern limits of the distribution of polar bears where prolonging the ice-free season would be likely to increase their nutritional stress. Thus both polar bear and ringed seal populations in the eastern Beaufort Sea and in Hudson Bay might be suitable indicators of significant climatic changes in Arctic ecosystems, and monitoring of populations may provide some indication of the degree of stress induced on marine populations in the arctic as a result of global change. Already, anecdotal evidence suggests that the availability of walrus, polar bears and other marine mammals to native hunters in the Arctic has been declining (see the Alaska regional report for more details on this issue).

4.5.3 Stratification

Increases in water temperature and precipitation under global climate change will likely result in enhanced stratification of the water column with important implications for productivity of coastal systems. The overall effect would be to increase the energy required for mixing in the water column, resulting in less turnover and a reduction in the mixed layer depth. Replenishment of nutrients in systems dependent on enrichment of the water column from bottom waters would be directly affected. The consequences of these changes can be expected to vary regionally as described below.

McGowan et al. (1998) attributed 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 and a subsequent decrease in overall levels of productivity in the system. Because zooplankton are a major food source for pelagic fishes, declines in secondary production may be linked to declines in fish production. For example, Nixon (1988) suggested that fishery yield is exponentially proportional to primary production. A 5% reduction in primary production could result in a 6 to 9% reduction in ultimate fishery yield (Gucinski et al. 1990).

In systems in which primary production is limited by light levels at depth, however, a shallower mixed layer depth may result in enhanced production. It has been hypothesized that increased productivity in the North Pacific Ocean during low wind regimes is linked to changes in the strength of the Aleutian Low Pressure System (Polovina et al. 1995). Off Alaska, this results in a reduction in the mixed layer depth and a concentration of phytoplankton in the photic zone where high production levels can be maintained. Conversely, during periods of higher wind stress and deepening of the mixed layer, phytoplankton cells can be driven into zones in which light is limiting with a resulting reduction in productivity. Brodeur and Ware (1992) also documented increases in zooplankton abundance and production during periods of low wind stress, presumably in response to higher levels of primary production. Increases in salmon production have in turn been linked to these periods of high plankton production.

In the tropical Pacific where nutrients are limiting and light penetration is high, increased mixed layer depth is hypothesized to increase overall levels of productivity by expanding the depths to which phytoplankton cells are distributed, providing access to more nutrients. Polovina et al. (1995) linked increases in productivity of spiny lobster and other species (including marine mammals and seabirds) to periods of higher mixing resulting from an increase in wind activity.

Frank et al. (1990) also note that increased stratification could result in reduced benthic production in areas with important nutrient input from land sources. This would result from the trapping of nutrients in the upper stratified area, which could result in a switch to a pelagic food web and a concomitant reduction in the abundance of the benthic components of affected ecosystems. The timing and intensity of stratification can have important localized effects. Prey organisms are often concentrated at the boundaries between water masses, and feeding success and condition of fish larvae may be higher under well stratified conditions when prey are concentrated.

Decreased mixing can also result in changes in food web structure which could favor dinoflagellate-based primary production rather than a diatom-based structure. Because dinoflagellates are motile, they can counter sinking rates that would take them out of the euphotic zone. By contrast, dinoflagellate-based systems involve additional links in the food web and therefore are generally less efficient than diatom-based systems. Accordingly, shifts to dinoflagellate systems can result in some losses in trophic efficiency and transfer to higher trophic levels.

4.5.4 Wind-Driven Processes: Transport, Turbulence and Upwelling

Many marine species depend on ocean current systems for transport of their early life history stages. Among the more dramatic examples is the 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 can affect the transport of larvae as well as other life stages and their successful recruitment to coastal locations.

A reduction in wind-driven forcing in the major current systems such as the Gulf Stream can also be expected to reduce the formation of meanders and rings that affect advective loss of continental shelf biota. For example, the frequency of warm core ring formation from the Gulf Stream has been related to recruitment success of a number of fish populations. In years in which a larger number of ring events occur, recruitment is reduced, presumably due to advection as the rings entrain water from the continental shelf and slope regions.

Many species depend on transport from spawning to nursery grounds to complete their life cycle. For example, blue crabs (*Callinectes sapidus*) in Chesapeake Bay spawn near the mouth of the bay and early developmental stages are completed on the adjacent inner shelf. Late stage larvae are transported back into the bay by near-bottom currents driven by wind and buoyancy-driven flows. Successful recruitment, then, is influenced by freshwater inputs that drive estuarine circulation and coastal wind fields, both of which may be influenced by climate change.

Wind mixing also increases turbulence levels in the water column. It has been shown that turbulent mixing can increase the contact rates between zooplankton and their prey. As turbulence increases beyond a certain point however, the probability of successful prey capture declines. This implies that the probability of feeding success is dome-shaped, with a maximum at intermediate levels of wind-speed and turbulence. The impact of changes in wind intensity must therefore be evaluated with respect to the optimal wind speeds and levels of turbulence. Lasker (1975) noted that for anchovy larvae in the California Bight, high wind stress is linked to lower levels of anchovy recruitment success. This is presumably due to a dissipation of food concentrations and declines in capture success.

Upwelling is a wind-driven phenomena as well, and upwelling zones support the highest volume fisheries on a global basis. Upwelling of nutrient rich water from depth results in high levels of primary production and corresponding high levels of production at higher trophic levels. Most upwelling regions have similar characteristic fish populations and corresponding large-scale fisheries for fishes such as sardine and anchovy. For example, prior to its collapse under heavy fishing pressure and the effects of a strong ENSO event in 1972, the Peruvian anchovetta was the largest single species fishery in the world, with catches of a single species alone approaching one fifth of the total global marine fish landings. Fisheries in such upwelling regions tend to fluctuate tremendously, and the sardine fishery mentioned earlier in this section is an important example of such a system off the west coast of North America.

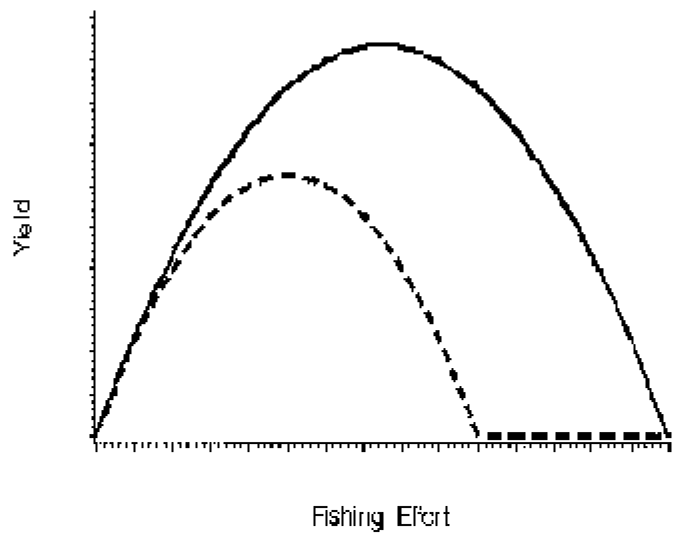

Figure 4.12. Equilibrium yield as a function of fishing pressure under two sets of environmental conditions. The upper (solid) curve represents the production function under favorable environmental conditions, while the lower (dashed) curve represents less favorable environmental conditions.

The potential effect of global climate change on upwelling systems has been subject to two interpretations. Bakun (1989) hypothesized that the temperature differential between land and sea will intensify under global change scenarios, leading to an intensification of alongshore winds and resulting in an increase in upwelling. Bakun provided empirical evidence for an increase in alongshore wind stress (and a derived upwelling index) over the preceding five decades. However it has also been suggested that a reduction in the latitudinal gradient of temperature due to enhanced warning in higher latitudes will result in a lessening of wind fields, leading to an overall reduction of upwelling (Gucinski et al. 1990).

4.5.5 Implications for Fisheries Management

Factors affecting the productivity of marine resources and ecosystem structure must be directly accounted for in any fishery management strategy. Levels of sustainable yield and optimal levels of exploitation are both directly tied to the state of the environment and its effects on productivity of marine populations. The effects of exploitation and environmental change can be synergistic and can serve to destabilize marine populations. In particular, environmental changes that result in an overall reduction in the productivity of a marine resource can result in the decline or collapse of a population under levels of exploitation that are sustainable only under more favorable environmental conditions.

Persistent shifts in productivity levels on longer time scales in particular must be taken into consideration in the development of management approaches. The multidecadal shifts in productivity in the Pacific provide an important indication of the types of changes that can occur and their effects on fishery yields. Rather than consider the effects of exploitation and climate change on marine populations as distinct and separate factors, we must instead recognize the potential interactions among environmental forcing mechanisms and human impacts and adjust management approaches accordingly. Under periods of low productivity, allowable exploitation rates must be reduced to account for reduced recruitment rates.

A simple production model will serve to illustrate these points. In general, one expects the yield from a fishery to be highest at some intermediate level of fishing pressure. The factors that affect fishery productivity can be linked to environmental conditions affecting both population levels and resulting yields. Accordingly, one can consider yield to be a function not only of fishing pressure but of the factors affecting productivity of the resource. If persistent shifts in environmental conditions occur on decadal time scales, one can envision a family of production curves. If the changes in production characteristics change in a way that is independent of population density, relationships such as those depicted in Figure 4.12 result, wherein the upper curve represents the fishery yields under favorable environmental conditions and the lower curve represents those under less favorable conditions. Notice that not only is the expected yield reduced under less favorable environmental conditions (the so called maximum sustainable yield), but the level of fishing pressure that can be sustained by the population is lower. The peak of the lower curve occurs at a lower level of fishing pressure and the population will collapse at fishing intensities that are sustainable under more favorable environmental conditions. It is clear that one must consider concepts such as maximum sustainable yield as being directly linked to prevailing environmental conditions.

Changes in the forcing factors considered here may operate synergistically or antagonistically in their effects on marine systems. For example, increased upwelling with increased alongshore winds could be countered by increased stratification of the water column, increasing the energy required to mix the water column and reducing the influx of nutrients into the upper levels or limiting the influx from mid-level depths with lower nutrient levels than that available from deeper waters. We must therefore develop projections of the effects of these interacting factors in order to determine their potential impacts on marine populations and their implications for fishery management strategies.

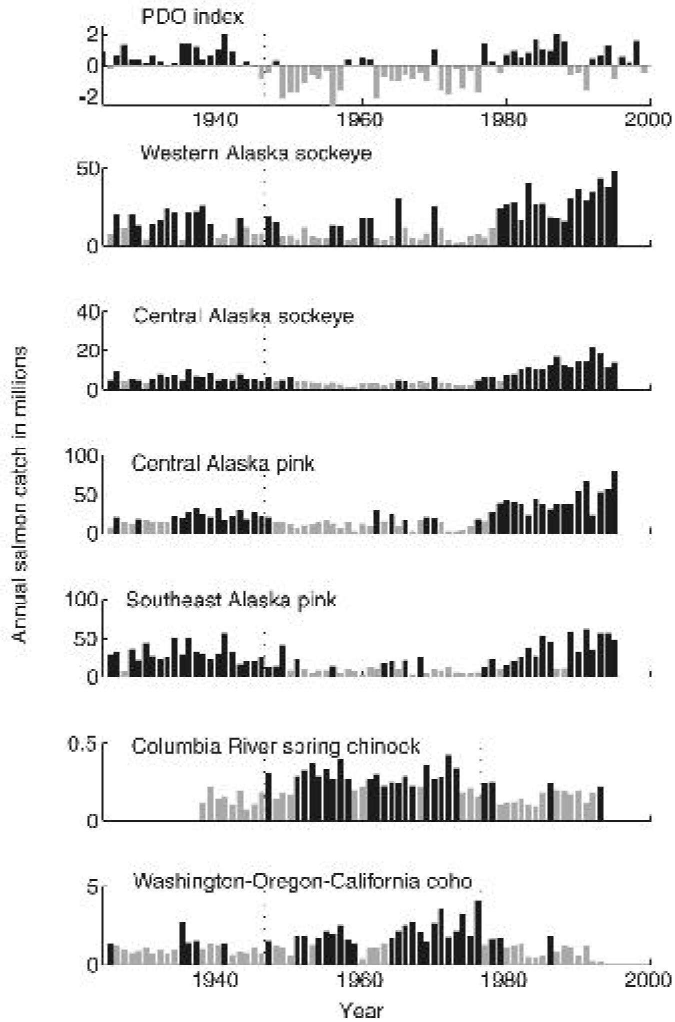

Figure 4.13. Variability in Alaskan and Pacific coast salmon landings related to positive and negative phases of the Pacific Decadal Oscillation (PDO) index. (Mantua et al. 1997).

Case Study: Pacific Salmon and Climate

Pacific salmon are a tremendously important cultural and economic resource throughout their range, above and beyond their irreplaceable ecological role in both freshwater and marine environments. Unfortunately, throughout the last century salmon have been in serious decline, and have completely disappeared from as much as 40% of their historical breeding range in the western contiguous United States (NRC 1996b). Of the 49 evolutionarily significant (population) units (ESU's) currently described in the west, 26 are either listed, or proposed to be listed, under the Endangered Species Act, and 8 more are currently candidates for ESA protection (NMFS 1998). By some estimates, as much as $3 billion has been spent over the last 20 years alone in attempts to reverse salmon declines, often with little or no success. Thus the endless debate over how to "fix" the salmon problem is the subject of much litigation and congressional intervention, and never fails to make headlines in regional and national newspapers.

The declines have largely, and correctly, been attributed to the combined impacts of habitat loss, hydropower, excessive harvest, and hatcheries (NRC 1996b). However, large-scale and long-term changes in ocean and atmospheric conditions are believed to play a significant role, complicating salmon recovery by dramatically affecting marine survival rates of both juveniles and adults over long time scales. Following the occurrence of a well characterized ocean regime shift between 1976 and 1977, ocean conditions appear to have favored salmon stocks from western Alaska to northern British Columbia and disfavored stocks from California to southern British Columbia (Mantua et al. 1997). Since this time, many salmon runs in Alaska have enjoyed record returns while populations along the California, Oregon, Washington and British Columbia coasts have continued their steep decline. By contrast, between about 1946 and 1976 many Alaskan salmon stocks were at alarmingly low population levels while many of the remaining West coast stocks were enjoying prolonged periods of high productivity. Similar patterns occurred even earlier, with strong runs in Alaska and weaker runs along the West coast between the mid 1920's and the late 1940's, and the converse between the beginning of the century and the mid-1920's.

Upon closer examination, these trends in North Pacific salmon production have been shown to be strongly linked to variation in the physical characteristics of the Aleutian Low pressure system, and related physical and biological changes in the marine environment. This reoccurring pattern of interdecadal climate variability is now commonly referred to as the Pacific (inter) Decadal Oscillation, or PDO (Mantua et al. 1997). The PDO appears to be a regional climate phenomenon which might superficially resemble the El Niño/Southern Oscillation (ENSO) signature on a decadal time scale. One index for the PDO has been defined as the leading principal component of North Pacific Sea Surface Temperature (SST) variability. Research indicates that the PDO has been predominantly positive between approximately 1925 and 1946, negative between 1947 and 1976, and positive since 1977 (Figure 4.13). Positive phases are generally associated with above average SSTs off the coast of British Columbia and the Pacific Northwest, and below average snowpack, precipitation, and streamflow in that region. Negative phases are on average associated with greater snowpack, higher streamflow, and cooler SSTs along the Northwest coast.

The pattern of the PDO also appears to be linked to other changes to the physical marine environment, including a decrease in subarctic gyre mixed layer depths, an increase in stratification of the upper ocean along much of the Pacific coast of North America, and a closely related overall warming of ocean surface layer temperatures. These in turn may have led to large scale "bottom up" changes in productivity regimes, as evidenced by an apparent doubling of zooplankton biomass in the subarctic gyre between the 1950's and the 1980's (Brodeur and Ware 1992) and a contrasting 70% decline in zooplankton abundance in the California current in that same period (Roemmich and McGowan 1995). Hare et al. (1999) suggest a possible mechanism for the linkage between the PDO and salmon, which is that these shifts in zooplankton biomass may provide favorable feeding conditions for Alaska-origin smolts during critical early life history stages and conversely create poor feeding conditions for west coast smolts on their migration route to the subarctic gyre. Additional research indicates that modes of decadal scale climate changes have significant impacts on other species of marine fishes, sea birds, and marine mammals throughout the North Pacific (NRC 1996c; Francis et al. 1998; McGowan et al. 1998).

The implication is that successful recovery of West coast salmon will be dependent upon a reversal of the current phase of the PDO. As the phases of the PDO are believed to have lasted an average of 20 to 30 years throughout this century, with the most recent change having occurred in 1977, it could be reasonably hypothesized that favorable marine conditions for West coast salmon could return within the next decade. However this does not imply that poor marine conditions alone should be “blamed” for the decline of West Coast salmon; instead this suggests that the recovery of salmon populations will be dependent on both improved marine survival rates and effective management actions to limit harvests, protect and improve freshwater and estuarine habitats, and minimize the impacts of poor hatchery practices. Thus, changes in management practices, and investment in restoration efforts which have not led to immediate increases in salmon production should not be considered failures. Instead, they should be illustrative of the nature by which resource managers should begin to incorporate knowledge of short- and long-term climate dynamics into decision-making processes and long-term planning.

Unfortunately, even as our knowledge of interdecadal patterns of variability is improved, the spectre of climate change may cast questions on the very future of Pacific salmon themselves. Recent modeling by Welch et al. (1998) suggest that large areas of the North Pacific may be unable to support growth and production of salmon in the future. This study used existing data from major fisheries and oceanographic surveys to examine the limits of Pacific salmon distributions. Their results, based on the results of the Canadian Climate model, indicate that the area of thermally acceptable marine habitat for salmonids is projected to shrink dramatically over the next 50 years,. This would be in addition to significant changes expected in freshwater life stages as a result of altered precipitation patterns and flow regimes. The most surprising prediction is that under these scenarios, none of the Pacific Ocean may lie within the thermal limits that have defined the distribution of sockeye salmon over the last 40 years. Furthermore, the distribution of all species of salmonids could be restricted to marginal seas in the North Pacific region, such as the Bering Sea and the Sea of Okhotsk.

