Confronting Climate Change in the Gulf Coast Region

Prospects for Sustaining Our Ecological Heritage

A REPORT OF

The Union of Concerned Scientists and
The Ecological Society of America

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PREPARED BY

Robert R. Twilley
Eric J. Barron
Henry L. Gholz
Mark A. Harwell
Richard L. Miller
Denise J. Reed
Joan B. Rose
Evan H. Siemann
Robert G. Wetzel
Roger J. Zimmerman

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Executive Summary

From Texas to Florida, the Gulf coast region is rich with ecological resources that support the region's economic wealth. Over time, human activities from dam construction to shoreline development have dramatically altered natural landscapes, waterways, and ecological processes. Pressures from human activities remain the most important agents of ecological change in the region today. Over the century ahead, land-use changes are likely to increase as rapid population growth continues. Global climate change, driven by rising levels of carbon dioxide and other heat-trapping greenhouse gases in the atmosphere, will interact with, and magnify, other human stresses on Gulf Coast ecosystems and the goods and services they provide. *Confronting Climate Change in the Gulf Coast Region* explores the potential risks of climate change to Gulf Coast ecosystems in the context of pressures from land use. Its purpose is to help the public and policymakers understand the most likely ecological consequences of climate change in the region over the next 50 to 100 years and prepare to safeguard the economy, culture, and natural heritage of the Gulf Coast. This summary highlights key findings.

What is the likely climate future for the Gulf Coast region?

Projecting climate changes for the Gulf Coast is challenging because of the complex interplay of regional and global processes that drive the climate here and the natural variability in air and sea-surface temperatures, rainfall, and hurricane activity the region experiences. Nevertheless, the two climate scenarios used in this report both predict warmer temperatures and an increase in the rate of sea-level rise over the next 100 years. Summer high temperatures are projected to rise between 3 and 7°F and winter low temperatures to warm by as much as 5°F to the east and 10°F to the west. This would bring a dramatic increase in the July heat index along the Gulf Coast and a significant decrease in winter cold spells, as well as a northern shift in the frost line.

Global sea-level rise will have a disproportionate effect along the Gulf Coast shoreline because of its flat topography, regional land subsidence, extensive shoreline development, and vulnerability to major storms. Climate models project sea-level rise along the Gulf Coast ranging from over 8 to almost 20 inches in the next century. Taking regional subsidence into account, the relative sea-level rise over the next 100 years could range from 15 inches along most of the Gulf Coast to as much as 44 inches along the Louisiana/Mississippi Delta.

Considerable uncertainty remains about whether the regional climate will become wetter or drier in the future. Because future trends in rainfall, runoff, and consequent soil moisture are critical to human and ecological well-being in the Gulf Coast, we believe the most prudent approach is to assess the potential impacts of both scenarios. Changes in vital climate-related phenomena such as stream flow and wildfire frequency will depend on the balance of rainfall received and moisture lost to evaporation in a warming climate in conjunction with human intervention and management. In major rivers such as the Mississippi, water flows will be determined by rainfall trends in watersheds far upstream from the Gulf Coast, as well as by massive human-engineered flood control structures.

Other vital but difficult to predict climate-driven changes include potential shifts in El Niño/La Niña cycles, hurricanes, storms, and coastal ocean currents. Even if storm intensities remain constant, however, disturbance from coastal flooding and erosion will increase because rising sea levels will generate higher storm surges even from minor storms.

What might these changes mean for Gulf Coast ecosystems and the goods and services they provide?

The ecological impacts of climate change will have important implications for the health and well-being of human populations as well as other goods and services that ecosystems provide to society. Global warming will have particularly important impacts on the region's water resources. Gulf Coast ecosystems are linked by the flow of water from the uplands through freshwater lakes, rivers, and wetlands to the coastal and marine systems downstream. Vast wetland areas, especially in the central and eastern parts of the region, require periods of flooding to maintain healthy habitats and sustain food webs. While there remains uncertainty about how global warming will affect rainfall, stream flow, soil moisture, and overall water availability, human consumption of water resources is almost certain to increase as a result of the region's population growth. If climate change results in reduced runoff and lower groundwater levels for parts of the year, the consequence could be a shortage of water to satisfy both ecosystem needs and the growing and competing human demands. Besides direct water shortages, the range of impacts could include the following:

- Permanent reductions of freshwater flows in rivers from both human activities and climate change could substantially reduce biological productivity in Mobile Bay, Apalachicola Bay, Tampa Bay, and the lagoons of Texas.
- More frequent or longer lasting droughts and reduced freshwater inflows could increase the incidence of extreme salt concentrations in coastal ecosystems, resulting in a decline of valuable habitats such as the mangroves and seagrasses in Florida Bay or South Texas lagoons.
- A drier climate along the Gulf Coast combined with such activities as dredging, constructing reservoirs, diverting surface water, and pumping groundwater could accelerate local subsidence and sinkhole formation in areas underlain by limestone.
- Changes in soil moisture could shift forest dynamics and composition. For instance, natural pine forests can tolerate lower soil moisture than oak-pine and oak-gum forests.

- The oxygen-poor (hypoxic) waters in the Gulf of Mexico off Louisiana now extend over as much as 8,000 square miles, depending on the amount of nitrate-laden fresh water discharged by the Mississippi River. The complex interaction of nutrient load and amount of runoff make future projections challenging. A 20 percent increase in discharge—as some climate models project—could increase the risk of hypoxia and expand the oxygen-poor "dead zone."

Sea-level rise will also affect the availability and distribution of high-quality fresh water because many Gulf Coast aquifers are susceptible to saltwater intrusion. Sea-level change and coastal storms are naturally occurring phenomena that help shape coastal ecosystems. However, these episodic disturbances, coupled with high rates of land subsidence and increasing human impacts on the coastal environment, will lead to further degradation in coastal ecosystems and damage to human communities. For example:

> Native plants and animals, already stressed and greatly reduced in their ranges, could be put at further risk by warmer temperatures and reduced availability of fresh water.

- The increasing drawdown of surface water systems and underground reservoirs could combine with sea-level rise to increase saltwater contamination of aquifers, particularly near the coast and in large urban areas such as Tampa and Houston.
- Drinking water supplies taken from the Mississippi River for coastal communities such as New Orleans will be more frequently threatened by saltwater intrusion caused by a combination of sea-level rise, land subsidence, and periodic low river flows.
- Wetland loss rates over the next 20 years in coastal Louisiana, due to the combination of sea-level rise and human alterations, will continue to convert land to open water, threatening the region's enormously valuable fisheries, aquaculture and coastal agriculture, as well as navigation and other industries located near the coast. Future wetland loss rates could increase as sea-level rise accelerates in the latter part of the 21st century.
- As a result of human development, interactions of sea-level rise with hurricanes will increasingly disrupt the normal landward migration of barrier islands and contribute to their erosion.
- Whether or not global warming increases the number or intensity of hurricanes, future storm damages are likely to rise substantially because of the increasing amount of development in harm's way and the aggravating impacts of higher sea levels and degraded coastal ecosystems. Predictions of future wave and storm surges accompanying severe hurricanes (categories 3–5) indicate that significant wave heights (between 3 and 6 feet) could reach further inland if barrier islands and wetlands are lost as buffers.
- The coastal systems most vulnerable to sea-level rise include freshwater marshes and forested wetlands in subsiding delta regions, mangroves in limestone areas, coastal marshes with human-altered patterns of water flow, and areas with extensive human development.

Climate changes such as warmer temperatures, fewer freezes, and changes in rainfall or storm frequency will tend to shift the ranges of plant and animals species and alter the makeup of biological communities. With increasing temperature, many invasive tropical species are likely to extend their ranges northward. Native plants and animals, already stressed and greatly reduced in their ranges, could be put at further risk by warmer temperatures and reduced availability of fresh water. The range of potential impacts on species and ecosystems include the following:

- Species that are already endangered such as the Cape Sable seaside sparrow and Florida panther could become more vulnerable as their preferred habitats change or shift with global warming. Current water-management practices and human development create additional challenges for species migration and adaptation.

- In the Big Thicket area of East Texas, known as "the American Ark," diverse forest communities could be threatened by altered growth rates, changes in fire frequency, and intensified invasions by nonnative species such as Chinese tallow trees.
- Extensive open grassland and forest areas in South Texas and South Florida could become more vulnerable to damaging invasion by Chinese tallow trees. Those in South Florida could in addition be threatened by melaleuca and casuarina trees.
- Coastal red mangrove communities might shift further to the north on the Florida and Texas Gulf Coast. Along the Louisiana coast, reduced frost frequency would allow expansion of black mangrove forests.
- Coral reefs off the South Florida coast already endure summer sea-surface temperatures near their maximum tolerance and face heat stress during episodes of elevated temperature, such as those that accompany El Niño events. Rising ocean temperatures will exacerbate that stress.
- In freshwater streams, warmer water temperatures and a longer growing season could reduce habitat for cool-water species, particularly fish, insects, snails, and shellfish. In very shallow water systems, higher temperatures could lead to oxygen-depletion and cause potentially massive die-offs of fish and invertebrates.
- Invasive species threaten both freshwater and coastal aquatic ecosystems, affecting native plants, fish, and shellfish and associated commercial and recreational fisheries.

Climate change will also indirectly affect natural and managed landscapes by changing the intensity and frequency of fires and pest outbreaks. For example:

- Most southern pine plantations are not burned regularly because of management costs and legal liabilities, despite awareness of the need to reduce fuel loads. High fuel loads increase the risk of wildfire, especially if the climate becomes more favorable to intensified fire cycles.
- Increases in drought-related fires would have severe impacts on managed forests and the timber-based economy of the region. Wildfires would also pose substantial risks to nearby human development.
- In contrast, wildfires are critical for maintaining grassland communities such as coastal prairies, and woody plants typically invade prairies that are not mowed or burned. Increased fire frequency should help prairie conservation and the maintenance of grazing lands.
- Warmer average temperatures and milder winters are likely to result in a higher incidence of damage by agricultural and forestry pests such as the Southern Pine bark beetle.

Plant growth and productivity could increase with higher atmospheric concentrations of carbon dioxide (CO_2) and modestly warmer temperatures, as long as rainfall is not reduced. However, increased plant growth in response to higher CO_2 varies among species and higher CO_2 could drive changes in the mix of species and interactions within communities. Further, gains in plant productivity due to increased CO_2 could be countered by other climate-driven changes such as reduced moisture availability, higher ultraviolet-B radiation, limited nutrient availability, increased water stress, increases in pests and fires, and air pollution. For example:

> Climate change will affect natural and managed landscapes by changing the intensity and frequency of fires and pest outbreaks.

- Certain agricultural crops such as corn, sorghum, and rice could become more productive due to higher CO_2 concentrations, assuming other stresses do not counter the fertilizer effects of CO_2.
- If the climate of the Gulf Coast turns drier overall, cotton, soybean, rice, and sorghum productivity could drop without irrigation and citrus production may shrink moderately in Florida.

Global warming will also increase some health risks in the Gulf Coast region. The ability of the health care system to reduce these health risks in the face of climate change, however, is an important consideration in any projections of vulnerability during the 21st century.