As a possible harbinger to such a change, highly unusual climatic conditions in the Bering Sea during the summers of 1997 and 1998 are suspected of playing a major role in the run failures of western Alaskan salmon runs over these two years. Throughout these two summers, researchers documented extensive die-offs of seabirds, unprecedented blooms of coccolithophores, high sea surface temperatures, extremely low streamflows in Bristol Bay lake systems, and altered ocean currents and atmospheric conditions throughout the Bering Sea (Macklin 1999; Hunt et al. 1999). These unpredicted low returns of salmon caused economic disasters throughout western Alaska, and have resulted in over $50 million in emergency aid relief to fishermen and communities dependent on salmon for 1998 alone. Although there is currently no evidence to link these unusual climate events to global climate change, and both salmon returns increased and climate conditions cooled in 1999, there is little doubt that these run failures are linked to the observed climate extremes. Perhaps more importantly, these events might be illustrative of the types of impacts on coastal and marine systems which could occur with increasing frequency under future climate change scenarios.

Chapter 5
Adaptation and Future Research

5.1 ADAPTATION AND COPING STRATEGIES

Assessing the effects of climate variability and change on coastal and marine ecosystems is especially difficult given that other human activities already have pervasive impacts on these environments and their exploited resources. Furthermore, the nature of climate effects, both detrimental and beneficial to resources in question, are likely to vary greatly in the diverse coastal regions of the U.S. Anthropogenic disturbance often results in a reduction in the resilience or adaptive capacity of systems to cope with change and stress, making the real or potential impacts of climate difficult to observe. It is in this context that the consequences of climate must be considered, adding to the cumulative impact of both natural and anthropogenic stresses on ecological systems and resources.

As a clear example of the synergistic nature of climate and human-induced stresses, consider coral reef systems. Coral reefs, both in U.S. waters and worldwide, are already heavily stressed, and many are degraded to the point of destruction. The prospects for the future are that in many, if not most, instances the degree of both climate-related stress and local or regional stress resulting from anthropogenic impacts will increase. The implication for coral reefs is that local and regional reef protection and management efforts must be even more effective in controlling local stresses to provide some compensation for large-scale impacts. If local and regional anthropogenic stresses continue or increase, many of the reefs that are heavily used or affected by humans will have dim prospects for survival in anything close to their original state. This would result in substantial impacts to the communities and regional economies which depend upon healthy reefs for fisheries, subsistence, recreation and tourism.

Clearly, ameliorating the impacts of future change to coral reefs will require an integration of management efforts. Using coral reefs as an example of the challenges facing coastal resources, several points illustrate both the difficulty and the necessity of integrated management.

The first is that because the stresses acting on coral reefs (and indeed, coastal ecosystems in general) are composites of both global factors and local impacts, and because both categories may be expected, on average, to increase, there is a clear implication that effective reef management and protection will have to compensate by further control of the local stresses to provide some compensation for the large-scale deterioration that cannot be managed locally. Second, effective conservation and management will require pre-emptive protection at or even before the initial signs of deterioration, often in areas far removed from actual reefs. This is due to the natural time constants and spatial scales of reef systems, the very high probability of increasing stresses of various sorts, and the potential for complexes of stresses to push reef systems across critical

thresholds while they still appear healthy.
One component of such an approach could be systematic functional classification of coastal zone systems in their environmental context such as the typology developed under the Land-Ocean Interactions in the Coastal Zone program (http://nioz.nl/loicz/). The "typology" approach to environmental classification for the purposes of up or down-scaling has the advantage of providing convenient conceptual and data management links across both disciplines and environments. Initial applications to coral reefs offer a potential example and test case for integrating coastal environmental science and its applications.

For coastal wetland survival, the effects of sea-level rise will interact with other climate and anthropogenic effects, which will largely determine their ability to adapt and cope with future change. Coastal wetlands can cope with changes in sea level when they are capable of remaining at the same elevation relative to the tidal range, which can occur if sediment buildup equals the rate of relative sea-level rise or if the wetland is able to migrate. However, if wetlands are unable to keep pace with relative sea-level change, or if their migration is blocked by bluffs, coastal development or shoreline protection structures, then the wetland will become immersed and eventually lost as rising seas submerge the remaining habitat. Vertical, as well as lateral, adjustment is therefore the key to wetland survival. The control of river discharge and sediment supply by dams, structures and navigation channels will continue to alter the flow and sediment deposition regimes that in the geologic, or even historic, past may have ensured wetland sustainability through vertical accumulation of substrate.

Thus, coping strategies adopted to remediate changes that may occur in coastal wetland systems should emphasize rehabilitation and sustainability of existing systems rather than recreation of lost habitats. The fisheries productivity, storm protection, and avian habitat provided by wetlands is dependent upon their landscape configuration, their internal structure and their linkages with other coastal and marine resources. Additionally, the potential role of coastal wetlands and other coastal habitats as sinks for carbon dioxide should be considered with regard to the importance of both protecting and possibly restoring degraded or threatened habitats. However, the architecture of coastal wetland habitats is challenging to recreate, and perhaps impossible to recreate at the scale of today's U.S. coastal wetlands. Thus, management and planning strategies that provide for sustainable vertical accumulation, biodiversity and linkages, both internally and with watershed and coastal ocean, are essential to wetland survival in the face of climate variability and long-term change. Because changes in coastal wetlands around the United States due to changing climate are highly likely, appropriate planning and management to facilitate change and adjustment of the coastal wetland landscape, rather than maintain a fixed extent of these valuable habitats, should be implemented.

For marine fisheries, adaptations to changes in the production characteristics of exploited populations will include adjustments in the recommended harvest levels or exploitation rates and in the size or age at which fish and invertebrate populations are first harvested. The limiting level of exploitation (which is the rate at which the risk of population collapse is high) for a population is directly related to the rate of recruitment at low abundance levels. Thus, environmental changes that result in a reduction in recruitment rates must be countered by reductions in exploitation rates.

Conversely, some higher levels of exploitation may be sustainable for some stocks under favorable environmental conditions. Adjustments in the size or age at first harvest may also be necessary under changes in environmental conditions that result in reduced growth or maturation rates. Adaptation of fishing effort and fishing strategy to changes in the composition of fish stocks will also be necessary. Thus, regional markets will likely have to adjust to shifts in species composition due to changes in the availability of different species.

These broader potential consequences of future climate change, such as changes in temperatures and temperature extremes, changes in the productivity of systems, altered freshwater discharges and subsequent variations in the delivery of sediments and nutrients, and the frequency and intensity of storm events and storm surges, have scarcely been assessed in most coastal and marine ecosystems. For example, in Chesapeake Bay, a particular focus of restoration efforts is the reduction of nutrient over-enrichment, or eutrophication, from both point discharges and diffuse sources throughout the watersheds draining into the estuaries. However efforts to reduce eutrophication may have to contend with multiple climate change-related problems such as sea-level rise, increased winter-spring discharges but reduced summer runoff, warmer water temperatures and greater shoreline erosion. Consequently, regional decision-makers may have to develop significantly greater nutrient management and watershed restoration efforts in order to achieve the same nutrient reduction goals currently being pursued.

In nearly all of these instances, scientific uncertainties and the long time scales relative to the nature of the problems are common barriers to the development and adoption of management responses. Anthropogenic stresses will doubtlessly continue and unlikely or unanticipated changes will probably occur. Effective coastal zone and marine assessment and management will require new institutional and technical approaches capable of operating over larger scales to help identify the most pressing (and most tractable) problems, and to focus the appropriate knowledge and resources on their solution.

5.1.1 Adaptation of Coastal Communities to Sea-level Rise

The challenges of adaptation by coastal communities to sea-level rise raises two fundamental questions. The first question is whether a given community will attempt to hold back the sea or allow the shore to retreat. The second question is whether to prepare now or wait for the effects of sea-level rise to emerge. This section examines these questions; and the case study analyzes how some federal programs might either impair and enhance this adaptation.

There are two fundamental ways for holding back the sea. Structures such as dikes, seawalls, bulkheads, and revetments, which form a barrier between water and land, generally sacrifice the beach, wetlands, and other intertidal zones but leave the dry land relatively unaffected. Another engineered approach would include elevation of all of the land surfaces, which can allow wetlands and beaches to survive. Figure 5.1 illustrates general variations of the three principal adaptation strategies. Along bay shores, shoreline armoring (bulkheads, revetments) are the most common way to hold back the sea. For example, in the last 20 years, 300 miles of shoreline was armored in Maryland alone (Titus 1998). Along bays, however, only Delaware, Mississippi, and perhaps

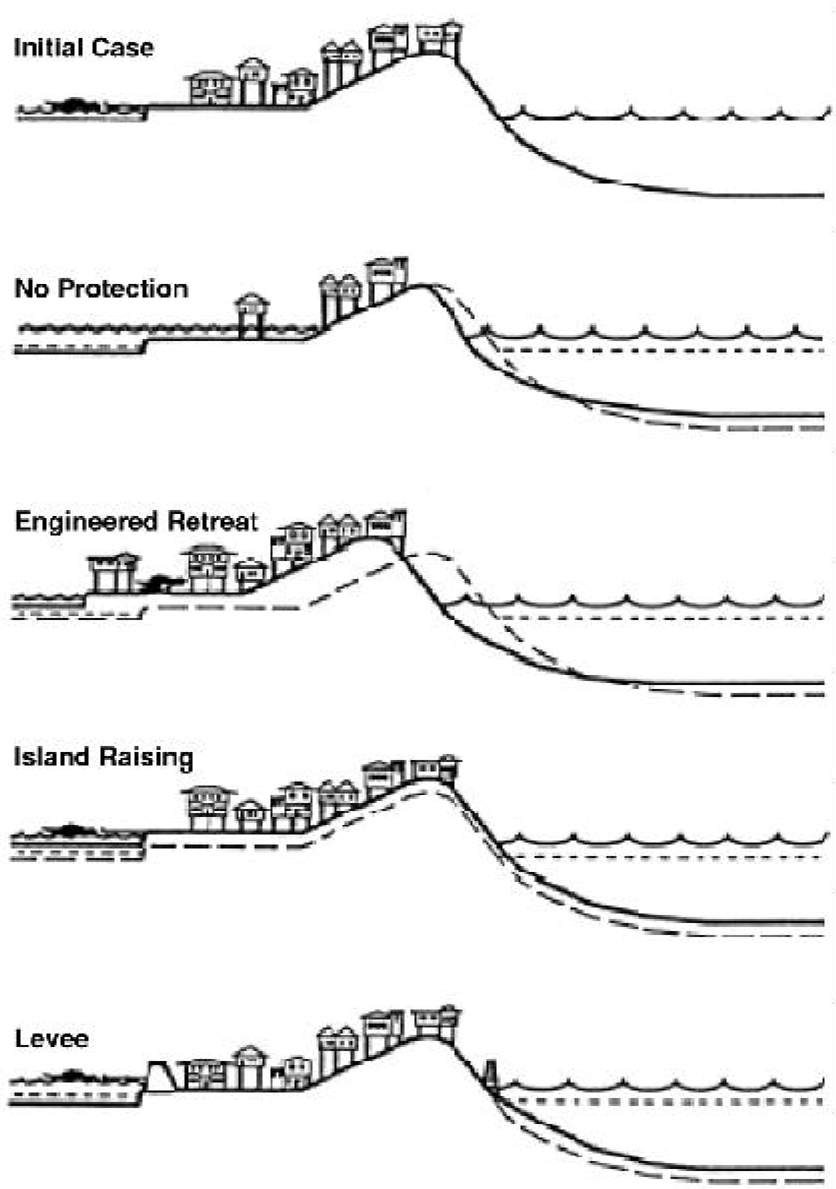

Figure 5.1. Strategies for coping with sea-level rise on barrier islands. A retreat strategy would involve no protection and no rebuilding as sea level rose, while adaptation strategies could include an engineered retreat, island raising or protection by levees, dikes and other structures. (Source: J. Titus, U.S. Environmental Protection Agency.)

New Jersey, regularly nourish beaches, and the use of sediment to artificially assist wetland accretion is feasible, but rare. By contrast, most states have major programs to place additional sand onto their ocean beaches to counteract the erosion, although this approach too is not feasible everywhere due to shoreline dynamics and the cost.

There are also two fundamental ways to ensure that human activities do not impede the natural inland migration of shorelines as sea level rises. The most obvious means is to prevent development or otherwise decrease the property owner's economic motivation to hold back the sea. Another option is the use of rolling easements, which allow development but explicitly prevent property owners from holding back the sea with structures that eliminate wetlands and beaches. Each of these policies can, in turn, be subdivided according to whether the government or the property owner absorbs the loss. Because land use is primarily a state and local responsibility, alterations in the rules of property ownership are outside the scope of appropriate federal activity. However, as the next section discusses, both the national refuge system and the wetland protection regulatory program could facilitate wetland migration in some instances.

Policy makers have two ways to decrease a property owner's motivation to erect a bulkhead; by increasing the cost, or by decreasing the benefit of erecting such a structure. Perhaps the most important way by which governments have increased the cost to property owners of these structures has been to reduce the subsidies for their construction. Nevertheless, even without subsidies, property owners in many areas continue to erect bulkheads or other structures to protect structures and property. Policies that prevent development can conserve natural shorelines in a wider variety of situations. The most common way to prevent development in vulnerable areas is to require a setback, which prohibits construction seaward of a setback line. Setbacks can be based on elevation, erosion rates, or estimates of how the shore might change in the future. Land subdivision policies requiring deeper lots along the shore can help to ensure that setbacks do not leave shorefront owners without permissible building sites. Building codes can require houses to be moveable or small. However alternatives would need to be found where subdivisions already exist and are developed, or for properties which cannot meet minimum setback requirements.

Policies that prevent development in areas vulnerable to erosion have generally been implemented through regulations that do not compensate landowners. At least conceptually, the mechanics of such policies would be essentially the same if the government compensated property owners by purchasing nondevelopment easements. In some cases, governments might choose simply to purchase coastal lands, thereby achieving other objectives as well, such as preserving natural habitat. Yet this option too is limited by the availability of funds for increasingly expensive and desirable coastal lands.

A more narrowly tailored way to ensure that natural shorelines survive rising sea level is simply to create a rule to guarantee this result. The term rolling easement originally came from the common law of Texas, and refers to a broad collection of arrangements under which human activities are required to yield the right of way to naturally migrating shores. Rolling easements can be implemented with the eminent domain purchases of options, easements, covenants, or defeasible estates that transfer title if a bulkhead is built or the sea rises by a certain degree, or by statutes that accomplish the same result.

The simplest way to implement rolling easements throughout a state would be to prohibit bulkheads or any other structures that interfere with naturally migrating shores. Alternatively, a governmental agency or conservancy can purchase a property right to take possession of privately owned land whenever the sea rises by a particular amount. Alternatively, the deed to the property could specify

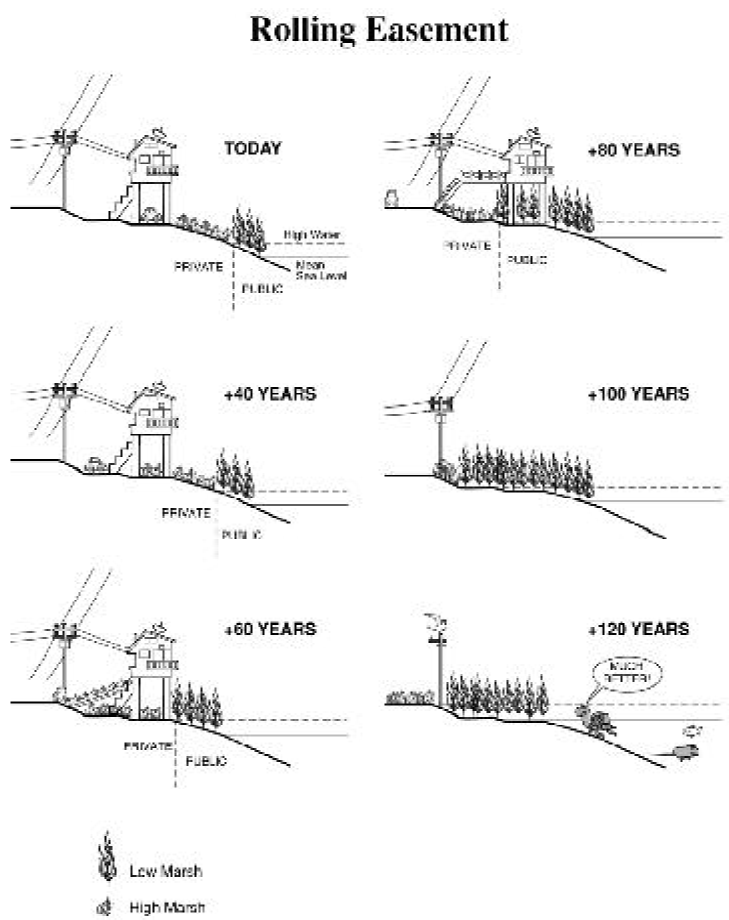

Figure 5.2. A prototype policy for a rolling easement in which bulkheads and filling of private land are prohibited where they interfere with wetland transgression, except to the extent necessary to maintain use of the property. (Source: J. Titus, U.S. Environmental Protection Agency.)

that the boundary between publicly owned tidelands and the privately owned dryland will migrate inland to the natural high water mark, whether or not human activities artificially prevent the water from intruding. A state government could also obtain a rolling easement by passing a statute that simply clarified existing property law by stating that all coastal land is subject to a rolling easement.

The first significant impact of a rolling easement is that the knowledge that the land might eventually have to be abandoned may lead an owner to avoid major capital expenditures to expand or otherwise upgrade the home; although again such a scenario might be unlikely given trends in the value of coastal property. This expectation might lead property owners to avoid major repairs in favor of stop-gap measures. Eventually, the sea rises enough to flood the yard severely whenever an extremely high tide occurs. Without a rolling easement, the homeowner would have the right to use fill to elevate the backyard, and possibly to install a bulkhead as well. However, a rolling easement would prevent these shore protection options, which would impair the ability of wetlands to migrate inland. One might also consider a beach prototype policy for property along sandy beaches and relatively large bodies of water, where property is more likely to be lost to erosion than to a gradual inundation and conversion to marsh.

Previous studies have analyzed the legal, economic, and policy implications of allowing wetlands to migrate inland using setbacks or rolling easements (Sax 1991; Fischman 1991; Titus 1998). The most important limitation of the setback approach is that eventually the sea would reach any setback line, unless development was prohibited in all of the areas that could conceivably be inundated or eroded. Rolling easements can be relatively inexpensive because the right to take over a property one-hundred years hence is equal to the value of the property discounted by the accumulation of interest of a period of one hundred years. This might be only a few cents on the dollar even in a developed area, although as with setbacks a chief limitation is the uncertainty about whether future generations would enforce them.