- The concentration of air pollutants such as ozone is likely to increase in Gulf Coast cities such as Houston and Galveston. These and other metropolitan areas are already now classified in "severe" noncompliance with federal air quality standards. Ground-level ozone has been shown to aggravate respiratory illnesses such as asthma, reduce lung function, and induce respiratory inflammation.
- Texas is particularly vulnerable to increased frequencies of heat waves, which could increase the number of heat-related deaths and the incidence of heat-related illnesses. However, longer periods of extreme heat can cause problems throughout the region, especially among the ill or elderly and people who cannot afford air conditioning.
- Gastrointestinal diseases, respiratory diseases, and skin, ear, and eye infections can result from eating contaminated fish and shellfish and diseases acquired during the recreational use of coastal waters. Since temperature, rainfall, and salinity all influence the risk of waterborne infectious diseases, this risk may increase with climate change.
- Hotter temperatures, extreme rainfall, and increased runoff can increase populations of disease-carrying insects and boost the potential for transmission of diseases such as malaria and dengue fever. But actual incidences of these diseases will depend primarily on the responsiveness of the public health system and on the adequate maintenance of water-related infrastructure.

How can residents of the Gulf Coast region address the challenge of a shifting climate?

To prevent or minimize the negative impacts and profit from the potential benefits of climate change, citizens and policymakers in the Gulf Coast region can and should take action now. Three basic strategies —mitigation, minimization, and adaptation—can reduce the region's vulnerability to the impacts of climate change and yield significant ecological, economic, and health benefits, even in the absence of major climate disruption. We consider them a prudent and responsible approach to ensuring environmental stewardship of the region's invaluable ecological resources. Because much of the region is held in private land ownership, strategies for dealing with both climatic and human stresses on ecosystems must involve private landowners as well as governmental agencies and other sectors of society.

The primary goal of mitigation is to reduce the magnitude of climate stresses on society and ecosystems. Reducing greenhouse-gas emissions, for instance, can be seen as a type of "insurance policy" that aims at directly reducing the risks of global warming. Clearly, in the Gulf Coast region, where the fossil-fuel industry is the biggest economic sector and where greenhouse-gas emissions are among the highest in the nation, it is critical to find ways to reduce greenhouse-gas emissions without reducing the economic vitality of Gulf states. For example, investment in the region's substantial renewable energy resources (e.g., solar, wind, and biomass) could provide incentives for new technology development and economic diversification while reducing air pollutants and greenhouse gases.

The second strategy is to reduce human disturbances and destruction of ecosystems. Employing "best practices" in land and resource use can minimize ecologically harmful side effects while continuing to provide significant, and often increased, economic benefits. For example, progressive zoning initiatives that integrate different land uses over a smaller area can protect natural resources and open space from suburban sprawl. Wise land-use practices can also help manage coastal areas, and best management practices in agriculture and aquaculture can achieve goals such as water conservation and reduced farm runoff.

Finally, Gulf Coast residents, planners, land managers, and policymakers can act now to minimize the potential impacts of global climate change and better prepare the region to deal with an uncertain future. One of the best ways to deal with uncertainty is to adopt learning-oriented, flexible approaches that include monitoring, periodic review, and adjustment of previous decisions in light of new information—a strategy known as adaptive management. The principal targets for adaptation include water resource management, agriculture and forestry, land and biodiversity conservation, and preparation of coastal communities to respond to sea-level rise and severe coastal storms such as hurricanes.

In addition, much must be done in the Gulf Coast region to raise awareness and understanding of global climate change. This can begin by educating people of all ages about the cultural and ecological heritage at stake. But it must also involve educating them about the fundamentals of ecology and climate, and what drives them to change. Many Gulf residents' livelihoods are inextricably linked to its natural resources, and visitors from around the world come to the Gulf to enjoy and learn about its ecological heritage. Raising people's concern and understanding of climate change would help to mobilize public support for climate protection. This report is intended to begin that process by sketching the scope of the potential impacts of global warming and starting a dialogue about the management and policy choices that will help preserve the Gulf Coast region's ecological and economic wealth.

Gulf Coast residents, planners, land managers, and policymakers can act now to prepare the region to deal with an uncertain future.

CHAPTER
One

Climate and People as Drivers of Ecosystem Change

Introduction

The natural landscapes, waterways, and ecological processes of the Gulf Coast have been significantly altered by human activities ranging from upstream dam construction to shoreline development. Such human-generated stresses will only increase with continuing rapid population growth in the region. Climate changes driven by rising levels of carbon dioxide (CO_2) and other heat-trapping greenhouse gases in the atmosphere will exacerbate these direct human influences on Gulf Coast ecosystems and the goods and services they provide. Increasing CO_2 levels will result in warmer temperatures, which in turn will contribute to an accelerated rise in sea level and to changes in evaporation, precipitation, storms, freshwater runoff, and fire occurrence.

Climate models predict significant temperature increases along the Gulf Coast over the 21st century, with summer highs projected to rise between 3 and 7°F and winter low temperatures to warm by as much as 5°F to the east and 10°F to the west. Over time, these temperature increases will have direct and increasing impacts on Gulf Coast ecosystems and the well-being of the human population, and will also influence changes in other climate factors. These include harder-to-predict changes in rainfall, evapotranspiration, and freshwater runoff. Ecosystems and economic activities vary in their vulnerability to each of these stressors, yet the critical question—and the one subject to the greatest uncertainty—is how these changes will interact with one another and with other ongoing human activities.

Climate models predict significant temperature increases along the Gulf Coast over the 21st century.

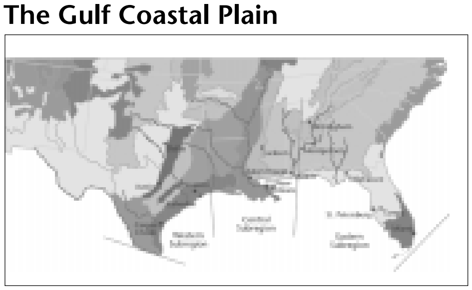
Sea-level rise, for instance, will have a disproportionate effect along the Gulf Coast shoreline because of its flat topography, the regional sinking (subsidence) of the land, sprawling urban developments along the shoreline, and susceptibility to major storms. Sea-level rise will also affect the availability and distribution of high-quality fresh water because many Gulf Coast aquifers (natural groundwater reservoirs) are susceptible to saltwater intrusion. Fresh water is vital for life, ecological health, and economic activity. It also links upland and coastal ecosystems in the region. Whether rainfall increases or decreases in the future, demand on water resources will grow along with the human population, bringing the question of water availability for both natural and managed ecosystems front and center for land and water managers in the future. Changes in the geographic and seasonal distribution of moisture would have significant ecological and economic consequences. In natural ecosystems, for instance, the result could be changes in or even loss of habitats and biodiversity; in forestry and agriculture, the consequence could be an increased need for irrigation or a need to switch to new crop or tree species. Any future reductions in moisture availability could also increase the frequency and intensity of fires, which would impact both natural habitats and human well-being. Other climate-driven changes, such as storminess or changes in the frequency and intensity of El Niño and La Niña events, are likely to exacerbate the problem of how to manage critical water resources.

This report synthesizes the latest scientific understanding of potential climate-change impacts on Gulf Coast ecosystems. Its purpose is to help the public and policymakers understand the key ecological consequences of climate change and prepare to cope with the expected impacts on natural ecosystems, economic activities, and human communities in the Gulf Coast region over the next 50 to 100 years. We first focus on the key factors (or "drivers") that determine the regional climate and discuss possible changes in these drivers as the Earth warms. Next we explore the unique ecosystems of the Gulf Coast, the benefits they provide to humans, and their vulnerability to various aspects of climate change. We also consider the effects of land use and other human pressures that, along with climate change, will affect regional ecosystems. We then discuss the likely consequences of climate change for Gulf Coast ecosystems and for essential ecological goods and services. Finally, we suggest strategies to minimize and adapt to negative impacts and to capitalize on potential benefits from climate change.

The Gulf Coastal Plain

The Gulf Coastal Plain arcs 1,550 miles from the tip of Florida to the tip of Texas (Figure 1). It is bordered by the foothills of the Appalachian Mountains on the northeast and the south central plains on the northwest and extends south to the Gulf of Mexico, including the shoreline and the coastal waters of the continental shelf. These coastal waters are greatly impacted by what happens on the Gulf Coastal Plain and also by ocean currents. While the Mississippi River watershed reaching as far north as Canada is not included in the study area, runoff from the Mississippi River and its tributaries also affects the Gulf Coast region.

FIGURE 1
The Gulf Coastal Plain



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for full-size color image of this figure

The Loop Current bounds the Gulf Coast region on the ocean side. It flows from the coast of Yucatan towards Louisiana, where it splits into an east and west flow outside the shelf regions where it reaches the deeper ocean. The eastward flow of the current exits the Gulf of Mexico through the Florida Straits along the Keys and is connected to the Gulf Stream that flows along the Atlantic coast. At times, fresh water from the Mississippi River becomes mixed with the Loop Current and can be transported great distances along the Florida shelf and out to the Atlantic Gulf Stream passing by the Florida Keys. The impact of the Loop Current on the movement and chemistry of waters on the continental shelves from Mississippi to Florida is not clearly understood, but this current is an important part of the oceanography of the Gulf Coast region.

Geologically, the region divides naturally into two parts, one lying east and the other west of the Mississippi Alluvial Plain.[1] Climatically, the region is divided into three distinct subregions: western, eastern, and central. The western subregion covers Texas; the central subregion reaches from Louisiana across to Mississippi and Alabama; and the eastern subregion includes all of Florida from the Panhandle to the Keys.

The region supports a diversity of terrestrial, freshwater, and coastal ecosystems, despite little variation in terrain. This diversity results from a combination of upland, alluvial (material deposited by flowing waters), and shoreline physical landscapes as well as the convergence of temperate and subtropical climates.

Upland ecosystems* include temperate hardwoods, pine flatwoods (or barrens), and scrub forests, as well as coastal prairies. ***Freshwater wetlands and aquatic ecosystems*** are also dominant features of the Gulf Coast, including swamps, freshwater marshes, lakes, rivers, and springs. The shoreline hosts a variety of ***coastal and nearshore marine ecosystems,*** including barrier islands, mangroves and salt marshes, seagrasses, estuaries and bays, and coral reefs. Few of these ecosystems remain unaltered by human intervention and many have been severely transformed. For example, many of the upland forests have been converted to intensely managed plantations or lost to other uses.

> The diverse mosaic of ecosystems that forms the Gulf Coast landscape is linked by the flow of water.

The diverse mosaic of ecosystems that forms the Gulf Coast landscape is linked by the flow of water. The downstream flow of streams, rivers, and aquifers links the uplands to the shore, and the movement of tidal waters influences coastal ecosystems upstream from the Gulf. Thus, activities at the top of the watershed in the upland systems greatly impact systems downstream. Over the past 50 years, human engineering in the form of levees, dikes, dams, and water-control structures has drastically changed water flow between ecosystems, and climate change will further stress these linkages (Figure 2).

Climate Change and Gulf Coast Ecosystems

Increasing levels of CO_2 in the atmosphere are raising temperatures around the globe and spurring consequent changes in rainfall, evaporation, and runoff (see box p.4). Since the Industrial Revolution, atmospheric CO_2 levels have increased by more than 30 percent, reaching concentrations higher than any observed in the last 420,000 years.[2] These increasing levels of CO_2 and other greenhouse gases have contributed to a rise in global temperatures of about 0.7 to 1.4°F since 1900, with the warmest temperatures occurring in the past 20 years.[3] Growing scientific evidence suggests that much of the rise in temperature over the past 50 years is caused by human activities. Without major reductions in human emissions of these greenhouse gases, scientists project the global temperature could increase between 2.5 and 10.4°F over the next 100 years.[3] Global warming will also affect precipitation, evaporation, and runoff from rivers, but changes in the regional and seasonal distribution of precipitation will vary from one area to another, leaving some areas wetter and others drier.

The changes in atmospheric composition and global temperature that have already been documented have generated international concern that human activities—such as increased consumption of fossil fuels by a growing population and world economy, as well as deforestation and other land-use changes—will adversely affect the climate and natural systems of the Earth. In the United States, government and independent scientists are contributing extensive research to the worldwide effort to better understand these global changes and the implications for regional climate.

FIGURE 2
Water Control Structure

See page 27
for full-size color image of this figure

* Major subregions and ecosystem types highlighted in bold when first mentioned.

Current Scientific Consensus on Climate Change

Addressing the challenges of global climate change requires understanding the natural and human forces that drive climate, including the many complex interactions and feedbacks among climate, biosphere, oceans, and ice formations. It also involves projecting the potential ecological and human impacts of changing regional climates and finding environmentally sound, technologically feasible, cost-effective, and socially acceptable ways to mitigate and adapt to these changes.

These daunting challenges have spawned an unprecedented global research effort and also mobilized policymakers and a wide array of interest groups to speak out on climate change. The range of motivations, passions, and understanding involved has generated heated political debates marked by often contradictory claims about climate change.

To provide a scientifically sound basis for global policymaking, the United Nations Environment Programme and the World Meteorological Organization in 1988 established an international consortium of scientists to review and assess the state of climate change science. This consortium, the Intergovernmental Panel on Climate Change (IPCC), has published three comprehensive assessments (in 1990, 1996, and 2001) and several more narrowly focused assessments, all based on extensive reviews of published and peer-reviewed research on all aspects of global warming.

The multiyear assessments are conducted by thousands of climate change experts—natural and social scientists, economists, and industry and nongovernmental experts on various aspects of global warming—from more than 100 countries. Each assessment undergoes an extensive multistage process of scientific peer review and finally a governmental review to generate what is widely recognized as the most comprehensive and credible evaluation of the state of climate change science. The IPCC reports provide short nontechnical summaries as well as detailed technical reviews of the issues, including frank discussions of issues that remain insufficiently understood and require further investigation. A joint statement by 16 national academies of science[4] and a separate statement by the US National Academy of Sciences[5] recognized the IPCC technical assessments as the most objective and comprehensive overviews of this controversial topic.

The scientific consensus emerging from the IPCC process is that global average temperature has risen by about 1°F over the past 140 years, and the average could rise by another 2.5 to 10.4°F by the end of the 21st century if greenhouse-gas emissions are not dramatically reduced. Other observed changes in the global climate such as increased rainfall and more extreme rainfall events, along with observed impacts of a changing climate—including thawing of mountain glaciers and permafrost, earlier breakup of river and lake ice, rising sea levels, longer growing seasons, and plant and animal range shifts—led the IPCC to conclude that these events create "a collective picture of a warming world that is already seeing the first signs of a changing climate."[3,6] The panel also found evidence of a human role in this change, concluding that human emissions of greenhouse gases "have contributed substantially to the observed warming over the last 50 years."[3]

Policymakers and the public are most concerned, of course, with the impacts of this warming on their parts of the world, since global average changes will not play out uniformly across all regions. Global climate models remain limited in their ability to project regional climate changes confidently. However, as the recent US government-sponsored effort to assess the potential consequences of climate variability and change* suggested, uncertainty in climate projections should not prevent us from assessing the vulnerability of our valued natural and managed ecosystems to likely scenarios of change. That major national undertaking tried to assess, using two global climate models, potential impacts from climate variability and change on particular US regions and sectors in the context of other environmental and economic changes. It also examined possible adaptation options to deal with these impacts.[7] A Southeast regional assessment formed part of this national effort, focusing primarily on the potential socioeconomic impacts of global warming.[8] This report focuses more on potential impacts on ecosystems and on the goods and services they provide to society.

* The *National Assessment of the Potential Consequences of Climate Variability and Change* is the result of a 1990 congressional mandate (P.L. 101-606) to undertake periodic scientific assessments of the potential consequences of global change on the United States in the context of other pressures on the public, the environment, and the nation's resources. The synthesis report of this effort was released in November 2000, while reports from the sectoral and regional component assessments are being released over time (1999–2001).

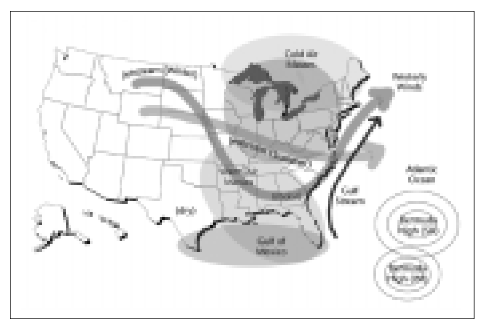
Current Regional Climate

Understanding how the climate of the Gulf Coast may change in the future and why it is difficult to project regional changes with certainty requires understanding the factors that create the current climate. Essentially, the Gulf Coast climate results from the interplay of global factors, including such far away processes as the El Niño/Southern Oscillation (ENSO), and regional factors—specifically, the latitude of the region and the influence of nearby oceans (Figure 3).

The Gulf Coast enjoys a climate uncharacteristic of its latitude, which typically hosts warm, arid, and semi-arid climates. The Gulf of Mexico, Caribbean Sea, and Atlantic Ocean substantially influence the region's climate. The region enjoys mild winters thanks to Gulf of Mexico waters, which moderate winter temperatures. Occasionally, however, these mild winters are punctuated by cold air masses reaching far south from the northern Pacific or the Arctic, bringing low temperatures and freezing conditions. This situation arises when the midlatitudinal jet stream that governs the tracks of storm systems shifts from a more east-west direction into north-south meanders, allowing cold air and winter storms to penetrate southern regions. Summers in the region tend to be hot and humid.

The Gulf and the Atlantic are also major sources of moisture, resulting in greater rainfall than typical for the latitude. A variety of processes bring rainfall to the region, including storm fronts in the winter and spring, and thunderstorms and tropical storms in the summer and fall. Hurricanes and tropical storms, which bring much-needed moisture and can also cause severe flooding, wind damage, and shoreline erosion, occur regularly in late summer and fall.

FIGURE 3
Influences on Gulf Coast Climate



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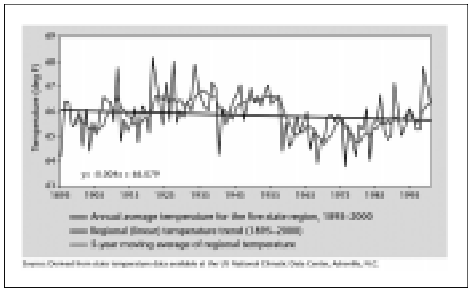
Differences in major atmospheric pressure patterns are also important for the Gulf Coast region. The duration of the wet season in South Florida depends on the relative position and strength of the Bermuda High pressure system during the summer. During the winter, the Bermuda High is small and located south and east of Florida. In the spring, it expands and moves northward. If the Bermuda High fails to weaken in the summer over South Florida, then the wet season rains are delayed, resulting in drought.

FIGURE 4
Gulf Regional Average Temperature (1895–2000)



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Weather events far from the region also influence the Gulf Coast. For example, weather patterns over the large continental landmass to the north impact the region by influencing runoff in the Gulf Coast because the region's rivers, principally the Mississippi River, have watersheds that reach far upstream where winter storms and snowmelt control patterns of runoff.

More remote influences on the climate of the region include the subtropical and tropical ocean circulation, especially the ENSO cycle. El Niño and La Niña episodes represent opposite extremes of the ENSO cycle. El Niño episodes feature the development of abnormally warm sea-surface temperatures across the eastern tropical Pacific, a reversal of the normal condition in which the warmest waters are in the western Pacific northeast of Australia. La Niña episodes feature abnormally cold sea-surface temperatures across the eastern tropical Pacific. The warmer temperatures in the eastern tropical Pacific during El Niños are associated with significant shifts in the position of the jet stream over North America and elsewhere, a phenomenon that brings changes in temperature and rainfall patterns worldwide.

El Niños significantly decrease temperatures in winter (especially in Florida) and spring. During La Niña, fall and winter seasons in the Gulf Coast are warmer, especially in Louisiana, followed by little change in spring, and higher temperatures in summer. El Niño is also linked to substantially increased winter rainfall in the Gulf Coast region. La Niña events, by contrast, are associated with regional drought such as occurred in the central and western Gulf Coast from 1998 to 2000.[9] Moreover, ENSO strongly influences the number of Gulf Coast hurricanes. During La Niña events, the average number of hurricanes coming ashore in the Gulf of Mexico is typically higher than during El Niño or non-ENSO years.[10]

The interaction of these regional climatic features creates notable climate gradients that divide the Gulf Coast into three climatic subregions (Figure 1). The western subregion is warm-temperate to subtropical and changes from semi-arid to humid, moving from west to east. Precipitation ranges from 7 inches each year at the Rio Grande to 47 inches near the Mississippi River. The central subregion is humid and warm. Rainfall in this subregion ranges from 40 to 70 inches per year with little seasonal pattern. The eastern subregion is humid and ranges from warm-temperate to subtropical. A distinct summer wet season and winter dry season characterize this subregion, and precipitation totals vary greatly from year to year, ranging from 33 to 90 inches.

Ocean currents also affect the marine and immediate coastal areas from the Florida Keys west across the Gulf of Mexico. A coastal boundary current comes up from the Yucatan straits and is deflected eastward off the Louisiana shelf and then southward along the length of the Gulf coast of Florida. Coastal currents connect Gulf and Atlantic waters of Florida through Florida Bay. The Atlantic coast of Florida is strongly influenced by the adjacent Gulf Stream. The salinity and other water characteristics of the coastal boundary current in the Gulf are influenced by the discharge patterns of regional rivers but also the Mississippi River (and thus discharge from much of the conterminous United States). Thus human activities such as the discharge of pollutants from agriculture and urban areas into streams are linked with the water quality of coastal waters in the Gulf of Mexico.

Climate Variability and Change over the Past Century

The Gulf Coast, like much of the world, has experienced substantial climatic variability and change over the past 100 years, including changes in air and sea-surface temperature, precipitation, and extreme events. While air temperatures have warmed over most of the United States during the 20th century, air temperatures cooled slightly on average in the Southeast. After a warm period between the 1920s and 1949, the region experienced significant cooling until the late 1960s. Since that time, temperatures have again been increasing (Figure 4).[10] Historical trends in sea-surface temperatures from 1900 to 1991 suggest a pattern of warming along the coast with cooling in the offshore waters.[11]

On average, the Gulf Coast region has seen an increase in rainfall from 1900 until 1992, particularly after 1950.[12] Geographically, changes have varied, with Texas, Alabama, and Mississippi experiencing small increases in rainfall while the rest of the region has seen little change or even decreases. As in other regions of the United States, extreme rainfall events have also increased over the last century.[13] These changes in rainfall are reflected in equally variable regional runoff patterns. With only a few exceptions, no evidence has been found of any clear trends in runoff patterns.[14] The only significant trend is a small decrease in flow in the Rio Grande and Nueces Rivers in southeast Texas between 1972 and 1993.[15]

The average global sea level has risen 0.04–0.08 inches per year (for a total of about 4–8 inches) over the past century.[16] Sea-level rise is more dramatic than the global average along the Gulf Coast due to local subsidence (sinking). Relative sea-level rise rates range from 0.08 inches per year along some parts of the Texas coast to 0.4 inches per year in the Mississippi River delta plain. Around 1930, the average rate of regional sea-level rise began to increase significantly.