Most of the key differences between how we manage our ocean and bay shores appear to imply that if current policies continue, natural shores might be more likely to survive along the ocean coast but gradually be eliminated along bay shores. This is due to several factors. First, a seawall strong enough to hold back the ocean can cost ten times as much as the bulkhead necessary to stop a bay shore from eroding. Thus, a property owner may find it difficult to justify spending $150,000 on a seawall in front of their home, while a $15,000 bulkhead or revetment along the bay would be worthwhile. Second, there is a strong public demand for the use of ocean beaches, so structures which threaten beaches are often opposed by the public. By contrast, along bay shores the primary demand for access to the shore tends to be access to the bay itself, not the beach, for example, for boat launching. Third, existing state coastal zone policies prohibit shoreline armoring along the ocean, but not the bay, in several states. Fourth, beach nourishment is currently employed along the ocean in many states, but only rarely used along bays. Finally, existing policies designed to protect ocean beaches, mostly at the state level, consider the dynamics of migrating shores while the federal regulatory program to protect wetlands ignores the implications of sea-level rise.

5.1.2 Should We Prepare for Sea-level Rise Now or Later?

The fact that eventually we will either hold back the sea or not hold it back in a given location does not, by itself, automatically imply that we must decide today what we are going to do. A community that might need a dike if the sea rises 2 feet has little reason to build that dike today. Nevertheless, if the land where they dike would be eventually constructed happens to be vacant, the prospect of future sea-level rise might be a good reason to leave it vacant. A homeowner whose house will be inundated in 30-50 years has little reason to move the house back today, since that person can enjoy the proximity to the water for several decades. Nevertheless, if the house happened to be destroyed by fire, it might be advisable to either not rebuild the house, or to rebuild on a part of the lot that would provide the house with a longer life.

Whether communities need to be concerned about long-term sea-level rise ultimately depends on the lead-time of response options, and on the costs and benefits of acting now versus later. A fundamental premise of cost-benefit analysis is that resources not deployed today can be invested profitably in another activity and yield a return on investment. Therefore, if a particular response can be delayed with little or no cost, it should theoretically be delayed. Most engineering responses to sea-level rise, such as dikes, seawalls, beach nourishment, jacking up structures and elevating roadways, fall into that category. Thus, to the extent that these options might constitute a response to sea-level rise, communities need not act in the immediate future; with two exceptions.

The first exception might be called the retrofit penalty for failing to consider long-term impacts. If one is building a road or a drainage system anyway, then it may be far cheaper to design for a rise in sea level than to come back later, because in the latter case, the project needs to be built twice. For example, designing a drain system might only cost an extra 3% of the value of a home to design for a one-foot rise in sea level; but that cost might be double if it had to be rebuilt after the sea rises. The design and siting of a house may be another example; if a house is designed to be moved, it can be moved, but a brick house on a slab foundation could be more problematic. Similarly, the cost of building a house 20 feet farther from the shore may be minor if the lot is large enough, moving it back 20 feet could cost $10,000.

The second exception consists of the incidental benefits of doing something sooner. If a dike is not needed until the sea rises 2 feet because at that point a 100-year storm would flood the streets with 4 feet of water, the community is implicitly accepting the 2 feet of water that such a storm would provide today. If a dike is built now, then it would stop this smaller flood as well as protect from the larger flood that will eventually occur. This reasoning was instrumental in building the Thames River barrier in the U.K. Some people argued that this expensive structure was too costly given the small risk of London flooding, but with rising sea levels others argued that such a structure would eventually have to be built. Hence the Greater London Council decided to build it during the 1970s.

While engineering responses can be delayed with little penalty, the same cannot be said about land-use decisions. Once an area is developed, the cost of vacating it as the sea rises is much greater than that cost would have been had the area not been developed. This is not to say that eventual inundation automatically should result in placing land off limits; even if a home has to be torn down 50-100 years from now, it might still be worth building. In some coastal areas where demand for beach access is great, rentals may cover the cost of home construction in less than a decade. However, in most states once an area is developed, as a practical matter, it will not be abandoned. Therefore, the only way to ensure that we continue to have natural shores would be to make such a decision before an area is developed. Because the coast continues to be developed today, it follows that the ongoing failure of regulators and communities to deal with this issue is, by default, a decision to allow the loss of wetlands and bay beaches wherever development takes place. Additionally, regulators and land use managers should consider early options to improve land use management practices to better control flooding, the overview of containment ponds and contaminant loads.

Case Study: Implications of Sea-Level Rise for Specific Federal Programs

The federal government is likely to have numerous impacts on how our coastal communities and ecosystems adjust to rising sea level. The role of the federal government can be divided into roughly five categories: property owner, regulator, program administrator, coordinator, and sponsor of research. This case study focuses on several aspects of the federal roles as a property owner, regulator, and program administrator.

The Federal Government as a Property Owner

The federal government currently owns a large fraction of coastal land below the 5 and 10 foot contours. The U.S. Fish and Wildlife Service, the National Park Service, the Department of Defense, the Department of Agriculture's Forest Service, and several other agencies all have large coastal landholdings. Wetlands and beaches are more likely to be able to migrate landward in these areas than in areas where private owners have or are likely to develop the land, and watersheds are more likely to be protected as well. Even land that is not part of a conservation area is more likely to retain natural shores than privately held lands. For example, the National Park spent millions of dollars moving the Cape Hatteras Lighthouse seaward on a special railroad track, to avoid having to choose between armoring the shore and allowing the historic lighthouse to topple into the sea. In general, National Seashores avoid constructing major infrastructure in areas likely to be threatened by erosion.

Some of the most important coastal conservation lands are those within the National Refuge System, administered by the Fish and Wildlife Service (FWS). The National Wildlife Refuge Administration Act directs Secretary of Interior to manage these lands to conserve fish, wildlife, plants, and habitat for the benefit both of the present generation and future generations. The Fish and Wildlife Service's policy is to purchase the minimum interest in land necessary to accomplish a conservation purpose. National refuges generally were not designed with an eye toward the eventuality of sea-level rise, which is understandable given that they were mostly set up before the 1980s when sea-level rise became a concern (Hoffman et al. 1983). While many coastal refuges generally include some high ground, as a buffer between the wetlands and development, this purpose is often satisfied without a large amount of upland.

Currently, the FWS does not undertake overt efforts to ensure that refuge system environments are able to migrate inland as sea level rises. Nevertheless, refuge system wetlands are more likely to be able to migrate inland, because the FWS would allow their wetlands to migrate inland as opposed to armoring their shores. The FWS has a variety of tools for achieving wetland migration, the most obvious being additional land acquisition. However, such an approach may not follow the statutory preference for obtaining the "minimum interest," for saving wetlands as sea level rises, because land may be acquired before sea-level rise necessitates it. An alternative more consistent with the minimum interest might be for FWS to acquire rolling easements on property likely to be inundated if rising sea levels flood existing refuge wetlands. Other options might include nondevelopment easements which functionally would act like setbacks. However, an important limitation to any policy of additional land acquisition is that increases in federal landholdings may be unpopular in some regions and among some people.

The Federal Government as a Regulator

As currently written in the law, Section 10 of the Rivers and Harbors Act of 1899 and Section 404 of the Clean Water Act require permits to dredge or fill any portion of the navigable waters of the United States. As a result, to fill coastal wetlands on private property, land owners must obtain a permit from the U.S. Army Corps of Engineers with the consent of the U.S. Environmental Protection Agency (USEPA).

Unlike the refuge program, the regulatory program to protect coastal wetlands does not inherently enable wetlands to migrate inland. While the natural tendency of a refuge manager is to acquire at least some of the dry land adjacent to coastal wetlands as a buffer, the regulatory program has no similar buffer. Instead, the program limits discharges of fill into navigable waters, not land that might one day become navigable. The program currently does not encourage property owners to consider the tendency for wetlands and beaches to migrate landward. Currently the U.S. Army Corps of Engineers has issued a nationwide permit for bulkheads and other erosion-control structures, effectively ensuring that many wetlands will not be able to migrate inland. Because this permit prohibits filling of vegetated wetlands, and allows very limited filling of nonvegetated wetlands, the Corps has concluded that the cumulative impact is minor. However, if the impacts of future sea-level rise is considered, the cumulative impact might include the loss of all the wetlands which might have been created landward of a structure, as well as the wetlands that are directly filled.

One possible regulatory response would be for USEPA and the Corps of Engineers to revise the nationwide permit for bulkheads. Depending on the level of wetland protection desired in a given area and the economic impact on coastal property owners, there might be numerous means to revise the nationwide permit program. These include denying bulkhead permits in areas where critically important wetlands could be eliminated (perhaps allowing soft engineering approaches like beach nourishment); applying a mitigation requirement along with all bulkhead permits (something analogous to the current mitigation banking program); or issuing bulkhead permits with limited lifetimes. A second opportunity concerns existing wetland mitigation. Currently, property owners seeking to fill wetlands might get a permit if they create wetlands elsewhere with a greater environmental benefit. Often, one must create two acres for every acre that one destroys. If longevity is a goal in mitigation, then one option might be to require permit seekers to demonstrate that the mitigation will last even if sea level rises by a predetermined amount. Alternatively, a program might provide additional credits for mitigation projects likely to outlive the wetlands that were filled.

The Federal Government as a Program Administrator

Unless or until comprehensive solutions are enacted, the federal government’s role in reducing vulnerability to climate change may be distributed throughout a large number of programs, each of which address a small part of the total problem. For example, section 320 of the Clean Water Act authorizes a National Estuary Program. This program could play an important role in helping ecosystems to survive climate change, for two reasons. First, unlike most of USEPA’s regulatory programs, the National Estuary Program focuses on preserving all of the various resources of an estuary, rather than implementing specific mandates of a statute. Second, managers in a given region need not await a national consensus before addressing the issue of sea-level change. The Maryland Coastal Bays program has listed the issue of sea-level rise in its management plan, in concert with efforts by the National Park Service and the U.S. Department of Agriculture, to ensure that wetlands in Worcester County, Maryland can migrate inland.

Like the National Estuary Program, the Coastal Zone Management Program, authorized by the Coastal Zone Management Act focuses on broad environmental objectives. Among other things, the Act specifically encourages states to protect wetlands, minimize vulnerability to flood and erosion hazards, and improve public access to the coast. The authorizing language of the Act also encourages administrators of the program to consider changes in sea level: "because global warming may result in a substantial sea-level rise with serious adverse effects in the coastal zone, coastal states must anticipate and plan for such an occurrence". Thus, the Act has encouraged states to periodically designate specific staff to keep track of the issue, although guidelines from administrators regarding how to deal with the sea-level rise issues would likely make these efforts more useful.

Under the National Flood Insurance Act, property owners in participating coastal communities can obtain federal flood insurance. Although some critics have suggested that the program encouraged people to build homes in hazardous areas, the direct effect of the program has generally been to encourage flood-resistant construction. One of the most important changes has been the tendency to elevate homes on pilings. In some cases, this elevation might make wetland migration more likely, because if a house is on pilings, a yard could gradually convert to marsh without threatening the home. Alternatively, this program might tend to encourage property owners to continue inhabiting shorefront property for a longer time than would have been the case without the program (Heinz Center, 2000). As the shore erodes, for example, the likelihood of severe damage from a storm increases. However, the Federal Emergency Management Administration does not currently increase insurance rates to reflect the increasing risk, and some property owners may be receiving an artificially low insurance rate; a concern raised in the 1994 National Flood Insurance Reform Act.

Finally, one of the most important measures that Congress has undertaken with regard to construction in the coastal zone was the Coastal Barrier Resources Act, which prohibits federal subsidies in specified undeveloped barrier islands. While most undeveloped barrier islands were included (although barrier islands where development had already begun were generally removed from COBRA maps), only a handful of parcels along estuaries were included in the designated areas. Federal spending on infrastructure increases the likelihood that particular areas will be developed, and subsequently protected from rising sea level. The natural processes which allow shorelines and wetlands to migrate in the absence of protection structures are more likely to occur on undeveloped barrier islands.

Clearly, future policies which would allow ecosystems to migrate inland as sea-level rises will involve a tradeoff between environment and the economic interests of property owners. In general, land use is a state and local responsibility, and states can implement the necessary policies to allow wetlands and beaches to migrate inland. Nevertheless, the federal government has been the primary instigator for wetland protection in the past. Thus, the federal government might also lead the way in adapting its own programs to cope with the potential consequences of future sea-level rise.

5.2 RESEARCH NEEDS AND ONGOING RESEARCH EFFORTS

Many unknowns remain in assessing the potential consequences of climate variability and change to coastal and marine resources. While enormous progress has been made in recent years in understanding and predicting the dynamics of short-term modes of variability such as the El Niño/ Southern Oscillation, a comprehensive understanding of longer-term cycles of variability in earth's climate system remains a key research objective (NRC 1998). Understanding just how climate has changed naturally in the past, and how populations and ecosystems have responded to such fluctuations, provides a context for evaluating the significance of future human induced changes. Regional scenarios of climate change are critical in understanding how local ecosystems will be affected, and might ultimately respond, to global change. Additionally, such knowledge will provide a foundation for resource managers and the public in developing adaptation strategies.

One major reason for the difficulty in discerning climate impacts is that human influences tend to dominate the effects on these resources, such that separating the stress of human activities from that due to climate is extremely difficult. In many instances, the impacts of climate change to various ecological systems or communities are just now beginning to be evaluated. The expansion of research efforts into the effects of future change on these ecosystems is critical. Research is also needed to understand how communities can adapt and respond to climate impacts, such as sea-level rise, changes in ocean temperature or future changes in erosion rates, with minimum impacts to the coastal resources upon which they depend. Additional research is also needed regarding the role of coastal ecosystems in global biogeochemical cycles, such as the potential role of coastal wetlands and other coastal and nearshore ecosystems to the production and sequestration of carbon dioxide and other important greenhouse gases. Undoubtedly, the difficulty in distinguishing human induced stresses from climate- induced stresses will continue to challenge managers and researchers alike as the magnitude of these impacts from both of these forces increases.

The Assessment has identified five important areas for research related to climate impacts on coastal and marine systems:

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

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

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

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

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

Despite the paucity of basic ecological and process-oriented research related to climate effects in coastal environments, numerous efforts to improve understanding of the synergy between climate effects and these ecosystems are ongoing. For many, the key objectives include producing research results that will ultimately help to sustain coastal ecosystems as well as coastal communities that depend upon them. Two research programs, the U.S. Global Ocean Ecosystem Dynamics (U.S. GLOBEC) program and a pilot program by the U.S. Geological Survey are presented here as case studies that illustrate ongoing efforts to address critical gaps in our knowledge. Several other research needs are presented here, however these should be considered only representative list rather than a comprehensive summary of key data and information gaps.

Because of the importance of freshwater flow to coastal ecosystems, particularly estuaries and wetlands, the need for improved assessments of potential changes in the extent and timing of runoff to coastal systems is extremely important. Currently, GCM scenarios of runoff estimates vary widely. However, developing improved regional assessments of potential changes in runoff is critical to understanding future conditions in many coastal systems. Equally important is research that would assess the wide array of consequences to coastal ecosystems of future changes in nutrient and contaminant fluxes, sediment supply, and physical processes, all of which are influenced by freshwater inflows. The response of some systems to alterations in freshwater delivery may be desirable with regard to one of these factors, yet deleterious with regard to another. Research will be necessary on a regional basis to understand real and potential consequences resulting from changes in precipitation and freshwater flux to individual systems.

Systematic, long-term observation of nutrient levels, primary productivity and pollutant levels is necessary in coastal and oceanic waters. While remote sensing satellites have become extremely useful in gathering an enormous volume of observations and measurements within the surface layers of the, ongoing data collection for ground truthing and for parameters beneath the surface remain absolutely essential. In 1991 the Global Ocean Observing System (GOOS) initiative was established to address these and other needs. GOOS is an international program advanced by three United Nations agencies and the International Council of Scientific Unions (ICSC), but implemented by individual nations. The ultimate objectives of GOOS are to provide a global framework for the coordination of long-term systematic observations of the world’s oceans, in order to help solve problems related to changes in regional and global environments on a wide range of timescales (NRC 1997b). Ultimately, a comprehensive monitoring program of a wide range of climate and ocean variables is essential in both documenting and distinguishing climate variability, climate change and the subsequent impacts to marine and coastal resources.

Despite great progress in both understanding and predicting the relationship and frequency of storms and hurricanes with respect to interannual and interdecadal variability, the limited historical records and the great interannual, decadal and longer variability of hurricanes make inferences of long-term trends difficult. The use of geologic records to quantify hurricane activity prior to when instrumental records were available needs to be thoroughly explored. In principle, using geologic evidence, the hurricane record could be extended over time scales of hundreds to thousands of years. However, at present, more research is required to improve and verify the required methodologies and analyses.

Additionally, the National Research Council has undertaken numerous studies to evolve strategies for researching global change and global change impacts. A science strategy for understanding decadal to centennial scale changes in the earth system in 1998, and among the recommendations for addressing key issues were: a long-term stable observing system, a hierarchical modeling program, appropriate process studies, and a means for producing and disseminating long-term proxy and instrument data sets. Understanding just how climate has changed naturally in the past provides a context for evaluating the significance of future human induced changes, and additionally will provide a foundation for developing adaptation strategies.

Ongoing Research: Global Ocean Ecosystem Dynamics

The U.S. Global Ocean Ecosystems Dynamics (U.S. GLOBEC) program is a research program designed to address the questions of how global climate change may affect the abundance and production of marine animals. It is operated in collaboration between the NOAA Coastal Ocean Program and the NSF Biological Oceanography Program. Sponsorship by both agencies provides a funding mechanism to allow collaborations between federal and academic scientists. Two U.S. GLOBEC activities are currently supported jointly by NOAA and NSF, one in the Northwest Atlantic and one in the Northeast Pacific. Highlights of the Atlantic program are presented here.

In the Atlantic, U.S. GLOBEC has an overall goal of improving predictability and management of living marine resources of the region through a better understanding of ecosystem interactions and the coupling between climate change, the ocean's physical environment and the ecosystem components. Particularly crucial physical drivers are the North Atlantic Oscillation and the salinity variations associated with the Labrador Current. Within the overall goal outlined above, the NW Atlantic/Georges Bank Study has four general goals.