> Sea-level rise is more dramatic along the Gulf Coast than the global average due to local subsidence.

Hurricane activity varies from decade to decade and historical records show no discernible global trends in the number or location of tropical storms.[17] After a very active period between 1941 and 1965, the US East Coast and the Gulf of Mexico experienced a relatively calm period until about 1990. Since then, the region seems to be reentering a period of greater hurricane activity (unrelated to human-induced climate change), and the number of intense (category 3, 4, and 5) hurricanes is projected to increase over the next 25 years.[18] While the ENSO cycle and hurricane activity show a clear correlation, ENSO is only one source of climate variability. Further, the impact of global warming on hurricanes is uncertain. Unfortunately, the historical record is too short to clearly link hurricane frequency to climate variability or change.

El Niño events historically occur on average every 3 to 5 years, with strong El Niños occurring once every 42 years. In recent decades, it appears El Niños and La Niñas may be occurring more frequently. There have been two very strong El Niños in the past 18 years and two major La Niñas in the past 11 years (1988 and 1999).

Projections of Future Climate in the Gulf Coast Region

Projecting climate changes for the Gulf Coast region presents a considerable challenge because of the complex interactions of regional and global climate processes. This report relies primarily on two model-based climate scenarios, the same ones used in the recent *US National Assessment* (see appendix).[7] For the southeastern United States, the Hadley climate model generally depicts a warmer, wetter future climate, while the Canadian climate model depicts a hot, dry future climate. Both scenarios agree that the region will see higher temperatures and an increase in sea level. Considerable uncertainty remains, however, about the direction and extent of changes in rainfall in the upland areas. Because future

Summary Comparison of Climate Change Scenarios for the Gulf Coast Region

CLIMATE CHANGE SCENARIOS	**Hadley Centre Model (HadCM2)**	**Canadian Climate Centre Model (CGCM1)**
Overall character of projection	Warm – moist	Hot – dry
Temperature increase		
• Summer maximum	Increase >3°F	Increase >7°F
• Winter minimum	Increase <3°F	Increase ~5°F
• July heat index*	Increase 10–20°F	Increase 20–25°F
Precipitation change		
• Across region	More intense rainfall events; longer dry periods in between rain events	More intense rainfall events; more droughts
• Upland regions, except	Significant increase	Significant decrease
eastern Texas		Modest increase
• Coastal regions, except	Less rainfall	Less rainfall
Central & upper Texas coast	More rainfall	More rainfall
South Florida	No change or less rainfall	More rainfall
Soil moisture change		
• Upland regions, except	Increase	Strong decrease
Central Texas	Strong increase	Increase
• Coastal regions, except	No change or decrease	Decrease
Mississippi River delta	Strong decrease	Strong decrease
South Texas	Strong decrease	Increase
Central/upper Texas coast	Increase	Increase
North Florida	Increase	Decrease
Runoff change		
• Mississippi watershed	Decrease	Increase
• Smaller regional rivers	Some increase	Decrease
Average regional sea-level rise (without subsidence)	8.4 inches	15.6–19.2 inches

* The July heat index is a measure of human comfort based on combining temperature and humidity.

trends in rainfall are critical to human and ecological well-being in the Gulf Coast, we believe the most prudent approach is to assess the potential outcomes of both drier and wetter conditions and the ability of natural and managed systems to cope with change in either direction. Other difficult to predict climate-driven shifts in ENSO events, storms, fire (driven by moisture changes), and coastal ocean currents will also impact the future climate of the Gulf Coast. The table above summarizes the major projections for both models, while subsequent sections provide additional detail.

Air and Coastal Ocean Temperatures

Although climatologists are quite confident about predictions of an increase in global average temperatures, model projections for regions the scale of the Gulf Coast are less certain. Both climate models used in this report, however, project significant increases in surface air temperature in the Gulf Coast by 2100. The Canadian model—which is at the upper end of commonly used GCM models in terms of its sensitivity to increases in greenhouse gases—projects increases in summer maximum temperatures of more than 7°F and increases in winter minimum temperatures approaching 5°F to the east and near 10°F to the west. The Hadley model, which is less responsive to increasing greenhouse gases, projects an increase in summer maximum temperatures of more than 3°F for much of the region and an increase in winter minimum temperatures of less than 3°F.

These temperature changes will change the frequency and magnitude of heat stress and the frequency and severity of Arctic cold fronts reaching the Gulf Coast. The July heat index (a measure of human comfort based on combining temperature and humidity) for the Gulf Coast increases dramatically in both climate models, approaching 20 to 25°F warmer for much of the region in the Canadian model and 10 to 20°F warmer in the Hadley model (see Figure 36). Although the increases in winter minimum temperatures appear to be smaller than the increases in summer maximum temperatures in both models, the changes are likely to be associated with significant decreases in winter cold spells because of the warming predicted for the central United States. A northern shift in the frost line should occur in the Gulf Coast along with the increases in winter temperatures.

Precipitation and Runoff

Globally, higher temperatures should lead to higher rainfall because a warmer climate increases the rate of evaporation and speeds up the hydrologic cycle. Regionally, the outcome is considerably more complex to predict, especially in the Gulf region given the many influences on its climate. A number of factors, as discussed above, influence rainfall. These factors respond differently to a warming climate and many of their interactions remain unclear. Global climate models also do not simulate smaller scale events such as hurricanes or thunderstorms, so projections of future rainfall do not include changes in Gulf precipitation from these types of storms, however important.

Despite these challenges, both climate models project a tendency toward lower rainfall for much of the immediate coastal areas. The exception is a segment of the Texas coast, which both models project should become more humid. Over South Florida, the two models disagree about the direction of change. The similarities in model projections along much of the coastline suggest that the Gulf of Mexico and the different responses of land and sea surfaces to warming may strongly influence changes in coastal precipitation.

The two models give different projections for upland regions in the Gulf Coast. The Canadian model projects large decreases in precipitation and the Hadley model projects large increases; either outcome would have major impacts on upland ecosystems. Other models show increases in rainfall during the growing season and decreases in the dormant season.[19] Interestingly, while precipitation projections from global climate models vary by model and region, many climate models—including the Hadley and Canadian—project more frequent brief, strong summer rainfall events (defined as 2 inches or more over a 24 hour period) with longer dry periods between them, independent of whether average rainfall goes up or down.

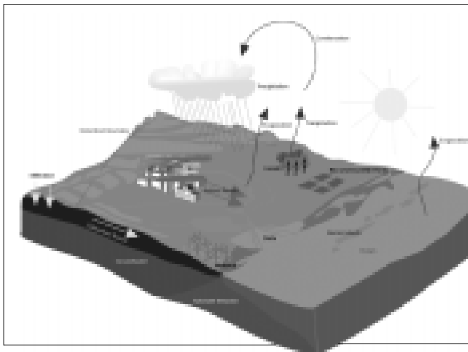
The most important factor for terrestrial and aquatic ecosystems is not just rainfall, but the amount of available moisture. Moisture availability depends on

- changes in evaporation
- the type of rainfall event
  (e.g., slow and steady versus short and intense)
- changes in river runoff

Each is discussed below.

As temperatures rise, evaporation should also increase. On land, this could lead to drier soils unless sufficient rainfall compensates for the loss of moisture. This drying process creates a feedback where less evaporation promotes even warmer temperatures, drier soils, less evaporation, and less rainfall. Conversely, where a sufficiently large increase in rainfall accompanies temperature increase, higher rates of evaporation do not lead to drier soils and the cooling effect of water evaporating from the surface helps moderate the temperature (Figure 5). This is the prediction of the Hadley model, which indicates increases in rainfall, little or no major soil moisture deficits in the Gulf region, and less warming than in the Canadian model. The Canadian model shows greater warming, allowing the atmosphere to evaporate more moisture from the soils than is available from rainfall. Thus, the Canadian model predicts drier soils and much warmer temperatures in all areas of the Gulf Coast except Texas, while the Hadley model predicts smaller decreases in soil moisture in much of the coastal region, and increases in much of Florida and Texas.

FIGURE 5
The Hydrologic Cycle



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The warming at the surface and the changes in moisture with height create the energy for intense rainfall events such as severe thunderstorms. Thus, both models create the conditions for more frequent and intense summer rains with longer dry periods in between, especially along the coast where sufficient moisture is available. Intense rainfall events have already increased over the past century.[13] Such rainfall events are significant for runoff because high rainfall cannot be absorbed quickly enough by soils. Moreover, the large areas of impervious surfaces created by humans (e.g., roadways, parking, etc.) promote rapid runoff during these intense storms.

> The discrepancies in model results suggest that we must consider the effects of either an increase or a decrease in regional rainfall in the assessment of ecological impacts.

Finally, the differences in the Hadley and Canadian models with regard to precipitation and evaporation carry through to their respective projections for runoff. Again, the balance between water lost to evaporation and gained as rainfall will be crucial.[19] If significantly increased evaporation (water lost from soil and water surfaces) and evapotranspiration (water lost through plants themselves) do occur without increased rainfall, freshwater runoff from regional rivers should decrease,[20] whereas if rainfall exceeds those losses, runoff should increase. The Canadian model projects decreased stream runoff, while the Hadley model indicates there could be some increases in regional runoff in the next century.

Importantly, these predictions of runoff also depend on the climate to the north of the Gulf Coast region. Runoff into the Gulf of Mexico comes from streams whose watersheds are relatively small, combined with rivers whose watersheds extend far beyond the Gulf Coast—such as that of the Mississippi River, one of the largest watersheds in the world. Thus projections for runoff must incorporate the moisture budget of the entire basin. Several studies suggest that precipitation and runoff from the greater Mississippi River watershed is likely to increase—including a 20-percent increase in precipitation in the Ohio River basin, which controls more than two-thirds of the Mississippi River discharge.[21] The Canadian model predicts much drier soils and a greater tendency toward drought in the Mississippi watershed, while the Hadley model predicts that much of the region south of North Dakota will experience increased rainfall. The timing of peak runoff may also change if snow cover decreases and snowmelt occurs earlier in the spring. Human factors are also important in runoff projections, such as the massive flood-control systems that have been engineered along the Mississippi River, which can significantly alter the relationship between rainfall upstream and runoff far downstream in the Gulf Coast. Altogether, the Gulf region may see increased discharge from the Mississippi River but decreased runoff from smaller rivers whose watersheds are primarily influenced by regional climatic changes.

Although specific projections are impossible to make, changes in precipitation, evapotranspiration, and runoff are likely to be extremely important for the many ecosystems in this region that rely heavily on reliable freshwater availability. The discrepancies in model results suggest that we must consider the effects of either an increase or a decrease in regional rainfall in the assessment of ecosystem impacts.

El Niño/La Niña

As described earlier, the ENSO cycle involves large-scale fluctuations of ocean temperatures, rainfall, atmospheric circulation, and vertical motion of air and air pressure changes across the tropical Pacific.[22] These fluctuations result in climate variations over much of the globe.

A small increase in overall ocean temperatures in recent decades may have tipped the system toward more frequent and intense ENSO events with the potential for more severe regional droughts and floods in different parts of the world. Unfortunately, current climate models are unable to assess with confidence how ENSO may change in the future. Some models suggest that El Niño and La Niña conditions will become more frequent and intense under global warming conditions, while others indicate little change.[3,23] Given the impacts of the ENSO cycle on regional precipitation patterns and hurricane activity, future changes in ENSO should be of great importance to the Gulf Coast region.

Fire

The El Niño/La Niña cycle of 1997–2000 demonstrates how extremes in rainfall create enormous consequences for wildfire frequency and intensity. Increased time between rain events leads to the drying of plant materials that serve as fuel, and this buildup in fuels greatly increases the risk of more intense wildfires (Figure 6). Several regional changes that are not climate related exacerbate this risk:

- increased numbers of dense young pine plantations with relative thick canopies close to the understory
- many more sources and a greater frequency of ignition, since most fires are human-caused through arson or carelessness
- increased litter accumulations where fires have been suppressed

Fire is an important factor shaping the community composition of both upland terrestrial and wetland ecosystems. Depending on changes in the balance of rainfall and evaporative moisture loss from ecosystems, the risk of wildfire may increase or decrease in the future. These climatic changes will interact with specific management practices to determine the importance of fire to Gulf Coast ecosystems in the future.

Sea-Level Rise

As described above, sea-level changes along a stretch of coastline result from both global and local processes. Global changes in sea level have several sources:

- expansion or contraction of seawater in response to temperature changes
- the melting or growth of snowpacks and glaciers
- changes in the size of major ice caps on Greenland and Antarctica.

Local rising or sinking of land along the shoreline also affect sea level. Scenarios of sea-level rise along the Gulf Coast must account for local effects such as faulting, subsidence (sinking), and shore erosion of the coastline, both natural and human-induced, together with projected changes in global rates of sea-level rise. Projections of future sea-level rise typically take the historic local trend in sea level and add to it the acceleration in historic global sea-level rise projected by climate models. The global projections for sea-level rise range from about 5 to 35 inches over the next 100 years.[3] For the Gulf Coast, the Hadley model predicts an average sea-level rise of 8.4 inches, while the Canadian model predicts 15.6 to 19.2 inches over the next 100 years. Projections in this report are based on a rise of 13 inches over 100 years above the current rate, which represents a midrange estimate rather than the most conservative or worst-case scenario. Taking regional subsidence

FIGURE 6
Wildfire

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FIGURE 7
Relative Sea-Level Rise Scenarios for the Gulf of Mexico

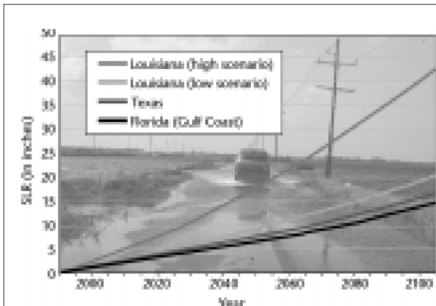

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FIGURE 8
Damage from Hurricane Andrew

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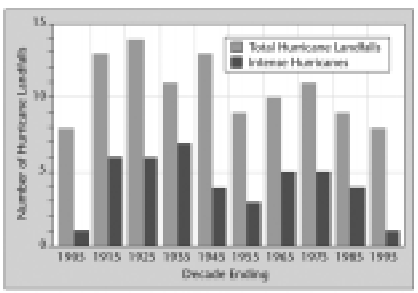
FIGURE 9
Gulf Landfalling Hurricanes by Decade



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rates into account,[24] the relative rise of sea level in the Mississippi River deltaic plain will range from 21 to 44 inches, whereas the rest of the region could see a rise from 15 to 17 inches over the next 100 years (Figure 7).

Hurricanes and Storms

The Gulf region experiences severe tropical and extratropical storms. Climate change may affect both, but the mechanisms and interactions of many influential factors are still incompletely understood. For example, predictions of future changes in hurricane frequency and intensity associated with global warming remain uncertain. The frequency of future hurricanes depends in part on whether global warming intensifies El Niño and La Niña conditions. As mentioned before, hurricane activity is linked with ENSO conditions, with El Niño events decreasing the probability that hurricanes will make landfall in the southeastern United States and La Niña events increasing it.[10,25]

Also important to Gulf Coast systems is the possibility that warmer tropical and extratropical sea-surface temperatures will increase the potential for more intense hurricanes with greater wind speed and precipitation.[26] The IPCC concluded in its latest assessment that the intensity of peak wind speeds and the total and peak precipitation associated with tropical cyclones are likely to increase. Any changes in hurricane frequency or track, however, remain unknown.[3]

Even if storm intensities remain constant, however, the disturbance from coastal flooding and erosion will increase as sea level rises (Figures 8 and 9). In other words, even coastal storms that are considered relatively minor today will exert the flooding impact of major storms in the future simply because higher sea levels will bring higher storm surges.

Passing storm fronts also strongly influence coastal sea levels; they can raise water levels more than 3 feet in the Mississippi River delta (compared with a tidal amplitude of 1 foot). However, changes in the frequency or tracks of frontal systems are also still uncertain. For example, ENSO—with its influence on the position of the jet stream and thus the ability of storm systems to penetrate far south—will influence local storm and flooding patterns.

Coastal Currents

Reductions in freshwater delivery to the coast from river runoff would cause changes in the coastal ocean circulation and a reduction in the westward-flowing coastal current along the Louisiana-Texas coast. Equally important would be changes in the eastward-flowing arm of the coastal currents that flow from the Mississippi River delta toward the Mississippi Sound.

Where runoff increases locally, we can expect increased stratification of fresh and salt water along the coast, with lighter fresh water on top and the heavier salt water below. This stratification, especially over warm, shallow coastal waters, increases the likelihood of hypoxia (oxygen-poor waters) and may affect the Loop Current.[27] Where runoff decreases, diminished stratification of fresh and salt water will also make wind mixing more effective and reduce the sea-surface temperature of the coastal ocean, thus making hypoxia less likely there. Areas where hypoxia occurs are sometimes called "dead zones," as living organisms dependent on oxygen either die or move elsewhere to oxygen-richer waters.

Human Drivers of Change in Gulf Coast Ecosystems

In addition to the climate drivers discussed above, other growing human pressures are causing significant changes to Gulf Coast ecosystems. While discussed in less detail below, these human impacts on the environment are currently the most important drivers of ecosystem change. They include population growth, engineering of natural water flows, and interference with coastal processes, habitat fragmentation, and water and air pollution (Figure 10). Human activities have already impacted the ecosystems of the Gulf Coast so heavily that few remain unaltered.

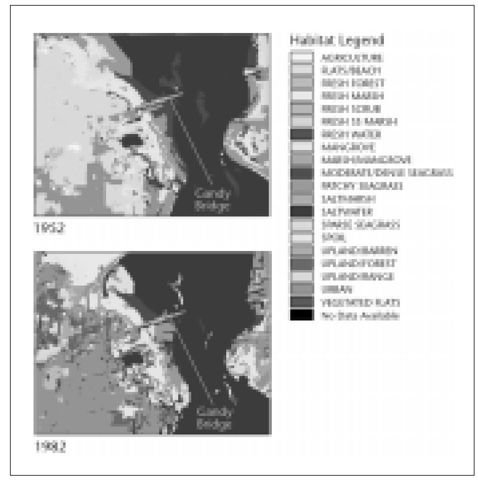
The population of the five Gulf Coast states increased over the past decade to more than 48.5 million in 2000. This 19.2 percent increase is higher than the average population increase for the United States as a whole during the past decade and primarily reflects significant increases in Florida and Texas. Population growth in coastal areas of the nation has been more rapid than elsewhere, with more than half the US population now living within 80 miles of coastal land.[28] Currently, Gulf Coast states host 18.3 percent of the total US population that lives near the coast. Over the next 25 years, the total population in Gulf Coast states living near the coast will increase by 44 percent compared with an average of 23 percent for the total United States.[29] Nearly 80 percent of the region's coastal residents live in Florida, where the population boomed from less than 3 million in 1950 to almost 16 million in 2000.[29] Population growth significantly affects the distribution of surface and groundwater, both of which are critical for Gulf Coast ecosystems.

To meet the demands of a growing population for flood protection, freshwater supply, wastewater processing, irrigation, water for industrial purposes, and other needs, major physical features of the Gulf Coast have been engineered over the past century (Figure 2).

Human alterations to water flows through upstream dams and impoundments, channelization, dredge and spoil operations, and diking affect both the quantity and quality of discharge as well as the sediment feeding into coastal waters. These alterations affect ecological services such as estuarine productivity, which depend on freshwater discharge from rivers, wetlands in the alluvial basins, and sand supplies from barrier islands.[30]

The sandy beaches of Gulf Coast barrier islands—the long, narrow islands with sandy beaches that parallel shorelines—make them highly valuable as resort and tourist destinations. Yet construction of buildings, roads, bulkheads, seawalls, and any other type of shore hardening disrupts the natural movement of sediment. In response, the beach face and nearshore erode, threatening buildings and narrowing the beach, while the "ribbon of sand" does not grow landward. Eventually, this process threatens not only human habitation but also the existence of the barrier islands and the habitats and protection to shorelines they provide.

FIGURE 10
Land-Use/Land-Cover Change, St. Petersburg-Tampa Area, Florida (1952–1982)



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Increased urbanization, industrialization, and agricultural land use also have significantly altered the natural landscapes of the central Gulf Coast. They have tended to reduce both water quantity and quality in the watersheds. The pressures on freshwater resources are particularly evident during water deficits, such as the summer drought of 2000, when both cities and farming areas suffered from salinization and reduced availability of critical water resources. Airborne contaminants and excess nutrients generated by human activities also impact the quality of freshwater resources when they are deposited on bodies of water.

Irrigation for agriculture is becoming increasingly important throughout the Gulf Coast to buffer the economic losses associated with extreme droughts. Four of the five states in this region are ranked among the top 20 US states in terms of acreage of land under irrigation.[31] Fresh water is also diverted in this region for thermoelectric power production, industrial uses such as the petrochemical industry, and household uses. Removing fresh water for human uses without regard for the needs of river and coastal habitats typically results in degradation of these aquatic ecosystems.

Human settlements and activities in the region have also greatly reduced or fragmented natural habitats. For example, increased development along the coastline has reduced wetland and mangrove habitat. In the upland areas, agriculture and timber plantations have replaced natural prairies and forests.

Humans are also both directly and indirectly responsible for the movement and establishment of nonnative invasive species that further degrade natural habitats and threaten native plant and animal species as well as human enterprises. Increasing human population and consumption of resources, which have led to increasing trade in the region and beyond, along with increases in human mobility, have resulted in unprecedented levels of introduction of nonnative species. When these introduced species become permanent residents and dramatically increase, they can produce severe, sometimes irreversible, impacts on agriculture, recreation, and natural resources as well as threatening biodiversity, habitat quality, and ecosystem functioning.[32]

In summary, while human alterations of the landscape have enabled the population of the Gulf Coast region to grow and thrive, they have also caused widespread degradation of natural ecosystems, species losses and invasions, structural changes in ecosystems, and changes in the interactions within plant and animal communities. Cumulatively, these human pressures on Gulf Coast water resources, ecosystems, biodiversity, and habitats are the most important drivers of ecosystem change in the region today. As a result, many ecosystems are vulnerable to any additional stressors, such as those that will arise from a rapidly changing climate.

> While human alterations of the landscape have enabled the population of the Gulf Coast region to grow and thrive, they have also caused widespread degradation of natural ecosystems. As a result, many ecosystems are vulnerable to additional stressors such as a rapidly changing climate.