The first is to determine the dominant processes which control the circulation and transport of biological, chemical and geological materials in a strongly tidal and buoyancy-driven marine system; especially those processes that control the population dynamics of target species. The second is to embody this understanding in diagnostic and prognostic models capable of elucidating ecosystem dynamics and responses on a range of time scales, including interannual fluctuations and longer term variability and trends. The third goal is to understand the effects of climate variability and change on the distribution, abundance and production of the target species in the region. The last key objective is to apply the understanding of biophysical processes which affect distribution, abundance and production of the target species to the identification of critical variables that support ecosystem. This effort is intended to be a prelude to the implementation of a long-term ecosystem monitoring strategy.

Ongoing Research: Predicting Coastal Evolution at Societally-Relevant Time and Space Scales

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

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

The relative susceptibility of different coastal environments to sea-level rise, however, may be quantified at a regional to national scale (Gornitz et al. 1994) using basic data on coastal geomorphology, rate of sea-level rise, and past shoreline evolution. A pilot project is underway at the U.S. Geological Survey, Coastal and Marine Geology Program to assess, from a geologic perspective, the susceptibility of the nation's coasts to sea-level rise. Figure 5.3 shows

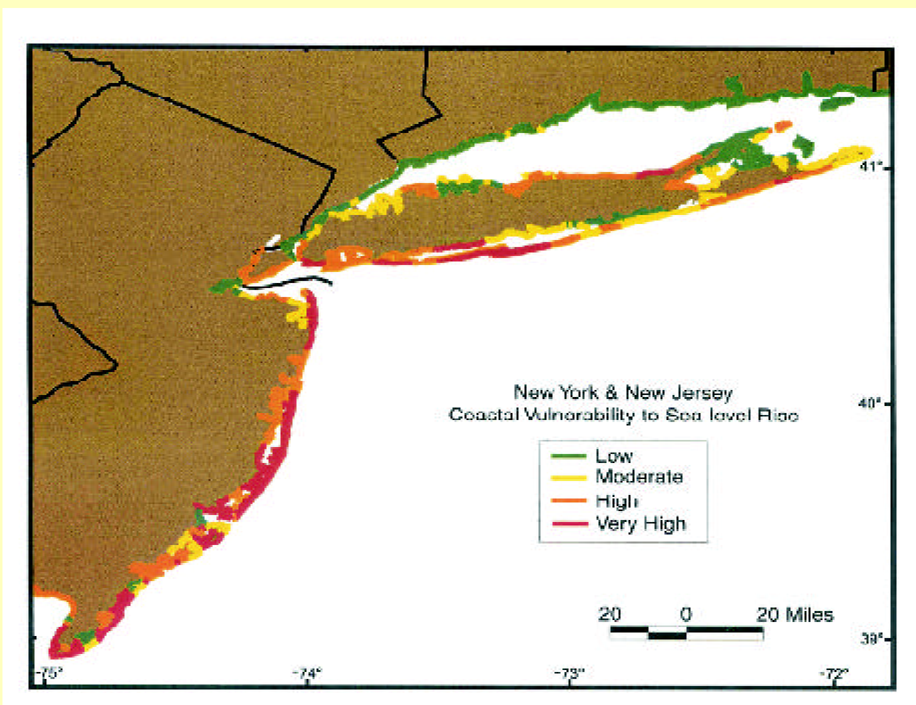

Figure 5.3. Vulnerability of coastlines to sea-level rise in the New York-New Jersey region is closely related to coastal landform type and trends in vertical land movement. (Source: USGS.)

preliminary results of these efforts to map coastal vulnerability to sea-level rise and geomorphological risks. The long-term goal of this project is to predict future coastal changes with a degree of certainty useful to coastal management, following an approach similar to that used to map national seismic and volcanic hazards. This information has immediate application to many of the decisions our society will be making regarding coastal development in both the short- and long-term.

5.3 RECOMMENDATIONS

The National Research Council (1994) assessment of priorities for coastal ecosystem science concluded that the paradigm of single-factor risk assessment is gradually shifting to one in which multiple-factor risk assessments and regulatory strategies take a broader range of impacts into account. These include indirect, cascading, and scale-related effects, such as eutrophication, hydrodynamic modifications, and losses of biodiversity, which increasingly require an ecosystem perspective. However, problems associated with managing these impacts remain complicated by the lack of a coherent strategy in governance, as the United States generally continues to manage oceans and coastal resources on a "sector by sector" basis (NRC 1997a). Such an approach often fails to account for these cumulative impacts to resources, especially as individual users and interest groups have become more defensive about the benefits they obtain from coastal waters.

While much remains to be learned in order to confidently project impacts of climate change on coastal areas and marine resources, the trends and relationships already apparent suggest that the managers, decision-makers and the public must take climate change impacts into account in policies and plans. To be successful, this will have to be done in the context of coastal and resource management challenges already being addressed. Although this assessment has not focused on the development of specific policy recommendations, some general directions are apparent:

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

In general, many of the strategies and challenges of coping with future change are already being devised, discussed and disseminated in response to current stressors on coastal and marine environments. The future impacts of climate will be deeply integrated with the ongoing impacts of human activities, and attempts to manage or mitigate these effects must be tightly coupled with the management of human behavior and direct human impacts on all manner of spatial and temporal scales. Most importantly, those who are or will likely be affected by the impacts of climate change in the future must be made better aware of the risks and potential consequences to their communities and their livelihoods.

5.3.1 Education and Public Awareness

Regardless of the actions taken to control or mitigate greenhouse gas emissions or otherwise address the causes and consequences of global change, one of the most important responses to global change will be to deliver timely information and current useful and relevant scientific findings to decision-makers and the public. The best available scientific information on the patterns, projections and consequences of both climate variability and change should be widely used, together with an understanding of associated uncertainties, and should lead to informed policy making that protects the environment, enhances socioeconomic development and ensures a sustainable future for the nation and the world.

The findings from this report, and the reports from the other sectors and regions as well as the National Assessment synthesis, should be disseminated into the hands of the decision-makers and the general public, particularly to those communities and individuals who are most likely to be directly affected by the consequences of future global change, as well as school children who are our future decision-makers and resource managers. Efforts should be undertaken to disseminate these findings through the media, the world wide web, and other channels, and such documents and findings should likewise be made widely and inexpensively available to those who are interested in the topic. Community-based workshops and teacher training programs with accompanying educational materials should be developed that will bring this information into local communities and schools. These programs should target both the formal (educational institutions) and informal (museums, parks, libraries and community centers) educational communities; making use of locally trusted institutions, programs and experts.

Selecting appropriate local responses will require input from a heterogeneous community that includes scientists, decision-makers at all levels of government, leaders from the private and non-profit sectors, as well as educators and the general public. All of these diverse groups need to understand that we live in a variable and changing world and to be aware of what we do and do not know about global and regional climate processes. They also need to understand the roles and limitations of science in predicting the future behavior of the earth system. Finally, they need to become aware of what steps and actions each can undertake to reduce the human impact on the global environment.

References

Adams, D.A. 1963. Factors influencing vascular plant zonation in North Carolina salt marshes. *Ecology* 44:445-456.

Alexander, C.E. 1998. *Classified Shellfish Growing Waters. NOAA's State of the Coast Report*. NOAA, Silver Spring, MD. Available on-line: http://state-of-coast.noaa.gov/topics/html/state.html.

Alexander, V. 1992. Arctic marine ecosystems. *In* R.L. Peters and T.E. Lovejoy (Eds.). *Global Warming and Biological Diversity.* Yale University Press, New Haven.

Allen, J.A., J.L. Chambers, and S.R. Pezeshki. 1997. Effects of salinity on baldcypress seedlings: Physiological responses and their relation to salinity tolerance. *Wetlands* 17:310-320.

Allen, J.R.L. 1990. Salt-marsh growth and stratification: A numerical model with special reference to the Severn Estuary, Southwest Britain. *Marine Geology* 95:77-96.

Alpine, A.E. and J.E. Cloern. 1992. Trophic interactions and direct physical effects control phytoplankton biomass and production in an estuary. *Limnology and Oceanography* 27:946-955.

Anderson, D.M. (Ed.). 1995. *ECOHAB: The Ecology and Oceanography of Harmful Algal Blooms: A National Research Agenda.* National Science Foundation, Arlington, VA, and National Oceanic and Atmospheric Administration, Silver Spring, MD.

Andrews, T.J., B.F. Clough, and G.J. Miller. 1992. Photosynthetic gas exchange properties and carbon isotope ratios of some mangroves in North Queensland. *Physiology and Management of Mangroves, Tasks for Vegetation Science* 9:15-23.

Aronson, R.B., W.F. Precht, and I.G. Macintyre. 1998. Extrinsic control of species replacement on a Holocene reef in Belize: The role of coral disease. *Coral Reefs* 17:223-230.

Bacon, P.R. 1994. Template for evaluation of impacts of sea-level rise on Caribbean coastal wetlands. *Ecological Engineering* 3:171-186.

Bailey, K.M., J.F. Piatt, T.C. Royer, S.A. Macklin, R.K. Reed, M. Shima, R.C. Francis, A.B. Hollowed, D.A. Somerton, R.D. Brodeur, W.J. Ingraham, P.J. Anderson, and W.S. Wooster. 1995. ENSO events in the Northern Gulf of Alaska and effects on selected marine fisheries. *California Cooperative Oceanic Fisheries Investigations Reports* 36:78-96.

Bakun, A. 1990. Global climate change and intensification of coastal ocean upwelling. *Science* 247:198-201.

Baldwin, A.H., W.J. Platt, K.L. Gathen, J.M. Lessmann, and T.J. Rauch. 1995. Hurricane damage and regeneration in fringe mangrove forests of Southeast Florida, USA. *Journal of Coastal Research* 21:169-183.

Ball, M.C., M.J. Cochrane, and H.M. Rawson. 1997. Growth and water use of the mangroves *Rhizophora apiculata* and *R. stylosa* in response to salinity and humidity under ambient and elevated concentrations of atmospheric CO_2. *Plant, Cell and Environment* 20:1158-1166.

Ball, M.C. and G.D. Farquahar. 1984. Photosynthetic and stomatal responses of two mangrove species, *Aegiceras corniculatum* and *Avicennia marina,* to long-term salinity and humidity conditions. *Plant Physiology* 74:1-6.

Barnes, J.T., M. Yaremko, L. Jacobson, N.C.H. Lo, and J. Stehly. 1997. *Status of the Pacific Sardine (*Sardinops sagax*) Resource in 1996*. NOAA Technical Memorandum, NMFS SWFSC 237.

Baumann, R.H., J.W. Day, and C.A. Miller. 1984. Mississippi deltaic wetland survival: Sedimentation versus coastal submergence. *Science* 224:1093-1095.

Beamish, R.J. 1993. Climate and exceptional fish production off the west coast of North America. *Canadian Journal of Fisheries and Aquatic Sciences* 50:2270-2291.

Bell, G.D. and J.E. Janowiak. 1995. Atmospheric circulation associated with the Midwest floods of 1993. *Bulletin of the American Meteorological Society* 76:681-695.

Berkelmans, R. and J.K. Oliver. 1999. Large-scale bleaching of corals on the Great Barrier Reef. *Coral Reefs* 18:55-60.

Biggs, G.R. 1996. *The Oceans and Climate.* Cambridge University Press, Cambridge, MA.

Blem, C.R. 1980. The energetics of migration. *In* S.A. Gauthreaux (Ed.). *Animal Migration, Orientation, and Navigation.* Academic Press, New York, NY.

Blood, E.R., P. Anderson, P.A. Smith, C. Nybro, and K.A. Ginsberg. 1991. Effects of Hurricane Hugo on coastal soil solution chemistry in South Carolina. *Biotropica* 23:348-355.

Blum, L.K. 1993. *Spartina alterniflora* root dynamics in a Virginia marsh. *Marine Ecology Progress Series* 102:169-178.

Boesch, D.F., M.N. Josselyn, A.J. Mehta, J.T. Morris, W.K. Nuttle, C.A. Simenstad, and D.J.P. Swift. 1994. Scientific assessment of coastal wetland loss, restoration and management in Louisiana. *Journal of Coastal Research* Special Issue 20:1-89.

Boynton, W.R., J.H. Garber, R. Summers, and W.M. Kemp. 1995. Inputs, transformations, and transport to nitrogen and phosphorus in Chesapeake Bay and selected tributaries. *Estuaries* 18:285-314.

Brander, K. 1995. The effect of temperature on growth of Atlantic cod (*Gadus morhua*). *ICES Journal of Marine Science* 52:1-10.

Bricker, S.B., C.G. Clement, D.E. Pirhall, S.P. Orlando, and D.R.G. Farrow. 1999. *National Estuarine Eutrophication Assessment: A Summary of Conditions, Historical Trends, and Future Outlook*. National Oceanic and Atmospheric Administration, Silver Spring, MD.

Bricker-Urso, S., S.W. Nixon, J.K. Cochran, D.J. Hirschberg, and C. Hunt. 1989. Accretion rates and sediment accumulation in Rhode Island salt marshes. *Estuaries* 12:300-317.

Brinson, M.M., R.R. Christian, and L.K. Blum. 1995. Multiple states in the sea level induced transition from terrestrial forest to estuary. *Estuaries* 18:648-659.

Brodeur, R.D. and D.M. Ware. 1992. Interannual and interdecadal changes in zooplankton biomass in the subarctic Pacific Ocean. *Fisheries Oceanography* 1:32-38.

Broecker, W.S. 1985. Does the ocean-atmosphere system have more than one stable mode of operation? *Nature* 315:21-26.

Broecker, W.S. 1991. The great ocean conveyor. *Oceanography* 4:79-89.

Broecker, W.S. 1997. Thermohaline circulation, the Achilles heel of our climate system: Will man-made CO_2 upset the current balance? *Science* 278:1582-1588.

Brokaw, N.V.L. and L.R. Walker. 1991. Summary of the effects of Caribbean hurricanes on vegetation. *Biotropica* 23:442-447.

Brown, B.E. 1997. Coral bleaching: Causes and consequences. *Coral Reefs* 16:S129-S138.

Buddemeier, R.W., D.G. Fautin, and J.R. Ware. 1997. Acclimation, adaptation, and algal symbiosis in reef-building corals. *In* J.C. den Hartog (Ed.). *Proceedings of the 6th International Conference on Coelenterate Biology.* National Museum of Natural History, Leiden. pp. 71-76.

Buddemeier, R.W. and D. Hopley. 1988. Turn-ons and turn-offs: Causes and mechanisms of the initiation and termination of coral reef growth. *Sixth International Coral Reef Symposium*, Townsville, Australia. pp. 485-490.

Buddemeier, R.W. and S.V. Smith. 1999. Coral adaptation and acclimatization: A most ingenious paradox. *American Zoologist* 39:1-9.

Burger, J. and B.L. Olla. 1984. *Behavior of Marine Animals, Vol 6. Shorebirds: Migration and Foraging Behavior*. Plenum Press, New York, NY.

Caddy, J. 1993. Toward a comparative evaluation of human impacts on fishery ecosystems of enclosed and semi-enclosed seas. *Review of Fishery Science* 1:57-96.

Cahoon, D.R., J.W. Day, Jr., D.J. Reed, and R.S. Young. 1998. Global climate change and sea-level rise: Estimating the potential for submergence of coastal wetlands. *In* G.R. Guntenspergen and B.A. Vairin (Eds.). *Vulnerability of Coastal Wetland in the Southeastern United States: Climate Change Research Results.* U.S. Geological Survey, Biological Science Report USGS/BRD/BSR. pp. 21-35.

Cahoon, D.R. and J.C. Lynch. 1997. Vertical accretion and shallow subsidence in a mangrove forest of Southwestern Florida, U.S.A. *Mangroves and Salt Marshes* 1:173-186.

Cahoon, D.R., D.J. Reed, J.W. Day, Jr., G.D. Steyer, R.M. Boumanns, J.C. Lynch, D. McNally, and N. Latif. 1995. The influence of Hurricane Andrew on sediment distribution in Louisiana coastal marshes. *Journal of Coastal Research* Special Issue 18:280-294.

Cane, M.A., A.C. Clement, A. Kaplan, Y. Kushnir, D. Pozdnakov, R. Seager, S. Zebiak, and R. Murtgudde. 1997. Twentieth-century sea surface temperature trends. *Science* 275:957-960.

Carnell, R.E. and C.A. Senior. 1998. Changes in mid-latitude variability due to increasing greenhouse gases and sulphate aerosols. *Climate Dynamics* 14:369-383.

Chabreck, R. H. 1972. *Vegetation, Water and Soil Characteristics of the Louisiana Coastal Regi*on. Louisiana State University Agricultural Experiment Station. Bulletin 72.

Chan, J.C.L. and J.E. Shi. 1996. Long-term trends and interannual variability in tropical cyclone activity over the western North Pacific. *Journal of Geophysical Research Letters* 23:2765-2767.

Chelton, D.B. and R.E. Davis. 1982. Monthly mean sea-level variability along the West coast of North America. *Journal of Physical Oceanography* 12:757-784.

Cleveland, C.C., A.R. Townsend, D.S. Schimel, H. Fisher, R.W. Howarth, L.O. Hedin, S.S. Perakis, E.F. Latty, J.C. von Fischer, A. Elseroad, and M.F. Wasson. 1999. Global patterns of terrestrial biological nitrogen (N_2) fixation in natural ecosystems. *Global Biogeochemical Cycles* 13:623-645.

Cloern, J.E. 1991. Tidal stirring and phytoplankton bloom dynamics in an estuary. *Journal of Marine Research* 49:203-221.

Cloern, J. E. 1996. Phytoplankton bloom dynamics in coastal ecosystems: A review with some general lessons from sustained investigation of San Francisco Bay, California. *Reviews of Geophysics* 34:127-168.

Cloern, J.E., A.E. Alpine, B.E. Cole, R.L.J. Wong, J.F. Aruther, and M.D. Ball. 1983. River discharge controls phytoplankton dynamics in Northern San Francisco Bay estuary. *Estuarine and Coastal Shelf Sciences* 12:415-429.

Clough, B.F., T.J. Andrews, and I.R. Cowan. 1982. Physiological processes in mangroves. *In* B.F. Clough (Ed.). *Mangrove Ecosystems in Australia: Structure, Function and Management.* Australian National University Press, Canberra, Australia. pp. 193-210.

Cohen, A. and J.T. Carlton. 1998. Accelerating invasion rate in a highly invaded estuary. *Science* 279:555-558.

Collins, M. 2000. The El Niño-Southern Oscillation in the second Hadley Centre Coupled Model and its response to greenhouse warming. *Journal of Climate* 13:1299-1312.

Colton, Jr., J.B. 1972. Temperature trends and the distribution of groundfish in continental shelf waters, Nova Scotia to Cape Hatteras as determined from research vessel survey data. *Fisheries Bulletin* 75:1-21.

Committee on Environment and Natural Resources (CENR). 2000. *Integrated Assessment of Hypoxia in the Northern Gulf of Mexico.* White House Office of Science and Technology Policy (OSTP), Washington, DC.

Connell, J.H. 1997. Disturbance and recovery of coral assemblages. *Coral Reefs* 16:S101-S113.

Conner, W.H. 1998. Impacts of hurricanes on forests of the Atlantic and Gulf Coasts, U.S.A. *In* A.D. Laderman (Ed.). *Coastally Restricted Forests.* Oxford University Press, New York, NY. pp. 271-277.

Conner, W.H. and G.R. Askew. 1992. Response of baldcypress and loblolly pine seedlings to short-term saltwater flooding. *Wetlands* 12:230-233.

Conner, W.H. and M. Brody. 1989. Rising water levels and the future of Southeastern Louisiana swamp forests. *Estuaries* 12:318-323.

Conner, W.H. and J.W. Day, Jr. 1991. Variations in vertical accretion in a Louisiana swamp. *Journal of Coastal Research* 7:617-622.

Conner, W.H., C.E. Sasser, and N. Barker. 1986. Floristics of the Barataria Basin Wetlands, Louisiana. *Castanea* 51:111-128.

Conner, W.H. and J.R. Toliver. 1990. Long-term trends in the baldcypress (*Taxodium distichum*) resource in Louisiana (U.S.A.). *Forest Ecology and Management* 33/34:543-557.

Conomos, T.J. (Ed.) 1979. *San Francisco Bay: The Urbanized Estuary*. American Association for the Advancement of Science, San Francisco, CA.

Costanza, R. 1999. The ecological, economic and social importance of the oceans. *Ecological Economics* 31:199-213.

Costanza, R., R. d Arge, R. de Groot, S. Farber, M. Grasso, B. Hannon, K. Limburg, S. Naeem, R.V. O'Neill, J. Paruelo, R.G. Raskin, P. Sutton, and M. van den Belt. 1997. The value of the world's ecosystem services and natural capital. *Nature* 387:253-260.

Council for Agricultural Science and Technology (CAST). 1999. *Gulf of Mexico Hypoxia: Land and Sea Interactions*. Task Force Report No. 134, Ames, IA.

Cox, S.P. and S.G. Hinch. 1997. Changes in size at maturity of Fraser River sockeye salmon (*Oncorhynchus nerka*) (1952-1993) and associations with temperature. *Canadian Journal of Fisheries and Aquatic Sciences* 54:1159-1165.

Craighead, Sr. , F.C. 1971. *The Trees of South Florida. Volume I. The Natural Environments and Their Succession*. University of Miami Press, Coral Gables, FL.

Cuffey, K.M. and S.J. Marshall. 2000. Substantial contribution to sea-level rise during the last interglacial from the Greenland ice sheet. Nature 404:591-594.

Culliton, T.J. 1998. *Population: Distribution, Density and Growth.* NOAA State of the Coast Report. NOAA, Silver Spring, MD. Available online: http://state-of-coast.noaa.gov/topics/html/pressure.html.

Curtis, P.S., B.G. Drake, and D.F. Whigham. 1989. Nitrogen and carbon dynamics in C_3 and C_4 estuarine marsh plants grown under elevated CO_2 in situ. *Oecologia* 78:297-301.

Davis, Jr., J.H. 1943. *The Natural Features of Southern Florida*. Bulletin No. 25. Florida Department of Conservation, Geological Survey, Tallahassee, FL.

Davis, S.M., L.H. Gunderson, W.A. Park, J.R. Richardson, and J.E. Mattson. 1994. Landscape dimension, composition, and function in a changing Everglades ecosystem. In S.M. Davis, and J.C. Ogden (Eds.). *Everglades: The Ecosystem and Its Restoration*. St. Lucie Press, Delray Beach, FL. pp. 419-445.

Day, Jr., F.P., J.P. Megonigal, and L.C. Lee. 1989. Cypress root decomposition in experimental wetland mesocosms. *Wetlands* 9:263-282.

DeAngelis, D.L. 1994. Synthesis: Spatial and temporal characteristics of the environment. *In* S.M. Davis and J.C. Ogden (Eds.). *Everglades: The Ecosystem and Its Restoration*. St. Lucie Press, Delray Beach, FL. pp. 307-320.

DeLaune, R.D., W.H. Patrick, and S.R. Pezeshki. 1987. Foreseeable flooding and death of coastal wetland forests. *Environmental Conservation* 14:129-133.

Dettinger, M.D. and D.R. Cayan. 1995. Large-scale atmospheric forcing of recent trends toward early snowmelt runoff in California. *Journal of Climate* 8:606-623.

Diaz, R.J. and R. Rosenberg. 1995. Marine benthic hypoxia: A review of its ecological effects and the behavioral responses of benthic macrofauna. *Oceanography and Marine Biology: An Annual Review* 33:245-303.

Doherty, R. and L.O. Mearns. 1999. *A Comparison of Simulation of Current Climate from Two Coupled Atmosphere-Ocean Climate Models Against Observations and Evaluation of Their Future Climates*. National Institute for Global and Environmental Change (NIGEC), Boulder, CO.

Dolan, R., F. Anders, and S. Kimball. 1985. *Coastal Erosion and Accretion in U.S.* Geological Survey National Atlas. Department of the Interior, U.S. Geological Survey, Reson, VA.

Dolan, R. and R.E. Davis. 1992. An intensity scale for Atlantic coast northeast storms. *Journal of Coastal Research* 8:352-364.

Done, T.J. 1999. Coral community adaptability to environmental change at the scales of regions, reefs and reef zones. *American Zoologist* 39:66-79.

Douglas, B. 1992. Global sea level acceleration. *Journal of Geophysical Research* 97:12,699-12,706.

Dowgiallo, M.J. (Ed.). 1994. *Coastal Oceanographic Effects of 1993 Mississippi River Flooding. Special NOAA Report*. NOAA Coastal Ocean Office/National Weather Service, Silver Spring, MD.

Doyle, T. 1999. Modeling global change effects on coastal forests. *In* G.R. Guntenspergen and B. A. Vairin (Eds.). *Vulnerability of Coastal Wetland in the Southeastern United States: Climate Change Research Results.* U.S. Geological Survey, Biological Science Report USGS/BRD/BSR. pp. 69-81.

Doyle, T.W., T.J. Smith, III, and M.B. Robblee. 1995. Wind damage effects of Hurricane Andrew on mangrove communities along the southwest coast of Florida, USA. *Journal of Coastal Research* Special Issue 21:159-68.

Driscoll, N.W. and G.H. Haug. 1998. A short circuit in thermohaline circulation: A cause for Northern Hemisphere glaciation? *Science* 282:436-438.

Duever, M.H., J.E. Carlson, J.F. Meeder, L.C. Duever, L.H. Gunderson, L.A. Riopelle, T.R. Alexander, R.L. Myers, and D.P. Spangler. 1986. *The Big Cypress Preserve.* National Audubon Society, New York, NY.

Duke, N.C. 1992. Mangrove floristics and biogeography. *In* A.I. Robertson and D. M. Alongi (Eds.) *Tropical Mangrove Ecosystems. Vol. 41, in Coastal and Estuarine Studies*. American Geophysical Union, Washington, D.C. pp. 63-100.

Duke, N.C. 1995. Genetic diversity, distributional barriers and rafting continents - More thoughts on the evolution of mangroves. *Hydrobiologia* 295:167-181.

Ellison, J.C. and D.R. Stoddart. 1991 Mangrove ecosystem collapse during predicted sea-level rise: Holocene analogues and implications. *Journal of Coastal Research* 7:151-165.

Emery, K.O. and D.G. Aubrey. 1991. *Sea-Levels, Land Levels and Tide Gauges*. Springer-Verlag, New York.

Emery, W.J., L. Kantha, G.A. Wick, and P. Schluessel. 1993. The relationship between skin and bulk sea surface temperatures. *In* I.S.F. Jones, Y. Sugimori, and R.W. Stewart (Eds.). *Satellite Remote Sensing of the Oceanic Environment.* Seibutsu Kenkyusha, Tokyo, Japan. pp. 25-40.

Ens, B.J., J.D. Goss-Custard, and T.P. Weber. 1995. *Effects of Climate Change on Bird Migration Strategies Along the East Atlantic Flyway.* Dutch National Research Program on Global Air Pollution and Climate Change. Report No. 410 100 075. Texel, The Netherlands.

Evans, P.R. 1991. Introductory remarks: habitat loss - effects on shorebird populations. *Acta XX Congressus Internationalis Ornithologici*. New Zealand Ornithological Congress Trust Board, Wellington, New Zealand.

Evans, P.R. 1997. Improving the accuracy of predicting the local effects of habitat loss on shorebirds: Lessons from the Tees and Orwell estuary studies. *In* J.D. Goss-Custard, R. Rufino, and A. Luis (Eds.). *Effects of Habitat Loss and Change on Waterbirds.* The Stationary Office, London, UK.

Evans, P.R. and N.C. Davidson. 1990. Migration strategies and tactics of waders breeding in arctic and north temperate latitudes. *In* E. Gwinner (Ed.). *Bird Migration.* Springer-Verlag, Berlin, Germany.

Fairbanks, R. 1989. A 17,000-year glacio-eustatic sea-level record: Influence of glacial melting rates on the Younger Dryas event and deep ocean circulation. *Nature* 342:637-642.

Farnsworth, E.J., A.M. Ellison, and W.K. Gong. 1996. Elevated CO_2 alters anatomy, physiology growth, and reproduction of red mangrove (*Rhizophora mangle* L.). *Oecologia* 108:599-609.

Felzer, B. 1999. *Hydrological implications of GCM results for the U.S. National Assessment. American Water Resources Association, May, 1999*, Abstract Volume, pp. 69-72. Federal Emergency Management Agency (FEMA). 1991. Projected Impact of Relative Sea-level Rise on the National Flood Insurance Program. Report to Congress. Federal Emergency Management Agency, Washington D.C. Federal Insurance Administration.

Felzer, B. and P. Heard. 1999. Precipitation differences amongst GCMs used for the U.S. National Assessment. *Journal of the American Water Resources Association* 35:1327-1339.

Field, C.B., G.C. Daily, F.W. Davis, S. Gaines, P.A. Matson, J. Melack, and N.L. Miller. 1999. *Confronting Climate Change in California: Ecological Impacts on the Golden State.* Union of Concerned Scientists, Cambridge, MA and the Ecological Society of America, Washington DC.

Field, C.D. 1995. Impact of expected climate change on mangroves. *Hydrobiologia* 295:75-81.

Fischman, R.L. 1991. Global warming and property interests: Preserving coastal wetlands as sea levels rise. *Hofstra Law Review* 15:565.

Fisher, A., D. Alber, E. Barron, R. Bord, R. Crane, D. DeWalle, C.G. Knight, R. Najjar, E. Nizeyimana, R. O'Conner, A. Rose, J. Shortle, and B. Yarnell. 2000. *Preparing for a Changing Climate, the Potential Consequences of Climate Variability and Change: Mid-Atlantic Overview*. Pennsylvania State University, University Park. 67 pp.

Francis, R.C., S.R. Hare, A.B. Hollowed, and W.S. Wooster. 1998. Effects of interdecadal climate variability on the oceanic ecosystems of the Northeast Pacific. *Fisheries Oceanography* 7:1-21.

Frangi, J.L. and A.E. Lugo. 1991. Hurricane damage to a flood plain forest in the Luquillo Mountains of Puerto Rico. *Biotropica* 23:324-335.

Frank, K.T., R.I. Perry, and K.F. Drinkwater. 1990. Predicted response of Northwest Atlantic invertebrate and fish stocks to CO_2-induced climate change. *Transactions of the American Fisheries Society* 119:353-365.

Fuller, D.A., J.G. Gosselink, J. Barras, and C.E. Sasser. 1995. Status and trends in vegetation and habitat modifications. *In* D.J. Reed (Ed.). *Status and Trends of Hydrologic Modification, Reduction in Sediment Availability, and Habitat Loss/Modification in the Barataria-Terrebonne Estuarine System.* BTNEP Publ. No. 20, Barataria-Terrebonne National Estuary Program, Thibodaux, LA. pp. 25-76.

Fyfe, J.C., G.J. Boer, and G.M. Flato. 1999. The Arctic and Antarctic Oscillations and their projected changes under global warming. *Geophysical Research Letters* 26:1601-1604.

Gallegos, A., S. Czitrom, J. Zavala, and A. Fernandez. 1993. Scenario modeling of climate change on the ocean circulation of the Intra-American Sea. *In* G.A. Maul (Ed.). *Climatic Change in the Intra-American Seas.* United Nations Environment Programme and Intergovernmental Oceanographic Commission Edward Arnold, London, UK. pp. 55-74.

Galloway, J.N., W.H. Schlesinger, C. Levy, A. Michaels, and J.L. Schnoor. 1995. N fixation: Anthropogenic enhancement - environmental response. *Global Biogeochemical Cycles* 9:235-252.

Gardner, L.R., W.K. Michener, B. Kjerfve, and D.A. Karinshak. 1991. The geomorphic effects of Hurricane Hugo on an undeveloped coastal landscape at North Inlet, South Carolina. *Journal of Coastal Research* Special Issue 8:181-186.

Gates, R.D. and P.J. Edmunds. 1999. The physiological mechanisms of acclimatization in tropical reef corals. *American Zoologist* 39:30-43.

Gattuso, J.P., D. Allemand, and M. Frankignoulle. 1999. Photosynthesis and calcification at cellular, organismal and community levels in coral reefs: A review on interactions and control by the carbonate chemistry. *American Zoologist* 39:160-183.

Gehrels, W.R. and S.P. Leatherman. 1989. Sea-level rise - Animator and terminator of coastal marshes: An annotated bibliography on U.S. coastal marshes and sea-level rise. *Public Administration Series: Bibliography P2634.* Vance Bibliographies, Monticello, IL.

Glynn, P.W. and W.H. de Weerdt. 1991. Elimination of two reef-building hydrocorals following the 1982-1983 El Niño warming event. *Science* 253:69-71.

Good, J.W. 1994. Shore protection policy and practices in Oregon: An evaluation of implementation success. *Coastal Management* 22:335-352.

Goodbred, Jr., S.L., E.E. Wright, and A.C. Hine. 1998. Sea-level change and storm-surge deposition in a late holocene Florida salt marsh. *Journal of Sedimentary Research* 68:240-52.

Goolsby, D.A. 2000. Mississippi Basin nitrogen flux believed to cause Gulf hypoxia. *Eos, Transactions, American Geophysical Union* 81:321, 326-327.

Goolsby, D.A., W.A. Battaglin, G.B. Lawrence, R.S. Artz, B.T. Aulenbach, and R.P. Hooper. 1999. *Gulf of Mexico Hypoxia Assessment, Topic #3, Flux and Sources of Nutrient in the Mississippi-Atchafalaya River Basin*. Committee on Environmental and Natural Resources, Hypoxia Work Group for the Mississippi River/Gulf of Mexico Watershed Nutrient Task Force.

Gornitz, V.M. 1995. Sea-level rise: A review of recent past and near-future trends. *Earth Surface Processes and Landforms* 20:7-20.

Gornitz, V.M., R.C. Daniels, T.W. White, and K.R. Birdwell. 1994. The development of a coastal risk assessment database: Vulnerability to sea-level rise in the U.S. Southeast. *In* C.W. Finkl, Jr. (Ed.). *Coastal Hazards: Perception, Susceptibility, and Mitigation*. Journal of Coastal Research Special Issue 12. pp. 327-338.

Gornitz, V.M. C. Rosenzweig, and D. Hillel. 1997. Effects of anthropogenic intervention in the land hydrologic cycle on global sea-level rise. *Global and Planetary Change* 14:147-161.

Goss-Custard, J.D. and M.E. Moser. 1988. Rates of change in the numbers of dunlin, *Calidris alpina*, wintering in British estuaries in relation to the spread of *Spartina anglica*. *Journal of Applied Ecology* 25:95-109.

Governor's Commission for a Sustainable South Florida. 1995. *Final Report to Florida Governor Lawton Chiles, October 1995*. Coral Gables, FL.

Greenstein, B.J., H.A. Curran, and J.M. Pandolfi. 1998. Shifting ecological baselines and the demise of *Acropora cervicornis* in the western North Atlantic and Caribbean Province: A Pleistocene perspective. *Coral Reefs* 17:249-261.

Gregory, J.M. and J. Oerlemans. 1998. Simulated future sea-level rise due to glacier melt based on regionally and seasonally resolved temperature changes. *Nature* 391:474-476.

Griffies, S.M. and K. Bryan. 1997. Predictability of North Atlantic multidecadal climate variability. *Science* 275:181-184.

Griggs, G.B and K.M. Brown. 1998. Erosion and shoreline damage along the Central California coast: A comparison between the 1997-98 and 1982-83 ENSO winters. *Shore and Beach* 66:18-23.

Gucinski, H., R.T. Lackey, and B.C. Spence. 1990. Global climate change: Policy implications for fisheries. *Fisheries* 15:33-38.

Gunderson, L.H. 1994. Vegetation of the Everglades: Determinants of community composition. *In* S.M. Davis and J.C. Ogden (Eds.). *Everglades: The Ecosystem and Its Restoration*. St. Lucie Press, Delray Beach, FL. pp. 323-340.

Gunderson, L.H. and J.R. Snyder. 1994. Fire patterns in the southern Everglades. *In* S.M. Davis and J.C. Ogden (Eds.). *Everglades: The Ecosystem and Its Restoration*. St. Lucie Press, Delray Beach, FL. pp. 291-306.