CHAPTER *Two*

Vulnerability of Gulf Coast Ecosystems

Gulf Coast Ecosystems

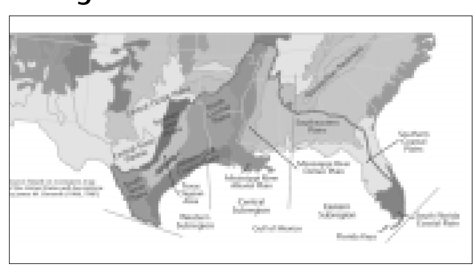
The flat Gulf Coast landscape formed as a result of changes in sea level over the past 125 million years. Rising and falling sea levels, along with sediment-carrying water flowing in rivers, repeatedly eroded and built up land. The resulting combination of uplands, alluvial plains built from waterborne sediments, shoreline landforms, and the most extensive wetland areas in the United States hosts a diversity of ecosystems that remain vitally linked by the flow of water (Figures 11a & 11b). Distributed across this landscape is a variety of natural as well as managed ecosystems, including forestry, agriculture, and aquaculture operations. Below we describe the ecosystems of the Gulf Coast, proceeding from the upland toward the ocean, then discuss the many valuable goods and services that the region's human communities obtain from them.

Upland Ecosystems

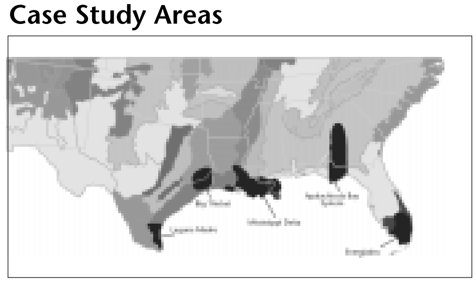
Nearly 70 million acres of coastal plain forests once stretched from Virginia to Florida to eastern Texas. Seven pine species are indigenous to this region, but longleaf pine dominated most of the historic forests. Unfortunately, only a few natural longleaf pine forests still exist due to logging, development, and human suppression of the natural fire cycle upon which they depend. The lower coastal plain was once a continuous moist pine barren known as ***Gulf Coast pitcher plant bogs***,[33] but only 3 percent of this habitat remains today[34] (Figure 12). ***Managed forests*** of shortleaf and loblolly pines now dominate the more upland and northern parts of the coastal plain, while plantations of slash pine dominate the lowland and more southern areas.

The drier western end of the Gulf Coast region once harbored extensive grasslands known as ***coastal plain prairies***. Many of the same prairie species found in the tallgrass prairie of the central United States characterize coastal plain prairies, such as Little Bluestem, Indian grass, tall dropseed, Texas cupgrass, goldenrod and blazing stars.[35] Less than 1 percent of the original prairie remains.[36] The rest has been converted to cropland, ranches, and urban areas. Coastal prairie is the sole habitat of the federally endangered Attwater's prairie chicken and serves as important habitat for

FIGURE 11a & 11b
Ecoregions of the Gulf Coast



Case Study Areas



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several other critically imperiled birds, such as the whooping crane (Figure 14).[37]

Freshwater Wetlands and Aquatic Ecosystems

Freshwater systems of the Gulf Coast include rivers, streams, lakes, swamps, marshes, and aquifers. Several ***river*** systems flow across the region with watersheds that vary in size from a few square miles around small streams and springs in Florida to the vast watershed of the Mississippi River, which drains about 40 percent of the continental United States and two provinces of Canada. ***Lakes*** in the region were formed either by major river systems or by dissolved limestone rock in Florida. A unique feature of Florida lakes is that many of their watersheds extend underground in the limestone terrain, connecting lake water "seeps" with deep ***aquifers***.[38] Seven aquifer (groundwater) systems within the Gulf Coast region supply much of the fresh water for agriculture, domestic needs, and industrial use.

The distribution of water in the rivers, lakes, and shallow aquifers of the Gulf Coast once supported the largest wetland region in the United States, including forested wetlands and freshwater marshes. Today, these wetlands have been reduced to less than half of their historic extent, yet they remain a noticeable and ecologically important part of the landscape.

FIGURE 12
Pitcher Plant Bog

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FIGURE 13
Hardwood Hammock

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Forested wetlands, swamps, and ***other wetlands*** cover a vast area and are unique in the biosphere, as they are adapted to tolerate the harsh conditions of saturated soils for long periods of time.[39] ***Freshwater marshes***, such as the Everglades in South Florida and the marshes of the Louisiana deltas, are another important component of the wetland landscape of the Gulf Coast (Figure 13). Marshes are wetlands dominated by herbaceous plants rooted in saturated soils with few trees and shrubs.[40] Changes either in drainage patterns or in the sources, quantity, and quality of fresh water can restrict the development or survival of wetlands. Several rare and endangered bird species live or nest in freshwater marshes, including the wood stork, Everglades snail kite, Cape Sable seaside sparrow, and Mississippi sandhill crane.

Coastal and Marine Ecosystems

The 1,550 miles of shoreline that extend from Florida Bay to Laguna Madre in Texas include 37 estuarine ecosystems that vary in geology, climate, and water salinity (saltiness). These represent the most diverse estuarine habitats in North America.

Gulf Coast ***estuaries, lagoons,*** and ***bays*** are water bodies where seawater from the Gulf of Mexico mixes with freshwater runoff from the land. An important aspect of estuarine health is how long fresh water remains in these systems. Seasonal variations in freshwater runoff into coastal waters can cause rapid changes in salinity, nutrient availability, and sediment supply. These physical and chemical characteristics of estuaries control the susceptibility of these systems to eutrophication (nutrient overenrichment). A variety of flora and fauna, such as seagrasses and shellfish, inhabit the submerged regions of the estuaries.

The Gulf Coast also includes extensive communities of ***coastal marsh vegetation*** in intertidal zones (areas influenced by the changing floods and ebbs of tide). Coastal marshes are the exclusive wintering ground of the federally endangered whooping crane, and coastal Louisiana provides wintering habitat for 70 percent of the migratory waterfowl using the central and Mississippi flyways.[41]

Mangrove communities are unique forested wetlands that dominate the intertidal zone of tropical and subtropical coastal landscapes. Four mangrove species are commonly found in the region: red mangrove, black mangrove, white mangrove, and button bush.[42] Mangroves provide habitat for a diverse set of plants and animals, including oysters, juvenile fish and shrimp, and sponges in reef environments (Figure 15). They also provide important rookeries for bird colonies, particularly along the shores of the Everglades National Park.

Long, narrow islands with sandy beaches that parallel shorelines all along the Gulf of Mexico from Texas to southwest Florida are known as ***barrier islands***. In the central region of the Gulf Coast, they typically formed when deltas eroded and sand deposits were reworked to form sandy islands and beaches.*[43] Barrier islands can migrate landward as sea level rises and thus are one of the most dynamic ecosystems of the region. Beach vegetation along the Gulf Coast is rich with a broad array of plants, such as sea oats, bitter panicum, beach morning glory, as well as small black mangroves in some of the back barrier marshes.[44] Shrubs and trees on stable barrier islands provide critical stopover habitat for migrating birds.[45] Sea turtles depend on beaches for nesting sites. These beaches are also important nesting grounds for several species of birds, including the federally listed, but slowly returning, brown pelican, and serve as wintering grounds for several waterfowl.

Coral reefs are diverse communities of marine plants and animals that colonize shallow subtropical waters.[46] The coral reefs of South Florida historically could cope with changes in sea level, and those living reefs that exist today occur in areas where stressors such as sediment turbidity and eutrophication are low.

FIGURE 14
Whooping Crane

See page 32
for full-size color image of this figure

FIGURE 15
Black Mangroves

See page 32
for full-size color image of this figure

Ecosystem Goods and Services

The ecosystems of the Gulf Coast contribute significantly to the region's economy and culture, producing resources, benefits, and amenities for human use and enjoyment. These ecological goods and life-support services are diverse and often taken for granted, but to the extent we can measure them, they add significantly to our regional and national wealth. Their estimated direct value, as detailed below, exceeds $160 billion per year. Forestry and timber processing, agriculture, commercial fishing, recreation, energy production and petrochemical industries, as well as light manufacturing, characterize the regional economies along the Gulf Coast. Many of these enterprises depend heavily on the region's ecological resources.

> The region's ecological goods and services are diverse and often taken for granted, but they add significantly to our regional and national wealth.

Estuaries and coastal marshes serve as nurseries to several commercially important fish and shellfish species such as penaeid shrimp, crabs, and various finfish during critical stages of their life cycles. Coastal marshes also provide water purification, sediment stabilization, and storm protection services. Mangroves, for example, have unique root systems that trap sediment and protect coastal shorelines from erosion and storm damage. Coral reefs provide numerous benefits to fisheries, recreation, tourism, and coastal protection wherever they exist. Similarly, barrier islands and beaches buffer coastal wetlands and upland ecosystems from the damaging

* In other areas, barrier islands are formed by the emergence of underwater shoals, or by the drowning and isolation of mainland dune lines during a rising sea level.

effects of tropical storms. With their extensive beaches, they are the foundation for much of the Gulf Coast region's coastal tourism industry.[47] Upland forests ensure freshwater flow and purify water as it moves through them.

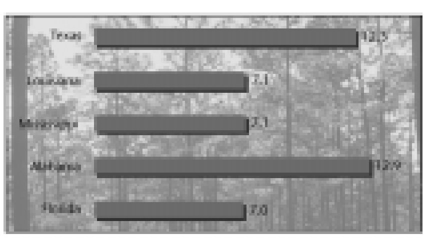
Agriculture and Forestry

The flat terrain and mostly mild and humid climate make this region well suited for agriculture and forestry.[48] The five Gulf Coast states produced 14 percent of the total value of agriculture in the United States in 1997, at a value of $28 billion.[49] About 44 percent of the agricultural value in the region derives from the region's major crops, including cotton, hay, soybeans, citrus, and rice, while livestock and poultry produce the remainder (Figure 16). Cattle and calf production is significant in Florida, and Texas cattle production is valued at $7.3 billion. Texas and Mississippi are ranked first and fourth nationally in cotton production, with a total value of $2 billion. Alabama and Mississippi are the fourth and fifth largest producers of poultry, at a value of $3.2 billion. Citrus crops in Florida are a $1.5 billion industry and represented 60 percent of the total US value produced from citrus in 1997.[50]

FIGURE 16
Typical Agricultural Crops

See page 33
for full-size color image of this figure

FIGURE 17
Value of Gulf Forest Industries (1996) (in $billion)



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Agriculture throughout the coastal region depends on the availability of fresh water, not only to support production, but also to prevent the encroachment of saltwater into shallow groundwater wells in coastal counties. Much agriculture in the Gulf Coast region is rainfed, nonirrigated agriculture. However, in East Texas and Louisiana, rice depends on irrigation, as do soybeans and cotton there and elsewhere in the central Gulf, as well as citrus and sugarcane in Florida, if to a lesser extent.[51] The extensive irrigation system in South Florida and in the more arid western coastal plain of Texas allows intensive production of citrus fruits, vegetables, sugarcane, grain sorghums, cotton, and beef. In regions where little irrigation is possible, rainfall determines yields from crops of cotton and grain sorghums, making them vulnerable to the risk of crop failure in years of insufficient rainfall.

Southern forestry is becoming increasingly important in the context of national timber production. Over the past decade, decreases in timber harvesting on public lands in the West have led to increasing harvests from the privately owned forests in the southeastern United States.[52] These plantations are grown for both timber and pulp fiber on cutting and replanting cycles of 20 to 40 years. In 1996, southeastern timber production was valued at $98.8 billion, or 37 percent of the entire US timber production value. The five Gulf states contributed almost half ($46.4 billion or 47 percent) of this southeastern production.*[53] Alabama and Texas are the most important states for forest products, together producing about 10 percent of the national inventory and more than half of Gulf Coast production. Alabama's forestry is valued at about $12.9 billion, Texas's at $12.3 billion, Louisiana's and Mississippi's at $7.1 billion each, and Florida's at $7.0 billion (Figure 17). Because the timber and wood products industry is such a large part of the regional economy, understanding how climate change may impact the health, composition, and productivity of forests in the region is vitally important.

Most of the forest area in the region is privately owned, with about 40 percent owned and managed by forest industries. The many nonindustrial private forests rarely have formal management plans. These private forests are increasingly being divided among more and more owners, and differences in management from one parcel to the next are disrupting the large-scale ecosystem processes found in large, unfragmented forest tracts.

* The southeast region includes 13 states.

Fisheries and Wildlife

The rich waters of the Gulf Coast states yielded 1.95 billion pounds of fish and shellfish in 1999, worth more than $758 million dockside*[54] (Figure 17). The 1999 harvest represents 21 percent by weight and 22 percent by value of the national commercial fishery harvest. The Gulf Coast has the largest and most valuable shrimp fishery in the United States, and in 1999 the region produced 78 percent of the national total shrimp landings.[54] The large acreage of coastal marshes along the Gulf Coast is thought to be the reason for this bountiful harvest of shrimp.[55] This region also contributed 58 percent of the national oyster production.[54,56] Recent figures on commercial landings indicate that Louisiana is second only to Alaska in domestic fisheries in the United States. Approximately 95 percent of Louisiana's harvested fish and shellfish depend on fragile coastal wetlands as nurseries and essential habitat. Reductions in harvest of natural fisheries in other US regions have placed increased demand on fisheries in the Gulf Coast region.

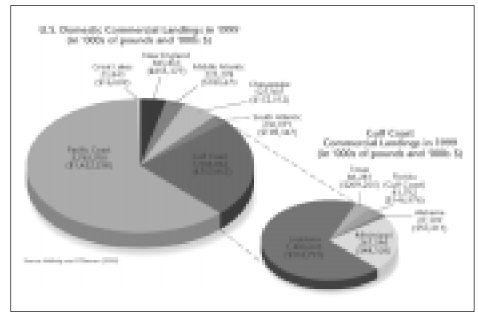
Aquaculture is also an important industry in the Gulf Coast, a fact made possible by the mild temperatures and availability of water. Mississippi has the most valuable aquaculture industry in the United States, at $290 million annually, followed by Florida (third), Alabama (fifth), Louisiana (seventh) and Texas (eleventh), for a total annual revenue of about $500 million.[57] This region produced 51 percent of the national value in aquaculture products in 1998, including food fish, baitfish, ornamental fish, shrimp, crawfish, and oysters.

Alluvial and shoreline ecosystems of the Gulf Coast are important regions for supporting wetland wildlife. For example, the region provides habitat for 5 million wintering waterfowl. About $50 million is spent annually on hunting waterfowl along the Mississippi River fly-way. Louisiana wetlands support direct income from wildlife resources, including the largest fur harvest in the United States (41 percent of total). More than 25,000 wild alligators are harvested yearly from wetlands, with hides and meat from both wild and farm harvests exceeding $11.5 million in 1992.[58]

Energy and Transportation

The economy of the Gulf Coast is perhaps best known for its rich energy resources. Approximately 95 percent of the oil and 98 percent of the natural gas produced on the federal outer continental shelf comes from the central and western regions of the Gulf of Mexico. The coastal zone and outer continental shelf of the Gulf of Mexico produce natural gas valued at $7.4 billion annually, and petroleum refining generates annual revenues of $30 billion for the domestic market nationwide. The Gulf Coast states provided 49 percent of the total US crude oil in 1998 by producing 1.1 billion barrels in that year (Figure 19).[59]

FIGURE 18
Fishery Landings (1999)



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The waterways of the Gulf Coast, especially the intracoastal waterway and the region's major rivers, form one of the most important transportation systems in the United States and include several international seaports. Eleven of the top twenty US ports by cargo volume in 1999 are found in the Gulf Coast region, including New Orleans, Houston, Mobile, and Tampa. Port facilities located between the mouth of the Mississippi River and Baton Rouge handle over 230 million tons of cargo annually, valued at more than $30 billion. The cargoes managed by these port facilities make up approximately 25 percent of the nation's total exported commodities.[60] This commercial-industrial infrastructure along the coast is significant to national and international commerce and requires intact landscape elements and ecosystems such as barrier islands and wetlands for protection from coastal storms.

> The waterways and infrastructure along the Gulf Coast are significant to national and international commerce and are protected by barrier islands and wetlands.

* Wholesale value off the vessels.

FIGURE 19
Oil Rig in the Gulf of Mexico

See page 34
for full-size color image of this figure

FIGURE 20
Recreational Fishing on Kissimmee River, Florida

See page 35
for full-size color image of this figure

Tourism and Recreation

The Gulf Coast region also supports a large recreation and tourism industry (Figure 20). For example, the 6,777 total fishable acres of fresh water in the five-state region (22 percent of the total in the United States) support an attractive and lucrative freshwater sport and recreational fishery. The tourism value of this fishery approaches that of the commercial catch. Coastal ecosystems support more than one-third of the national marine recreational fishing, hosting 4.8 million anglers in 1995 who caught an estimated 42 million fish.[62]

Tourism in the Gulf Coast states contributes an estimated $20 billion to the economy each year, much of which is beach and outdoor-oriented. Evidence of increased investment in a growing ecotourism industry across the region includes new state parks and wildlife sanctuaries, businesses, and conservation groups.[63]

This diverse environment, with the wealth of goods and services it provides to Gulf residents, is vulnerable in many ways both to changes in climate and to the growing pressures from human development and activities. The interaction of all these drivers of change will determine the future of Gulf Coast ecosystems.

CHAPTER
Three

Consequences of Climate Change for Gulf Coast Ecosystems

Natural ecosystems must constantly adjust to natural variations in climate. Generally they are more sensitive to climate extremes than to changes in average conditions. In addition to natural and human-induced changes in climate, other human disturbances increasingly buffet natural systems. Because both human and climate-related disturbances can have important impacts on the goods and services that ecosystems provide, it is important to evaluate the significance of ecosystem changes driven by human activities relative to those driven by climate change. Not every driver of change is equally certain or equally significant for ecosystems. Here we highlight those potential consequences of climate change that will require special consideration in the management of both ecological and economic systems in the future.

General Cross-Cutting Impacts

Changes in Water Availability and Flow

Gulf Coast ecosystems are linked by the flow of water from the uplands through freshwater lakes, rivers, and wetlands to the coastal and marine systems downstream. Especially in the central and eastern parts of the region, vast wetland areas require some duration of flooding to maintain healthy habitats and sustain food webs.[64] The prospect of changes in rainfall, stream flow, and overall water availability makes the Gulf Coast particularly vulnerable to climate change. In addition, engineering projects and growing water demand will exacerbate climate-driven changes in water flow. Besides the direct impact on water flow, changes in moisture availability will influence the intensity and frequency of fires, which will affect forest, mangrove, and prairie ecosystems.[64]

> The prospect of changes in rainfall, stream flow, and overall water availability makes the Gulf Coast particularly vulnerable to climate change.

In general, Gulf Coast estuaries should benefit from any degree of increased rainfall, but even a slight decrease in fresh water could cause severe changes in habitat and water quality. These impacts are likely to be greatest in areas that have massive engineered water-management systems,* or in coastal areas that are already water-scarce. Permanent reductions of freshwater flows due to combined effects of human activities and climate changes could lead to major reductions of biological productivity in bay systems such as the lagoons of Texas, or in Mobile Bay, Apalachicola Bay, and Tampa Bay (see Figure 5).

FIGURE 21a
Open Prairie

See page 35
for full-size color image of this figure

FIGURE 21b
Invasion by Chinese Tallow Trees

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for full-size color image of this figure

Sea-Level Rise and Coastal Storms

Sea-level change and coastal storms are naturally occurring phenomena that help shape coastal ecosystems. However, increased frequency of storms combined with higher sea levels can increase the salinity (salt concentrations) in coastal ecosystems and freshwater aquifers and cause other negative impacts. The systems most vulnerable to sea-level rise include freshwater marshes and forested wetlands in subsiding delta regions, mangroves in limestone areas, coastal marshes with human-altered water flow patterns, and areas with extensive coastal development. Because of high rates of land subsidence in the central subregion, for instance, ecosystems in that area face greater than average stress from rapid sea-level rise and coastal storms. The greatest economic impacts can be expected in the most highly developed and populated areas.

Even if storms remain at current intensities, damage to ecosystems could increase because a growing human population inhibits natural recovery. If storms and hurricanes occur more frequently, there could be increased local damage to mangrove forests, temporary increases in sediments and organic material discharged to coastal waters, increased physical damage to coral reefs, and increased physical disturbance to upland pine forests. Although the native forests of the region are adapted to hurricanes, replacement of natural forests with plantation monocultures, and other habitat alterations by humans have put many ecosystem types at greater risk.

Changes in Biodiversity, Ecosystem Composition, and Species Invasion

Climate changes such as warmer temperatures, fewer freezes, and changes in rainfall will tend to shift the ranges of plant and animal species and thus alter the makeup of biological communities in the future.

Increased air temperatures may cause a migration of species from subtropical ecosystems typical of the eastern and western subregions towards what is now the warm temperate central subregion. Warmer water temperatures could result in the expansion of tropical wetlands and tropical and subtropical species northwards, although any such shifts of species' ranges may be impeded by human developments.

Changes in the frequency of freezing weather will alter ecosystems in the eastern and western sections of the Gulf region. Vegetation along the shoreline of the Gulf Coast is strongly influenced by the frequency of frost. With global warming likely to reduce frost frequency, tropical communities such as mangroves may shift further north over time, and the specific species currently found at any given site are likely to change. For example, coastal red mangrove communities might shift further to the north on the Florida and Texas Gulf Coast. Along the Louisiana coast, reduced frost frequency would allow greater expansion of black mangrove forests (see Figure 15).

With increasing air and water temperatures, many exotic (non-native) tropical species are likely to extend their ranges northward. This would allow some nonnative invasive species to gain a greater foothold. Extensive open areas such as those in

* While freshwater delivery to estuaries can be controlled through canal systems, they do not allow water storage in floodplain wetlands and freshwater release during dry periods. Thus, brown marsh and freshwater/saltwater stratification are likely problems during droughts in estuaries with upstream freshwater management systems.

South Texas or South Florida are especially vulnerable. Invasion by exotic plant species is also one of the most serious threats to forests and grasslands in the region. For example, Chinese tallow tree is already a major component of forest understories, and climate change is likely to enhance its establishment and dominance (Figure 21).[65] Melaleuca and casuarina (Australian pine)—two other invasive exotic species widely regarded as pests in southern Florida—have high potential to move northward if temperatures permit. Increased frequency of hurricanes or wildfires could accelerate the invasion of these species, which might gain ground as ecosystems recover from such disturbances.

If droughts become more frequent or intense, the risk of wildfire could increase.