Guntenspergen, G.R., D.R. Cahoon, J. Grace, G.D. Steyer, S. Fournet, M. Townson, and A.L. Foote. 1995. Disturbance and recovery of the Louisiana coastal marsh landscape from the impacts of Hurricane Andrew. *Journal of Coastal Research* Special Issue 21:324-339.

Hallegraeffe, G.M. 1993. A review of harmful algal blooms and their apparent global increase. *Phycologia* 32:79-99.

Hare, S.R., N.J. Mantua, and R.C. Francis. 1999. Inverse production regimes: Alaska and west coast Pacific salmon. *Fisheries* 24:6-14.

Hargreaves, N.B., D.M. Ware, and G.A. McFarlane. 1994. Return of the Pacific sardine (*Sardinops sagax*) to the British Columbia coast in 1992. *Canadian Journal of Fisheries and Aquatic Sciences* 51:460-463.

Harris, L.D. and W.P. Cropper, Jr. 1992. Between the devil and the deep blue sea: Implications of climate change for Florida's fauna. *In* R.L. Peters and T.E. Lovejoy (Eds.). *Global Warming and Biological Diversity.* Yale University Press, New Haven, CT. pp. 309-324.

Harshberger, J.W. 1914. *The Vegetation of South Florida, South of 27°30' North, Exclusive of the Florida Keys*. Transactions of Wagner Free Institute of Science, Philadelphia, PA.

Harvell, C.D., K. Kim, J.M. Burkholder, R.R. Colwell, P.B. Epstein, D.J. Grimes, E.E. Hofmann, E.K. Lipp, A.D.M.E. Osterhaus, R.M. Overstreet, J.W. Porter, G.W. Smith, and G.R. Vasta. 1999. Emerging marine diseases: Climate links and anthropogenic factors. *Science* 285:1505-1510.

Harwell, M.A. 1998. Science and environmental decision making in South Florida. *Ecological Applications* 8:580-590.

Harwell, M.A., J.F. Long, A.M. Bartuska, J.H. Gentile, C.C. Harwell, V. Myers, and J.C. Ogden. 1996. Ecosystem management to achieve ecological sustainability: The case of South Florida. *Environmental Management* 20:497-521.

Health Ecological and Economic Dimensions (HEED). 1998. *Marine Ecosystems: Emerging Diseases as Indicators of Global Change*. Year of the Ocean Special Report on Health of the Oceans from Labrador to Venezuela. NOAA Office of Global Programs and National Aeronautics and Space Administration.

Heinz Center. 2000. *The Hidden Costs of Coastal Hazards: Implications for Risk Assessment and Mitigation*. Island Press, Washington, DC.

Henderson-Sellers, A., H. Zhang, G. Berz, K. Emanuel, W. Gray, C. Landsea, G. Holland, J. Lighthill, S.-L. Shieh, P. Webster, and K. McGuffie. 1998. Tropical cyclones and global climate change: A post-IPCC assessment. *Bulletin of the American Meteorological Society* 79:19-38.

Hendry, M. 1993. Sea-level movements and shoreline changes. *In* G.A. Maul (Ed.). *Climatic Change in the Intra-American Seas.* United Nations Environment Programme and Intergovernmental Oceanographic Commission Edward Arnold, London, UK. pp. 115-161.

Herbert, P.J., J.D. Jarrell, and M. Mayfield. 1996. *The Deadliest, Costliest, and Most Intense Hurricanes of This Century (and Other Frequently-Requested Hurricane Facts)*. NOAA Technical Memorandum NWS TPC-1, National Hurricane Center.

Hoegh-Guldberg, O. 1999. Climate change, coral bleaching and the future of the world's coral reefs. *Marine and Freshwater Research* 50:839-66.

Hoffman, J.S., D. Keyes, and J.G. Titus. 1983. *Projecting Future Sea-Level Rise*. Environmental Protection Agency, Washington, DC.

Holbrook, S.J., R.J. Schmitt, and J.S. Stephens, Jr. 1997. Changes in an assemblage of temperate reef fishes associated with a climate shift. *Ecological Applications* 7:1299-1310.

Holland, G.J. 1997. The maximum potential intensity of tropical cyclones. *Journal of Atmospheric Science* 54:2519-2541.

Horvitz, C.C., S. McMann, and A. Freedman. 1995. Exotics and hurricane damage in three hardwood hammocks in Dade County Parks, Florida. *Journal of Coastal Research* Special Issue 24:145-158.

Houghton, J. 1997. *Global Warming: The Complete Briefing*. Cambridge University Press, Cambridge, MA. 251 pp.

Houghton, J.T., L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell. 1996. *Climate Change 1995: The Science of Climate Change*. Cambridge University Press, Cambridge, UK. 572 pp.

Houston, J.R. 1996. International tourism and U.S. beaches. *Shore and Beach* 64:27-35.

Howarth, R.W. 1998. An assessment of human influences on inputs of N to the estuaries and continental shelves of the North Atlantic Ocean nutrient cycling. *Agroecosystems* 52:213-223.

Howarth, R.W., G. Billen, D. Swaney, A. Townsend, N. Jaworski, K. Lajtha, J.A. Downing, R. Elmgren, N. Caraco, T. Jordan, F. Berendse, J. Freney, V. Kudeyarov, P. Murdoch, and Zhu Zhao-liang. 1996. Regional N budgets and riverine N and P fluxes for the drainages to the North Atlantic Ocean: Natural and human influences. *Biogeochemistry* 35:75-139.

Howarth, R. W., D. Swaney, T. J. Butler, and R. Marino. (in press). Climatic control on eutrophication of the Hudson River estuary. *Ecosystems.*

Hughes, T.P. 1994. Catastrophes, phase shifts, and large-scale degradation of a Caribbean coral reef. *Science* 265:1547-1551.

Hughes, T.P. and J.H. Connell. 1999. Multiple stressors on coral reefs: A long-term perspective. *Limnology and Oceanography* 44:932-940.

Hunt, Jr., G.L., C.L. Bandduini, R.D. Brodeur, K.O. Coyle, N.B. Kachel, J.M. Napp, S.A. Salo, J.D. Schumacher, P.J. Stabeno, D.A. Stockwell, T.E. Whitledge, and S.I. Zeeman. 1999. The Bering Sea in 1998: The second consecutive year of extreme weather-forced anomalies. *Eos Transactions of the American Geophysical Union* 80:565-566.

Imbrie, J., A. Berger, E.A. Boyle, S.C. Clemens, A. Duffy, W.R. Howard, G. Kukla, J. Kutzbach, D.G. Martinson, A.C. Mix, B. Molfino, J.J. Morley, L.C. Peterson, N.G. Pisias, W.L. Prell, M.E. Raymo, N.J. Shackleton and J.R. Tuggweiler. 1993. On the structure and origin of major glaciation cycles. 2. The 100,000 year cycle. *Paleoceanography* 8:699-735.

Imbrie, J., A. Boyle, S.C. Clemens, A. Duffy, W.R. Howard, G. Kukla, J. Kutzbach, D.G. Martinson, A.C. Mix, B. Molfino, J.J. Morley, L.C. Peterson, N.G. Pisias, W.L. Prell, M.E. Raymo, N.J. Shackleton, and J.R. Tuggweiler. 1992. On the structure and origin of major glaciation cycles. 1. Linear responses to Milankovitch forcing. *Paleoceanography* 7:701-738.

Intergovernmental Panel on Climate Change (IPCC). 1996. *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analysis*. Cambridge University Press, Cambridge, MA.

Jameson, S.C., J.W. McManus, and M.D. Spalding. 1995. State of the Reefs: Regional and Global Perspectives. Available online: http://www.ogp.noaa.gov/misc/coral/sor/.

Jassby, A.D., W.J. Kimmerer, S.G. Monismith, C. Armor, J.E. Cloern, T.M. Powell, J.R. Schubel, and T.J. Vendlinski. 1995. Isohaline position as a habitat indicator for estuarine populations. *Ecological Applications* 5:272-289.

Jaworski, N.A., R.W. Howarth, and L.J. Hetling. 1997. Atmospheric deposition of N oxides onto the landscape contributes to coastal eutrophication in the northeast United States. *Environmental Science and Technology* 31:1995-2004.

Jickells, T.D. 1998. Nutrient biogeochemistry of the coastal zone. *Science* 281:217-222.

Jobling, M. 1996. Temperature and growth: Modulation of growth rate via temperature change. *In* C.M. Wood and D.G. MacDonald (Eds.). *Global Warming: Implications for Marine and Freshwater Fish*. Cambridge University Press, Cambridge, MA. pp. 225-253.

Johannessen, O.M., E.V. Shalina, and M.W. Miles. 1999. Satellite evidence for an Arctic sea ice cover in transformation. *Science* 286:1937-1939.

Jørgensen, B.B. and K. Richardson. 1996. *Eutrophication in Coastal Marine Systems.* American Geophysical Union, Washington, DC.

Justi , D., N.N. Rabalais, and R.E. Turner. 1997. Impacts of climate change on net productivity of coastal waters: Implications for carbon budget and hypoxia. *Climate Research* 8:225-237.

Kaminsky, G.M., P. Ruggeiero, and G. Gelfenbaum. 1998. Monitoring coastal change in Southwest Washington and Northwest Oregon during the 1997/98 El Niño. *Shore and Beach* 66:42-51.

Karl, T.R. and R.W. Knight. 1998. Secular trends of precipitation amount, frequency and intensity in the United States. *Bulletin of the American Meteorological Society* 79:231-241.

Karl, T.R., R.W. Knight, D.R. Easterling, and R.G. Quayle. 1995b. Indices of climate change for the United States. *Bulletin of the American Meteorological Society* 77:279-292.

Karl, T.R., R.W. Knight, and N. Plummer. 1995a. Trends in high-frequency climate variability in the twentieth century. *Nature* 377:217-220.

Karlson, R.H. and H.V. Cornell. 1999. Integration of local and regional perspectives on the species richness of coral assemblages. *American Zoologist* 39:104-112.

Kennedy, V.S. 1990. Anticipated effects of climate change on estuarine and coastal fisheries. *Fisheries* 15:16-25.

Kerr, E.A. 1999. Thermodynamic control of hurricane intensity. *Nature* 401:665-669.

Kerr, R.A. 1999. Big El Niños ride the back of slower climate change. *Science* 283:1108-1109.

Kinsey, D.W. 1988. Coral reef system response to some natural and anthropogenic stresses. *Galaxea* 7:113-128.

Kleypas, J.A., R.W. Buddemeier, D. Archer, J.P. Gattuso, C. Langdon, and B.N. Opdyke. 1999a. Geochemical consequences of increased atmospheric carbon dioxide on coral reefs. *Science* 284:118-120.

Kleypas, J.A., J.W. McManus, and L.A.B. Menez. 1999b. Environmental limits to coral reef development: Where do we draw the line? *American Zoologist* 39:146-159.

Knutson, T.R. and R.E. Tuleya. 1999. Increased hurricane intensities with CO_2-induced warming as simulated using the GFDL hurricane prediction system. *Climate Dynamics* 15:503-519.

Knutson, T.R., R.E. Tuleya, and Y. Kurihara. 1998. Simulated increase of hurricane intensities in a CO_2 warmed climate. *Science* 279:1018-1020.

Komar, P.D. 1986. The 1982-83 El Niño and erosion on the coast of Oregon. *Shore and Beach* 54:3-12.

Komar, P.D. 1998. The 1997-98 El Niño and erosion on the Oregon coast. *Shore and Beach* 66:33-41.

Komar, P.D. and D.B. Enfield. 1987. Short-term sea-level changes and coastal erosion. *In* D. Nummedal, O.H. Pilkey, and J.D. Howard (Eds.). *Sea-level Fluctuation and Coastal Evolution*. Society of Economic Paleontologists and Mineralogists Special Publication 41:17-27.

Krabill, W., W. Abdalati, E. Frederik, S. Manizade, C. Martin, J. Sonntag, R. Swift, R. Thomas, W. Wright, and J. Yungel. 2000. Greenland Ice Sheet: High-elevation balance and peripheral thinning. *Science* 289:428-430.

Kruse, G.H. 1998. Salmon run failures in 1997-98: A link to anomalous oceanic conditions. *Alaska Fisheries Research Bulletin* 5:55-63.

Kuhn, N.L., I.A. Mendelssohn, and D.J. Reed. 1999. Altered hydrology effects on Louisiana salt marsh function. *Wetlands* 19:617-626.

Lambert, S.J. 1995. The effect of enhanced greenhouse warming on winter cyclone frequencies and strengths. *Journal of Climate* 8:1447-1452.

Landsea, C.W. and W.M. Gray. 1992. The strong association between western Sahel monsoon rainfall and intense Atlantic hurricanes. *Journal of Climate* 5:435-453.

Landsea, C.W., N. Nicholls, W.M. Gray, and L.A. Avila. 1996. Downward trends in the frequency of intense Atlantic hurricanes during the past five decades. *Geophysical Research Letters* 23:1697-1700.

Lasker, R. 1975. Field criteria for the survival of anchovy larvae: The relation between inshore chlorophyll maximum layers and successful first feeding. *Fisheries Bulletin* 73:847-855.

Leatherman, S.P. 1989. Nationwide cost of nourishing recreational beaches in response to sea-level rise. *Potential Effects of Global Climate Change on the United States*. U.S. EPA, Washington, DC.

Lee, T.M., C. Rooth, E. Williams, M. McGowan, A. Szmant, and M.E. Clarke. 1992. Influence of Florida current, gyres and wind-driven circulation on transport of larvae and recruitment in the Florida Keys coral reefs. *Continental Shelf Research* 12:971-1002.

Lee, T.N. and E. Williams. 1999. Mean distribution and seasonal variability of coastal currents and temperature in the Florida Keys with implications for larval recruitment. *Bulletin of Marine Science* 64:35-56.

Levitus, S., J.I. Antonov, T.P. Boyer, and C. Stephans. 2000. Warming of the world ocean. *Science* 287:2225-2229.

Light, S.S. and J.W. Dineen. 1994. Water control in the Everglades: A historical perspective. *In* S.M. Davis, and J.C. Ogden (Eds.). *Everglades: The Ecosystem and Its Restoration*. St. Lucie Press, Delray Beach, FL. pp. 47-84.

Lirman, D. 1997. *Disturbance Ecology of the Caribbean Coral* Acropora palmata. Ph.D. dissertation, Rosenstiel School of Marine and Atmospheric Science, University of Miami, FL. 250 pp.

Lluch-Belda, D.S., H. Vasquez, D.B. Lluch-Cota, C.A. Salinas-Zavela, and R.A. Schwartzlose. 1992. The recovery of the California sardine as related to global change. *California Cooperative Oceanic and Fisheries Investigations Reports* 33:50-59.

Louisiana Coastal Wetlands Conservation and Restoration Task Force and Wetlands Conservation and Restoration Authority. 1998. *Coast 2050: Toward a Sustainable Coastal Louisiana*. Louisiana Department of Natural Resources, Baton Rouge, LA.

MacKenzie, B.R., T.J. Miller, S. Cry, and W.C. Leggett. 1994. Evidence for a dome-shaped relationship between turbulence and larval fish ingestion rates. *Limnology and Oceanography* 39:1790-1799.

Macklin, S.A. 1999. *Report on the FOCI International Workshop on Recent Conditions in the Bering Sea*. NOAA ERL Special Report.

Malakoff, D. 1999. Death by suffocation in the Gulf of Mexico. *Science* 281:190-192.

Malcolm, J.R. and A. Markham. 1997. *Climate Change Threats to the National Parks and Protected Areas of the United States and Canada*. World Wildlife Fund, Washington, DC.

Malone, T.C. 1977. Environmental regulation of phytoplankton productivity in the lower Hudson estuary. *Estuarine and Coastal Marine Science* 5:57-171.

Manabe, S. and R.J. Stouffer. 1993. Century-scale effects of increased atmospheric CO_2 on the ocean-atmosphere system. *Nature* 364:215-218.

Mann, K.H. and J.R.N. Lazier. 1996. *Dynamics of Marine Ecosystems.* 2^{nd} Ed. Blackwell Science, London.

Mantua, N.J., S.R. Hare, Y. Shang, J.M. Wallace, and R.C. Francis. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin of the American Meteorological Society* 78:1069-1079.

Markham, A. 1996. Potential impacts of climate change on ecosystems: A review of implications for policymakers and conservation biologists. *Climate Research* 6:179-191.

Marshall, C.T. and K.T. Frank. 1999. Implications of density-dependent juvenile growth for compensatory recruitment regulation of haddock. *Canadian Journal of Fisheries and Aquatic Sciences* 56:356-363.

Maslanik, J.A., M.C. Serreze, and T. Agnew. 1999. On the record reduction in 1998 Western Arctic Sea-ice cover. *Geophysical Research Letters* 26:1905-1908.

Mathews-Amos, A. and E.A. Berntson. 1999. *Turning Up the Heat: How Global Warming Threatens Life in the Sea*. Marine Conservation Biology Institute. Available online: http://www.mcbi.org/.

McBride, R., S. Penland, B. Jaffe, J. Williams, A. Sallenger, and K. Westphal. 1989. Erosion and deterioration of the Isles Dernieres barrier island arc, Louisiana. *Transactions of the Gulf Coast Association of Geological Societies* 39: 431-444.

McGowan, J.A., D.R. Cayan, and L.M. Dorman. 1998. Climate, ocean variability and ecosystem response in the Northeast Pacific. *Science* 281:210-217.

McKee, K.L. and I.A. Mendelssohn. 1989. Response of a freshwater marsh plant community to increased salinity and increased water level. *Aquatic Botany* 34:301-316.

McMillan, R.L. and C.L. Sherrod. 1986. The chilling tolerance of black mangrove, *Avicennia germinans*, from the Gulf of Mexico coast of Texas, Louisiana and Florida. *Contributions in Marine Science* 29:9-16.

Meehl, G.A., F. Zwiers, J. Evans, T. Knutson, L. Mearns, and P. Whetton. 2000. Trends in extreme weather and climate events: issues related to modeling extremes in projections of future climate change. *Bulletin of the American Meteorological Society* 81:427-436.

Meeuwig, J.J., J.B. Rasmussen, and R.H. Peters. 1998. Turbid waters and clarifying mussels: Their moderation of empirical chl:nutrient relations in estuaries in Prince Edward Island, Canada. *Marine Ecology Progress Series* 171:139-150.

Miller, M.L. and J. Auyong. 1991. Coastal zone tourism: A potent force affecting environment and society. *Marine Policy* 15:75-99.

Miller, S.L. and M.P. Crosby. 1998. *The Extent and Condition of U.S. Coral Reefs. NOAA's State of the Coast Report*. National Oceanic and Atmospheric Administration, Silver Spring, MD. Available online: http://state-of-coast.noaa.gov/bulletins/html/crf_08/crf.html.

Milliman, J.D. 1993. Coral reefs and their responses to global climate change. *In* G.A. Maul (Ed.). *Climatic Change in the Intra-American Seas.* United Nations Environment Programme and Intergovernmental Oceanographic Commission Edward Arnold, London, UK. pp. 306-321.

Mitsch, W.J., J.W. Day, Jr., J. Wendell Gilliam, P.M. Groffman, D.L. Hey, G.W. Randall, and N. Wang. 1999. Reducing nutrient loads, especially nitrate-nitrogen, to surface water, groundwater, and the Gulf of Mexico. *NOAA Coastal Ocean Program Decision Analysis Series No. 19*. National Oceanic and Atmospheric Administration, Silver Spring, MD.

Mitsch, W.J. and J.G. Gosselink. 1993. *Wetlands.* 2nd ed. Van Nostrand Reinhold, New York, NY.

Moffat, A.S. 1998. Global nitrogen overload problem grows critical. *Science* 279:988-989.

Moore, H.B. 1972. Aspects of stress in the tropical marine environment. *Advances in Marine Biology* 10:217-269.

Moore, M.V., M.L. Pace, J.R. Mather, P.S. Murdoch, R.W. Howarth, C.L. Folt, C.Y. Chen, H.F. Hemond, P.A. Flebbe, and C.T. Driscoll. 1997. Potential effects of climate change on freshwater ecosystems of the New England/Mid-Atlantic region. *Hydrological Processes* 11:925-947.

Mrosovsky, N. and J. Provancha. 1992. Sex ratio of hatchling loggerhead sea turtles: Data and estimates from a five-year study. *Canadian Journal of Zoology* 70:530-538.

Mrosovsky N. and C.L. Yntema. 1980. Temperature dependence on sexual differentiation in sea turtles: Implications for conservation. *Biological Conservation* 18:271-280.

Murowski, S.A. 1993. Climate change and marine fish distributions: forecasting from historical analogy. *Transactions of the American Fisheries Society* 122:657-658.

Myers, J.P. 1983. Conservation of migrating shorebirds: Staging areas, geographical bottlenecks and regional movements. *American Birds* 37:23-25.

Myers, R.S., G.P. Shaffer, and D.W. Llewellyn. 1995. Bald cypress (*Taxodium Distichum* [L.] Rich.) restoration in southeast Louisiana: The relative effects of herbivory, flooding, competition, and macronutrients. *Wetlands* 15:141-148.

NPA Data Services, Inc. 1999. *Analytic Documentation of Three Alternate Socioeconomic Projections. 1997-2050*. Washington, DC.

Najjar, R.G., H.A. Walker, P.J. Anderson, E.J. Barro, R.J. Bord, J.R. Gibso, V.S. Kennedy, C.G. Knight, J.P. Megonigal, R.E. O'Connor, C.D. Polsky, N.P. Psuty, B.A. Richards, L.G. Sorenson, E.M. Steele, and R.S. Swanson. 2000. The potential impacts of climate change on the mid-Atlantic coastal region. *Climate Research* 14:219-233.

National Assessment Synthesis Team (NAST). 2000. *Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change*. U.S. Global Change Research Program, Washington, DC. 145 pp.

National Marine Fisheries Service. 1998. *Status of Fisheries of the United States: A Report to Congress*. National Oceanic and Atmospheric Administration, Silver Spring, MD. 88 pp.

National Marine Fisheries Service. 1999. *Our Living Oceans: Report on the Status of U.S. Living Marine Resources, 1999*. National Oceanic and Atmospheric Administration, Silver Spring, MD. NOAA Technical Memorandum NMFS-F/SPO-41.

National Oceanographic and Atmospheric Administration (NOAA). 1985. *Climatography of the United States No. 20, Climate Summaries for Selected Sites, 1951-1980, Florida*. National Climatic Data Center, Asheville, NC.

National Oceanic and Atmospheric Administration (NOAA). 1998. *Year of the Ocean Discussion Papers*. National Oceanic and Atmospheric Administration, Silver Spring, MD.

National Research Council (NRC). 1993. *Managing Wastewater in Coastal Urban Areas.* National Academy Press, Washington, DC.

National Research Council (NRC). 1994. *Priorities for Coastal Ecosystem Science*. National Academy Press, Washington, DC.

National Research Council (NRC). 1996a. *Understanding Marine Biodiversity.* National Academy Press, Washington, DC.

National Research Council (NRC). 1996b. *Upstream: Salmon and Society in the Pacific Northwest*. National Academy Press, Washington DC.

National Research Council (NRC). 1996c. *The Bering Sea Ecosystem*. National Academy Press, Washington DC.

National Research Council (NRC). 1997a. *Striking a Balance: Improving Stewardship of Marine Areas.* National Academy Press, Washington DC.

National Research Council (NRC). 1997b. *The Global Ocean Observing System: Users, Benefits and Priorities*. National Academy Press, Washington DC.

National Research Council (NRC). 1998. *Decade-to-Century-Scale Climate Variability and Change: A Science Strategy*. National Academy Press, Washington DC.

National Research Council (NRC). 1999. *Sustaining Marine Fisheries*. National Academy Press, Washington DC.

National Research Council (NRC). 2000. *Clean Coastal Waters: Understanding and Reducing the Effects of Nutrient Pollution*. National Academy Press, Washington, DC.

Natural Resources Defense Council. 1997. *Testing the Waters VII: How Does Your Vacation Beach Rate?* NRDC, New York, NY.

Neumann, J.E., G. Yohe, R. Nicholls, and M. Maino. 2000. *Sea-Level Rise and Global Climate Change: A Review of Impacts to U.S. Coasts.* Pew Center on Global Climate Change, Arlington, VA.

Niebauer, H.J. 1988. Effects of El Niño-Southern Oscillation and North Pacific weather patterns on interannual variability in the subarctic Bering Sea. *Journal of Geophysical Research* 93:5051.

Niebauer, H.J. 1991. Physical oceanographic interactions at the edge of the Arctic ice pack. *Journal of Marine Systems* 2:209-232.

Nixon, S.W. 1988. Physical energy inputs and the comparative ecology of lake and marine ecosystems. *Limnology and Oceanography* 33:1005-1025.

Nixon, S.W. 1995. Coastal marine eutrophication: A definition, social causes and future concerns. *Ophelia* 41:199-219.

Noel, J.M., A. Maxwell, W.J. Platt, and L. Pace. 1995. Effects of Hurricane Andrew on cypress (*Taxodium distichum* var. *nutans*) in south Florida. *Journal of Coastal Research* Special Issue 24:184-196.

Nyman, J.A., C.R. Crozier, and R.D. DeLaune. 1995. Roles and patterns of hurricane sedimentation in an estuarine marsh landscape. *Estuarine, Coastal and Shelf Science* 40:665-679.

Obeysekera, J., J. Browder, L. Hornung, and M.A. Harwell. (in press). The natural South Florida system I: Climate, geology, and hydrology. *Ecological Applications*.

O'Neil, T. 1949. *The Muskrat in the Louisiana Coastal Marshes*. Louisiana Wildlife and Fisheries Commission, New Orleans, LA.

Opdyke, B.N. and R.W. Buddemeier. (submitted). Anthropogenic CO_2 addition and future tropical surface water chemistry: A comparison to the past 70 million years. *Geochemistry, Geophysics, Geosystems.*

Oppenheimer, M. 1998. Global warming and the stability of the West Antarctic Ice Sheet. *Nature* 393:325-332.

Orson, R.A., R.S. Warren, and W.A. Niering. 1998. Interpreting sea-level rise and rates of vertical marsh accretion in a Southern New England tidal salt marsh. *Estuarine, Coastal and Shelf Science* 47:419-429.

Park, R.A., M.S. Trehan, P.W. Mausel, and R.C. Howe. 1989. The effects of sea-level rise on U.S. coastal wetlands. *Potential Effects of Global Climate Change on the United States.* U.S. Environmental Protection Agency, Washington, DC.

Penland, S., J. Suter, and R. Boyd. 1988. The transgressive depositional systems of the Mississippi River System delta plain: A model for barrier shoreline and shelf sand development. *Journal of Sedimentary Petrology*. 58:932-949.

Peterson, D., D. Cayan, J. DiLeo, M. Noble, and M. Dettinger. 1995. The role of climate in estuarine variability. *American Scientist* 83:58-67.

Pethick, J.S. 1981. Long-term accretion rates on tidal salt marshes. *Journal of Sedimentary Petrology.* 51:571-77.

Pezeshki, S.R. and R.D. DeLaune. 1993. Effects of soil hypoxia and salinity on gas exchange and growth of *Spartina patens*. *Marine Ecology Progress Series* 96:75-81.

Pezeshki, S.R., R.D. DeLaune, and W.H. Patrick, Jr. 1987b. Response of the freshwater marsh species, *Panicum hemitomon* Schult., to increased salinity. *Freshwater Biology* 17:195-200.

Pielke, Jr., R.A. and R.A. Pielke, Sr. 1997. *Hurricanes: Their Nature and Impacts on Society.* John Wiley and Sons, New York, NY.

Pielke, Jr., R.A. and R.A. Pielke, Sr. 1997. Vulnerability to hurricanes along the U.S. Atlantic and Gulf Coasts: Considerations of the use of long-term forecasts. *In* H.F. Diaz and R.S. Pulwarty (Eds.). *Hurricanes: Climate and Socioeconomic Impacts.* Springer, New York, NY. pp. 147-184.

Pilkey, O.H. and K.L. Dixon. 1996. *The Corps and the Shore*. Island Press, Washington, DC.

Pittock, A.B. 1999. Coral reefs and environmental change: Adaptation to what? *American Zoologist* 39:10-29.

Polovina, J.J., G.T. Mitchum, and G.T. Evans. 1995. Decadal and basin scale-variation in mixed layer depth and the impact on biological production in the Central and North Pacific 1960-88. *Deep Sea Research* 42:1701-1716.

Pool, D.L., S.C. Snedaker, and A.E. Lugo. 1977. Structure of mangrove forests in Florida, Puerto Rico, Mexico, and Costa Rica. *Biotropica* 9:195-212.

Postma, H. 1980. Sediment transport and sedimentation. *In* E. Olausson and I. Cato (Eds.). *Chemistry and Biogeochemistry of Estuaries.* Wiley Publishers, New York, NY. pp. 153-187.

Pugh, D.T and G.A. Maul. 1999. Coastal sea-level prediction for climate change. *In* C.N.K. Mooers (Ed.). *Coastal and Estuarine Studies 56: Coastal Ocean Prediction*. American Geophysical Union. pp. 377-404.

Rabalais, N.N., R.E. Turner, D. Justi , Q. Dortch, and W.J. Wiseman, Jr. 1999. *Characterization of Hypoxia. NOAA Coastal Ocean Program Decision Analysis Series No. 15.* National Oceanic and Atmospheric Administration, Silver Spring, MD.

Radovich, J. 1982. The collapse of the California sardine fishery: What have we learned? *California Cooperative Oceanic Fisheries Investigations Reports* 23:56-78.

Ray, G.C., B.P. Hayden, A.J. Bulger, Jr., and M.G. McCormick-Ray. 1992. Effects of global warming on the biodiversity of coastal-marine zones. *In* R.L. Peters and T.E. Lovejoy (Eds.). *Global Warming and Biological Biodiversity.* Yale University Press, New Haven, CT.

Reed, D.J. 1990. The impact of sea-level rise on coastal salt marshes. *Progress in Physical Geology* 14:24-40.

Reed, D.J. 1995. The response of coastal marshes to sea-level rise: Survival of submergence. *Earth Surface Processes and Landforms* 20:39-48.

Reid, W.V. and M.C. Trexler. 1992. Responding to potential impacts of climate change on U.S. coastal biodiversity. *Coastal Management* 20:117-142.

Rheinhardt, R.D. and C. Hershner. 1992. The relationship of below-ground hydrology to canopy composition in five tidal freshwater swamps. *Wetlands* 12:208-16.

Robblee, M.B., T.R. Barber, P.R. Carlson, Jr., M.J. Durako, J.W. Fourqurean, L.K. Muehlstein, D. Porter, L.A. Yarbro, R.T. Zieman, and J.C. Zieman. 1991. Mass mortality of the tropical seagrass *Thalassia testudinum* in Florida Bay (USA). *Marine Ecology Progress Series* 71:297-299.

Robertson, Jr., W.J. 1962. Fire and vegetation in the Everglades. *Proceedings of the Tall Timbers Fire Ecology Conference* 1:67-80.

Roemmich, D. and J. McGowan, 1995. Climatic warming and the decline of zooplankton in the California Current. *Science* 267:1324-1326.

Roessler, M.A. and D.C. Tabb. 1974. *Studies on Effects of Thermal Pollution in Biscayne Bay, Florida*. EPA 660/3-74-014. U.S. Environmental Protection Agency Office of Research and Development, Washington, DC. 145 pp.

Roth, L.C. 1992. Hurricanes and mangrove regeneration: Effects of Hurricane Joan, October 1988, on the vegetation of Isla del Venado, Bluefields, Nicaragua. *Biotropica* 24:375-384.

Rothrock, D.A., Y. Yu, and G.A. Maykut. 1999. Thinning of the Arctic sea-ice cover. *Geophysical Research Letters* 26:3469-3472.

Royer, T.C. 1982. Coastal freshwater discharge in the Northeast Pacific. *Journal of Geophysical Research* 87:2,017-2,021.

Rozema, J., F. Dorel, R. Janissen, G.M. Lessen, R.A. Broekman, W.J. Arp, and B.G. Drake. 1991. Effect of elevated atmospheric CO_2 on growth, photosynthesis and water relations of salt marsh grass species. *Aquatic Botany* 39:45.

Rozema, J., G.M. Lenssen, R.A. Broekman, and W.P. Arp. 1990. Effects of atmospheric carbon dioxide enrichment on salt-marsh plants. *In* J.J. Beukema, W.J. Wolff, and J.J.W.M. Brouns (Eds.). *Expected Effects of Climatic Change on Marine Coastal Ecosystems.* Amsterdam, The Netherlands. pp. 49-54.

Ruggiero, P., P. Komar, W. McDougal, and R. Beach. 1996. Extreme water levels, wave runup and coastal erosion. *Proceedings 25th International Coastal Engineering Conference*. pp. 2793-2805.

Sagarin, R.D., J.P. Barry, S.E. Gilman, and C.H. Baxter. 1999. Climate-related change in an intertidal community over short and long time scales. *Ecological Monographs* 69:465-490.

Sallenger, A.H. (in press). Storm impact scale for barrier islands. *Journal of Coastal Research*.

Sammarco, P.W. 1994. Larval dispersal and recruitment processes in Great Barrier Reef corals: Analysis and synthesis. *In* P.W. Sammarco and M.L. Heron (Eds.). *The Bio-Physics of Marine Larval Dispersal: Coastal and Estuarine Studies*. American Geophysical Union, Washington, DC. pp. 35-72.

Sarmiento, J.L. and C. Le Quere. 1996. Oceanic carbon dioxide uptake in a model of century-scale global warming. *Science* 274:1346-1350.

Sasser, C.E. 1994. *Vegetation Dynamics in relation to Nutrients in Floating Marshes in Louisiana, USA*. Ph.D. Dissertation. Utrecht University.

Sax, J.L. 1991. The fate of wetlands in the face of rising sea levels: A strategic proposal. UCLA *Journal of Environmental Law and Policy* 9:143-148.

Schneider, S. and R. Chen. 1980. Carbon dioxide warming and coastline flooding: Physical factors and climatic impact. *Annual Energy Review* 5:107-140.

Short, F.T. and H.A. Neckles. 1998. The effects of global climate change on seagrasses. *Aquatic Botany* 63:169-196.

Siegenthaler, U. and J.L. Sarmiento. 1993. Atmospheric carbon dioxide and the ocean. *Nature* 365:119-125.

Slater, H.H., W.J. Pratt, D.B. Baker, and H.A. Johnson. 1995. Effects of Hurricane Andrew on damage and mortality of trees in subtropical hardwood hammocks of Lone Pine Key, Everglades National Park, Florida, USA. *Journal of Coastal Research* Special Issue 21:197-207.

Smart, M. 1987. International conventions. *In* N.C. Davidson and M.W. Pienkowski (Eds.). *The Conservation of International Flyway Populations of Waders.* Wader Study Group Bull. 49, Suppl./IWRB Special Publ. 7.

Smith, S.V. and R.W. Buddemeier. 1992. Global change and coral reef ecosystems. *Annual Reviews of Ecology and Systematics* 23:89-118.

Smith, S.V., W.J. Kimmerer, E.A. Laws, R.E. Brock, and T.W. Walsh. 1981. Kaneohe Bay sewage diversion experiment: Perspectives on ecosystem responses to nutritional perturbation. *Pacific Science* 35:279-402.

Snedaker, S.C. 1993. Impact on mangroves. *In* G.A. Maul (Ed.). *Climatic Change in the Inter-Americas Sea.* United Nations Environment Programme and Intergovernmental Oceanographic Commission Edward Arnold, London, UK. pp. 282-305.

Snedaker, S.C. 1995. Mangroves and climate change in the Florida and Caribbean region: Scenarios and hypotheses. *Hydrobiologia* 295:43-49.

Snedaker, S.C., J.F. Meeder, M.S. Ross, and R.G. Ford. 1994. Discussion of mangrove ecosystem collapse during predicted sea-level rise: Holocene analogues and implications. *Journal of Coastal Research* 10:497-498.

Solecki, W.D., J. Long, C. Harwell, V. Myers, E. Zubrow, T. Ankersen, C. Deren, C. Feanny, R. Hamann, L. Hornung, C. Murphy, and G. Snyder (in press). Human-environment interactions in South Florida's Everglades region: Systems of ecological degradation and restoration. *Ecological Applications*.

Solomon, A.S. 1986. Transient responses of forests to CO_2-induced climate change: Simulation modeling experiments in eastern North America. *Oecologia* 68:567-579.

Sousounis, P. 2000. A synoptic assessment of climate change model output: Explaining the differences and similarities between the Canadian and Hadley climate models. *Eleventh Symposium on Global Change Studies*, 80th American Meteorological Society Annual Meeting, Long Beach, CA.

Spalding, M., F. Blasco, and C. Field. 1997. *World Mangrove Atlas*. International Society for Mangrove Ecosystems, Okinawa, Japan. 178 pp.

Spalding, M.D. and A.M. Grenfell. 1997. New estimates of global and regional coral reef areas. *Coral Reefs* 16:225-230.

Stabeno, P.J. 2000. The significance of seasonal wind patterns in forcing biological processes in the eastern Bering Sea. *American Geophysical Union Ocean Sciences Meeting, January, 2000*. San Antonio, TX.

Stirling, I. 1997. The importance of polynyas, ice edges, and leads to marine mammals and birds. *Journal of Marine Systems* 10:9-21.

Strong, A.E., E.J. Kearns, and K.K. Gjovig. 2000. Sea Surface Temperature Signals from Satellites - An Update. *Geophysical Research Letters* 27:1667-1670.

Swenson, E.M. and C.M. Swarzenski. 1995. Water levels and salinity in the Barataria-Terrebonne estuarine system.. *In* D.J. Reed (Ed.). *Status and Trends of Hydrologic Modification, Reduction in Sediment Availability, and Habitat Loss/Modification in the Barataria-Terrebonne Estuarine System.* BTNEP Publ. No. 20, Barataria-Terrebonne National Estuary Program, Thibodaux, LA. 388 pp. plus Appendices. pp. 129-202

Sy, A., M. Rhein, J.N.R Lazier, K.P. Koltermann, J. Meincke, A. Putzka, and M. Bersch. 1997. Surprisingly rapid spreading of newly formed intermediate waters across the North Atlantic Ocean. *Nature* 386:675-679.

Timmerman, A., J. Oberhuber, A. Bacher, M. Esch, M. Latif, and E. Roeckner. 1999. Increased El Niño frequency in a climate model forced by future greenhouse warming. *Nature* 398:694-696.

Titus, J.G. 1990. Greenhouse effect, sea-level rise, and barrier islands: Case study of Long Beach Island, New Jersey. *Coastal Management* 18:65-90..

Titus, J.G. 1998. Rising seas, coastal erosion and the takings clause: How to save wetlands and beaches without hurting property owners. *Maryland Law Review* 57:1279-1399

Titus, J.G. and V.K. Narayanan. 1996. The risk of sea-level rise. *Climatic Change* 33:151-212.

Titus, J.G., R.A. Park, S.P. Leatherman, J.R. Weggel, M.S. Green, P.W. Mausel, S. Brown, C. Gaunt, M. Trehand, and G. Yohe. 1991. Greenhouse effect and sea-level rise: Potential loss of land and the cost of holding back the sea. *Coastal Management* 19:171-204.

Trenberth, K.E. and C.J. Guillemot. 1996. Physical processes involved in the 1998 drought and 1993 floods in North America. *Journal of Climate* 9:1288-1298.

Trenberth, K.E. and T.J. Hoar. 1996. The 1990-1995 El Niño-Southern Oscillation event: Longest on record. *Geophysical Research Letters* 23:57-60.

Tynan, C.T. and D.P. DeMaster. 1997. Observations and predictions of Arctic climatic change: Potential effects on marine mammals. *Arctic* 50:308-322.

U.S. Army Corps of Engineers (COE). 1994. *Central and Southern Florida Project (C&SF) Comprehensive Review Study*. U.S. Army Corps of Engineers, Jacksonville District, Jacksonville, FL.

U.S. Army Corps of Engineers (COE). 1998. *Central and Southern Florida Project (C&SF) Comprehensive Review Study. Draft Integrated Feasibility Report and Programmatic Environmental Impact Statement*. U.S. Army Corps of Engineers, Jacksonville District, Jacksonville, FL.

U.S. Department of State, Bureau of Oceans and International Environmental and Scientific Affairs. 1999. *Coral Bleaching, Coral Mortality, and Global Climate Change*. Available online: http://www.state.gov/www/global/global_issues/coral_reefs/ 990305_coralreef_rpt.html.

U.S. Environmental Protection Agency (USEPA). 1989. *The Potential Effects of Global Climate Change on the United States: A Report to Congress*. Office of Policy, Planning, and Evaluation, Office of Research and Development, Washington, DC.

U.S. Environmental Protection Agency (USEPA). 1995. *Probability of Sea-Level Rise*. Office of Policy, Planning, and Evaluation, Washington, DC. EPA 230-R-95-008.

U.S. Environmental Protection Agency (USEPA). 1996. *National Water Quality Inventory: 1996 Report to Congress*. Available online: http://www.epa.gov/305b/.

U.S. Environmental Protection Agency (USEPA). 1997. *Natural Resource Valuation: A Report by the Nation's Estuary Program*. USEPA, Washington, DC.

U.S. GLOBEC. 1994. *Eastern Boundary Current Program*. U.S. GLOBEC Report. 11. 134 pp.

Valiela, I., P. Peckol, C. D'Avanzo, J. Kremer, D. Hersh, K. Foreman, K. Lajtha, B. Seely, W.R. Geyer, T. Isaji, and R. Crawford. 1998. Ecological effects of major storms on coastal watersheds and coastal waters: Hurricane Bob on Cape Cod. *Journal of Coastal Research* 14:218-38.

Van de Staaij, J., J. Rozema, and M. Stroetenga. 1990. Expected Changes in Dutch Coastal Vegetation Resulting from Enhanced Levels of Solar UV-B. *In* J.J. Beukema, W.J. Wolff, and J.J.W.M. Brouns (Eds.). *Expected Effects of Climatic Change on Marine Coastal Ecosystems.* Amsterdam, The Netherlands. pp. 211-217.

Veron, J.E.N. 1995. *Corals in Space and Time*. UNSW Press, Sydney, Australia. 321 pp.

Vicente, V.P., V.C. Singh, and A.V. Botello. 1993. Ecological implications of potential climatic change and sea-level rise. *In* G.A. Maul (Ed.). *Climatic Change in the Intra-American Seas.* United Nations Environment Programme and Intergovernmental Oceanographic Commission Edward Arnold, London, UK. pp. 262-281.

Vinnikov, K.Y., A. Robock, R.J. Stouffer, J.E. Walsh, C.L. Parkinson, D.J. Cavalieri, J.F.B. Mitchell, D. Garrett, and V.F. Zakharov. 1999. Global warming and Northern Hemisphere sea ice extent. *Science* 286:1934-1937.

Visser, J.M., C.E. Sasser, R.H. Chabreck, and R.G. Linscombe. 1998. Marsh vegetation types of the Mississippi River Deltaic Plain. *Estuaries* 21:818-28.

Vitousek, P.M., J. Aber, S.E. Bayley, R.W. Howarth, G.E. Likens, P.A. Matson, D.W. Shindler, W.H. Schlesinger, and G.D. Tilman. 1997. Human Alteration of the global nitrogen cycle: Sources and consequences. *Ecological Applications* 7:737-750.

Vörösmarty, C.J., P. Green, J. Salisbury, and R.B. Lammers. 2000. Global water resources: Vulnerability from climate change and population growth. *Science* 289:284-288.

Wanless, H.R., R.W. Parkinson, and L.P. Tedesco. 1994. Sea-level control on stability of Everglades wetlands. *In* S.M. Davis, and J.C. Ogden (Eds.). *Everglades: The Ecosystem and Its Restoration*. St. Lucie Press, Delray Beach, FL. pp. 199-223.

Wanless, H.R., L.P. Tedesco, J.A. Risi, B.G. Bischof, and S. Gelsanliter. *The Role of Storm Processes on the Growth and Evolution of Coastal and Shallow Marine Sedimentary Environments in South Florida*. Pre-Congress Field Trip Report, August 11-13, 1995. The 1st SEPM Congress on Sedimentary Geology, August 13-16, 1995. St. Petersburg, FL.

Webb, J.W. 1983. Soil water salinity variations and their effects on *Spartina alterniflora*. *Contributions to Marine Science* 26:1-13.

Weggel, R., S. Brown, and E. Doheny. 1989. The cost of defending developed shorelines along sheltered waters of the United States. *Potential Effects of Global Climate Change on the United States*. U.S. Environmental Protection Agency, Washington, D.C.

Weinreb, M.P., G. Hamilton, S. Brown, and R.J. Koczor. 1990. Nonlinearity corrections in calibration of advanced very high resolution radiometer infrared channels. *Journal of Geophysical Research* 95:7381-7388.

Welch, D.W., Y. Ishida, and K. Nagasawa. 1998. Thermal limits and ocean migrations of sockeye salmon (*Oncorhynchus nerka*): Long-term consequences of global warming. *Canadian Journal of Fisheries and Aquatic Sciences* 55:937-948.

Welch, D.W., Y. Ishida, K. Nagasawa, and J.P. Eveson. 1998b. Thermal limits on the ocean distribution of steelhead trout *(Onchorhynchus mykiss). North Pacific Anadromous Fisheries Commercial Bulletin* 1:394-404.

Weller, G.A. and P.A. Anderson (Eds.). 1998. *Implications of Global Change in Alaska and the Bering Sea Region*. Proceedings of a Workshop, June 3-5, 1997. Center for Global Change and Arctic System Research, University of Alaska, Fairbanks, AK.

Wheeler, P.A., M. Gosselin, E. Sherr, D. Thibault, D.L. Kirchmans, R. Benner, and T.E. Whitledge. 1996. Active cycling of organic carbon in the Central Arctic Ocean. *Nature* 380:697-699.

Wick, G.A., W.J. Emery, and P. Schloessel. 1992. A comprehensive comparison between satellite-measured data and multi-channel seas surface temperature. *Journal of Geophysical Research* 97:5569-5595.

Wigley, T.M.L. 1999. *The Science of Climate Change: Global and U.S. Perspectives*. Pew Center on Global Climate Change, Arlington, VA.

Wilkinson, C. 1998. *Status of the World's Coral Reefs.* Available online: http://www.aims.gov.au/pages/research/reefs/wcr-status/wcr-00.html.

Wilkinson, C., O. Linden, H. Cesar, G. Hodgson, J. Rubens, and A.E. Strong. 1999. Ecological and socioeconomic impacts of 1998 coral mortality in the Indian Ocean: An ENSO impact and a warning of future change? *Ambio* 28:188-196.

Wilkinson, C.R. and R.W. Buddemeier. 1994. *Global Climate Change and Coral Reefs: Implications for People and Reefs.* Report of the UNEP-IOC-ASPEI-IUCN Global Task Team on the Implications of Climate Change on Coral Reefs, Gland, Switzerland, IUCN.

Williams, T.M. 1993. Salt water movement within the water table aquifer following Hurricane Hugo. *Proceedings of the Seventh Biennial Southern Silvicultural Research Conference, Mobile, AL*. 17-19 November 1992. USDA Forest Service, Southern Forest Experiment Station, General Technical Report SO-93. New Orleans, LA. pp. 177-183.

Williams, Jr., E.H., C. Goenaga, and V. Vincente. 1987. Mass bleachings on Atlantic coral reefs. *Science* 238:877-888.

Wolock, D.M. and G.J. McCabe. 1999. Simulated effects of climate change on mean annual runoff in the conterminous United States. *Journal of the American Water Resources Association* 35:1341-1350.

Wood, F.J. 1986. *Tidal Dynamics: Coastal Flooding, and Cycles of Gravitational Force*. Kluwer Academic Publishers, Boston, MA.

Wood, R.A., A.B. Keen, J.F.B. Mitchell, and J.M. Gregory. 1999. Changing spatial structure of the thermohaline circulation in response to atmospheric CO_2 forcing in a climate model. *Science* 399:572-575.

Woodroffe, C.D. 1990. The impact of sea-level rise on mangrove shorelines. *Progress on Physical Geology* 14:483-520.

Woodroffe, C.D. 1992. Mangrove sediments and geomorphology. *In* A.I. Robertson and D.M. Alongi (Eds.). *Tropical Mangrove Ecosystems.* Coastal and Estuarine Studies 41. American Geophysical Union, Washington, DC. pp. 7-41.

Working Group on Sea-Level Rise and Wetland Systems. 1997. Conserving coastal wetlands despite sea-level rise. *Eos: Transactions of the American Geophysical Union* 78:257, 260-263.

Wright, D.G., R.M. Hendry, J.W. Loder, and F.W. Dobson. 1986. *Oceanic Changes Associated with Global Increases in Atmospheric Carbon Dioxide: A Preliminary Report for the Atlantic Coast of Canada*. Canadian Technical Reports on Fisheries and Aquatic Sciences No. 1426.

Yohe, G. 1989. The cost of not holding back the sea. *Journal of Ocean and Shoreline Management* 15:233-255.

Yohe, G. 1990. The cost of not holding back the sea: Toward a national sample of economic vulnerability. *Coastal Management* 18:403-431.

Yohe, G., J. Neumann, P. Marshall, and H. Ameden. 1996. The economic cost of greenhouse induced sea-level rise for developed property in the United States. *Climatic Change* 32:387-410.

Zhang, K., B.C. Douglas, and S.P. Leatherman. 1997. East Coast storm surges provide unique climate record. *Eos Transactions of the American Geophysical Union* 78:389, 396-397.

OTHER TITLES IN THE DECISION ANALYSIS SERIES

1. Able, Kenneth W. and Susan C. Kaiser. 1994. Synthesis of Summer Flounder Habitat Parameters.
2. Matthews, Geoffrey A. and Thomas J. Minello. 1994. Technology and Success in Restoration, Creation and Enhancement of Spartina Alterniflora Marshes in the United States. 2 vols.
3. Collins, Elaine V., Maureen Woods, Isobel Sheifer, and Janice Beattie. 1994. Bibliography of Synthesis Documents on Selected Coastal Topics.
4. Hinga, Kenneth R., Heeseon Jeon, and Noelle F. Lewis. 1995. Marine Eutrophication Review.
5. Lipton, Douglas W., Katherine Wellman, Isobel C. Sheifer, and Rodney F. Weiher. 1995. Economic Valuation of Natural Resources: A Handbook for Coastal Policymakers.
6. Vestal, Barbara, Alison Reiser, et al. 1995. Methodologies and Mechanisms for Management of Cumulative Coastal Environmental Impacts. Part I — Synthesis with Annotated Bibliography, Part II — Development and Application of a Cumulative Impacts Assessment Protocol.
7. Murphy, Michael L. 1995. Forestry Impacts on Freshwater Habitat of Anadromous Salmonids in the Pacific Northwest and Alaska — Requirements for Protection and Restoration.
8. William F. Kier Associates. 1995. Watershed Restoration — A Guide for Citizen Involvement in California.
9. Valigura, Richard A., Winston T. Luke, Richard S. Artz, and Bruce B. Hicks. 1996. Atmospheric Nutrient Inputs to Coastal Areas — Reducing the Uncertainties.
10. Boesch, Donald F., et al. 1997. Harmful Algal Blooms in Coastal Waters: Options for Prevention, Control and Mitigation.
11. McMurray, Gregory R., and Robert J. Bailey, editors. 1998. Change in Pacific Northwest Coastal Ecosystems.
12. Fonseca, Mark S., W. Judson Kenworthy, and Gordon W. Thayer. 1998. Guidelines for the Conservation and Restoration of Seagrasses in the United States and Adjacent Waters
13. Macklin, S. Allen, editor. 1998. Bering Sea FOCI (1991-1997) - Final Report
14. Wiseman, William, editor. 1999. Nutrient Enhanced Coastal Ocean Productivity in the Northern Gulf of Mexico
15. Rabalais, et al. 1999. Characterization of Hypoxia.
16. Diaz, Robert J., and Andrew Solow. 1999. Ecological and Economic Consequences of Hypoxia.
17. Goolsby, Donald A. et al. 1999. Flux and Sources of Nutrients in the Mississippi-Atchafalya River Basin.
18. Brezonik, Patrick L. Victor Bierman, Jr., et al. 1999. Effects of Reducing Nutrient Loads to Surface Waters within the Mississippi River Basin and the Gulf of Mexico.
19. Mitch, William J., et al. 1999. Reducing Nutrient Loads, Especially Nitrate-Nitrogen to Surface Water, Ground Water, and the Gulf of Mexico.
20. Doering, Otto C., et al. 1999. Evaluation of the Economic Costs and Benefits of Methods for Reducing Nutrient Loads

Coastal Sector Contribution to the National Assessment on the Potential consequences of Climate Variability and Change for the United States

The overall goal of the National Assessment is to analyze and evaluate what is know about the potential consequences of climate variability and change for the Nation in the context of other pressures on the public, the environment, and the Nation's resources. The National Assessment process has been broadly inclusive, drawing on inputs from academia, government, the public and private sectors, and interested citizens. Starting with broad public concerns about the environment, the Assessment is exploring the degree to which existing and future variations and changes in climate might affect issues that people care about.

The National Assessment has three major components:

1. Regional analyses: Workshops and assessments are characterizing the potential consequences of climate variability and change in selected regions spanning the U.S. The reports from these activities address the interests of those in the particular regions by focusing on the regional patterns and texture of changes where people live. Most workshop reports are already available (see http://www.nacc.usgcrp.gov) and regional assessment reports, of which this is the first, will become available over the next several months.

2. Sectoral analyses: Workshops and assessments are being carried out to characterize the potential consequences of climate variability and change for major sectors that cut across environmental, economic, and societal interests. The sectoral studies analyze how the consequences in each region affect the Nation, making these reports national in scope and of interest to everyone. The sectors being focused on in this first phase of the ongoing National Assessment include Agriculture, Forests, Human Health, Water, and Coastal Areas and Marine Resources, Publications and assessment reports will start to become available in late 1999.

3. National overview: The National Assessment Synthesis Team has responsibility for summarizing and integrating the findings of the regional and sectoral studies, with the broader literature, and then drawing conclusions about the importance of climate change and variability for the United States. Their report is to be available by spring 2000.

Each of the regional, sectoral, and synthesis activities is being lead by a team comprised of experts, from both the public and private sectors, from universities and government, and from the spectrum of stakeholder communities.

OUR SEAS AND OUR SKIES

30 Years

OF EXCELLENCE AT NOAA

U.S. Department of Commerce
National Oceanic and Atmospheric Administration
National Ocean Service
Center For Sponsored Coastal Ocean Research
Coastal Ocean Program
1315 East West Highway
Silver Spring, Maryland 20910