Although exotic species from tropical areas have already invaded the region, especially South Florida, climate change might, directly or indirectly (such as through altered fire frequency), favor these highly opportunistic species to the disadvantage of native plants and animals.[66] While a majority of the 119 native fish species of Florida are temperate species existing near the southern limit of their distribution, almost all of the 28 exotic species established in recent years are subtropical or tropical.[67] Warmer winter minimum temperatures along with fewer frosts will most likely produce a northward shift in the range of subtropical exotics. The high connectivity of lakes, streams, and wetlands in Florida, through both natural waterways and human-made channels and other connections, further enhances the potential for the rapid spread of invasive subtropical aquatic species northwards as the climate warms. One current example is the ongoing northward spread of the exotic walking catfish, which is replacing less competitive native species.[68]

Populations of native plants and animals—already stressed and greatly reduced in their ranges—could experience further stress from warmer temperatures, putting those species at increased risk for loss of local populations or even complete extinction.[69] Examples include the endangered Cape Sable seaside sparrow and Florida panther. Moreover, some species may not be able to migrate in response to changing climate, if they exist in habitat fragments or reserves hemmed in by farms, cities, roads, and engineering works.[70]

In addition to direct stress, warmer air or water temperatures can also impact native species indirectly. For example, evidence suggests that the gender of sea turtles is determined by the surrounding temperature at critical stages in development, with warmer temperatures producing more females.[71] Warmer temperatures could thus create reproductive problems for an already declining species.

The potential effects of a changing climate on isolated parks and reserves and on small tracts of forest tucked between human settlements and farms could be substantial because of the limited opportunities for natural species to migrate and the greater potential for the spread of exotics in disturbed areas. Furthermore, if climate change increases the incidence of droughts, fire danger will also increase, threatening these areas. Tracts of land near human populations are more likely to burn because most wildfires are caused by carelessness or arson.[72]

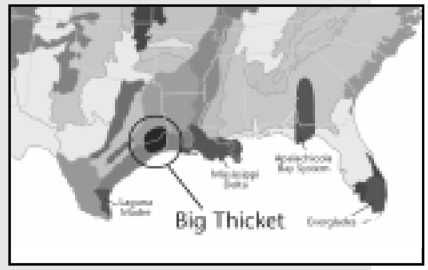
Ecosystem-Specific Impacts

Upland Systems

The Gulf Coast region's upland ecosystems are particularly sensitive to potential changes in the water cycle and fire frequency. Variations in soil moisture are important factors in forest dynamics and composition: many natural pine forests can tolerate low soil moisture, while oak-pine and oak-gum forests require medium to high soil moisture.[73] Over time, increasing temperature and decreasing soil moisture would almost certainly change the distribution of trees and other plant species in these systems.

If droughts become more frequent or intense, the risk of wildfire could increase. In ecosystems that are not adapted to fire, recovery from catastrophic fires can take decades or longer. Increases in drought-related fires would have severe impacts on managed forests and the timber-based economy of the region.

AT THE BIOLOGICAL CROSSROADS: THE BIG THICKET AND EAST TEXAS



The exceptional diversity of the Big Thicket area of East Texas has led conservationists to call this region the "Biological Crossroads of North America" and the "American Ark." There, within a limited geographical area, can be found several of the major forest types of the eastern United States.[74] Upland areas of the Big Thicket, formerly dominated by longleaf pine, are now mostly loblolly and slash pine plantation forests. Wetter parts of the Big Thicket host loblolly-shortleaf pine forests. The most rapidly expanding forest type is oak-hickory-pine forest. In the low-lying flood plains, bottomland hardwood forests predominate, harboring species such as sweetgum and water oak (Figure 22).

The forested areas of the Big Thicket also support a high diversity of vertebrate animals, with 400 species occurring in a 10-square-mile area. These forests are the primary habitat for the red-cockaded woodpecker.[75] Coastal prairies in the Big Thicket provide habitat for several endangered bird species. The Big Thicket is also a popular area for fishing, hunting, birding, hiking, camping, and canoeing.

FIGURE 22
The Big Thicket

See page 36
for full-size color image of this figure

Climate change has the potential to impact these diverse plant communities by altering the growth rates of species, changing the intensity and frequency of disturbance, and potentially facilitating invasion by exotic plant species. Historically, fire played a critical role in determining the dominant vegetation of the Big Thicket by preventing encroachment of hardwood saplings into pine forests and allowing successful recruitment of young pines.[74] Fire frequency is likely to increase if climate change leads to drier conditions in the area.[76] With greater demand for water in the Neches River and higher moisture deficits, invasion by Chinese tallow trees is likely to intensify. Climate change will also influence the spread of pests, especially the Southern pine beetle, in an area where losses to the forest industry are already running about $236 million per year.[77] Moreover, any barriers to dispersal or migration by plants and animals would hinder their ability to respond to changes in climate.[78]

Wildfires already cause extensive loss of standing timber and release large amounts of carbon to the atmosphere.

In contrast, wildfires are critical for grassland communities such as coastal prairies and bogs, which are well adapted to natural cycles of burning.[79] Because woody plants typically invade prairies that are not mowed or burned, increased fire frequency should help prairie conservation and help maintain grazing lands in good condition.[36,37]

Any increase in storm and hurricane frequency could hasten forest turnover, possibly resulting in the accelerated replacement of canopy trees with different, more competitive species, even under current climate conditions. The changing climate and the availability of species best suited for a site may limit the type of species that dominate forests after future disturbances and the rate at which they take over.[78]

Carbon dioxide (CO_2) serves as a natural fertilizer of plant growth, so higher concentrations of CO_2 in the air could increase forest productivity (tree growth). These CO_2-driven gains could offset or possibly reverse predicted declines in growth of pine forests caused by higher temperatures and the higher plant respiratory demands that warmer temperatures cause.[80]

While market forces exert a dominant influence on agricultural crop production and farm income, it is useful to look at climatic and other environmental influences on crop yields. Model studies suggest that certain agricultural crops such as corn, sorghum, and rice could also become more productive due to higher CO_2 concentrations, assuming warmer temperatures do not create additional water stress. Crops such as wheat, rice, barley, and most vegetable crops are expected to increase yields by 15 to 20 percent with a doubling of CO_2. Corn, sorghum, sugar cane, and many tropical grasses are expected to show increases of only 5 percent.[81] However, limited water availability could reduce or cancel out these productivity gains, especially in areas where irrigation is not possible. Other factors that could potentially counter any benefits of higher CO_2 include

- higher ultraviolet-B (UV-B) radiation
- limited nutrient availability
- increased water stress
- increases in pests and fires
- air pollution from nitrogen, sulfur, and toxic compounds

Freshwater Systems

The freshwater ecosystems of the Gulf Coast depend on the availability and flow of water through the region. Several climate-related factors, such as rainfall, runoff, and groundwater (aquifer) recharge, have dramatic impacts on Gulf Coast water cycles and leave freshwater ecosystems vulnerable to climate change.

> This combination of increased demand for fresh water and diminishing or uncertain groundwater recharge rates suggests potentially serious consequences in a warming climate.

Bays and estuaries along the Florida and Texas coasts have historically received a significant influx of fresh water from groundwater. However, upstream water-management systems have largely reduced these outflows of groundwater (Figure 23). Along with this reduction in outflow has come increased water use by agricultural, industrial, and urban interests, as well as the draining of wetlands for flood control. This combination of increased demand for fresh water and diminishing or uncertain groundwater recharge rates (the time it takes to replenish groundwater reserves) suggests potentially serious consequences in a warming climate, since more surface water will be lost to evaporation and not be available to recharge groundwater resources. In one recent study for Austin, Texas, scientists projected that climate warming could increase the average annual loss from lakes and reservoirs via evaporation by more than a foot.[82]

FIGURE 23
Perry Lake, Alabama

See page 36
for full-size color image of this figure

Sea-level rise also threatens the groundwater reserves in coastal plain aquifers. The risk of saltwater intrusion into these aquifers increases as the level of the seawater rises, especially if underground freshwater levels are declining because of greater human consumption and potentially lower recharge rates. The risk is greatest if climate turns drier in the future, but it will remain significant even if the climate grows wetter, because human water use and sea-level rise are both certain to increase.

Changing surface runoff patterns driven by changes in rainfall could also alter river, lake, and coastal ecosystems. For example, if rainfall and runoff from urban and agricultural areas increase, they most likely will carry more fertilizer and other contaminants into lakes and coastal waters, increasing the risk of eutrophication (excessive nutrient enrichment). Such effects would exacerbate human-driven stresses that are already driving changes in the region's rivers and lakes.[83]

Changes in flooding patterns could also significantly affect river ecosystems. Flowing rivers remodel landscapes, carrying sediment and nutrients downstream to form new land and support plant growth. They also erode land and carve new channels. Periodic rejuvenation of floodplains by erosion and deposition is essential to the health of river ecosystems. From an ecological perspective, flood pulses are not disturbances, but rather essential processes that define the biology and water quality of river ecosystems. If climate change results in more intense rainfall events, humans are likely to try to reduce flooding by increasing channelization of rivers and building dams, levees and reservoirs, all of which are functionally less effective in flood control than maintaining floodplain habitats that can receive and slow the overbank flows.

FIGURE 24
Swamp Forest Impacted by Saltwater

See page 36
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FIGURE 25
Brown Marsh in Coastal Louisiana

See page 37
for full-size color image of this figure

Higher water temperatures and a longer growing season would reduce habitat for cool-water species, particularly fish, insects, snails, and shellfish. Warmer water holds less dissolved oxygen, which is critical for all living organisms. In shallow water systems, high surface temperatures can lead to anoxia or hypoxia (oxygen-free or oxygen-poor waters) and cause potentially massive die-offs of fish and invertebrate species. Low-oxygen conditions would become more extensive in a warmer climate with longer periods of low flow, and the consequences for stream ecosystems could be severe.

Plant growth (productivity) in freshwater wetland ecosystems would increase with higher concentrations of CO_2 and modestly warmer temperatures, as long as precipitation is not reduced. For freshwater marshes, this may mean increased accumulation of organic matter, enhanced rates of soil formation, and—for systems close to the coast—an increased ability to cope with sea-level rise. However, increased plant growth in response to higher CO_2 levels varies among species, and higher CO_2 could change the mix of species and interactions within aquatic communities. As with forests and agricultural systems, gains in aquatic plant productivity due to increased CO_2 could be countered by other climate-driven changes. For example, a significant reduction in rainfall would lower wetland productivity far more than elevated CO_2 could increase it.

Coastal and Marine Systems

Sea-level rise will alter coastal wetlands along the entire Gulf Coast, causing increased flooding, greater saltwater penetration, and higher rates of coastal erosion. Wetlands naturally respond to sea-level rise by building additional substrate or moving inland onto adjacent uplands (Figure 24). Thus, the accelerated sea-level rise projected for the next 50 to 100 years would normally be unlikely to have a catastrophic impact on most Gulf Coast wetlands. However, where sea-level rise coincides with human land-use changes in the drainage basin, the consequences could be severe, leading to losses of wetlands in areas where coastal development hinders natural inland migration.[84]

Increased droughts in upland and coastal areas would also have negative impacts on coastal and marine ecosystems by reducing the flow of fresh water into estuaries, bays, and lagoons. If droughts occur more frequently or last longer, the incidence of hypersalinity (extreme salt concentrations) in coastal ecosystems will increase, resulting in a decline of valuable habitats such as the mangroves and seagrasses in Florida Bay or South Texas lagoons and coral reefs in the Florida Keys where their salt tolerance is exceeded. The 25-month drought in coastal Louisiana that extended through summer 2000, for example, along with reduced river flow contributed to severe dieback of some 100,000 acres of marsh (Figure 25).[85]

FIGURE 1
The Gulf Coastal Plain
from page 2

The Gulf Coastal Plain arcs 1,550 miles from the tip of Florida to the tip of Texas. The region is divided into three subregions that differ in climate: western (Texas), central (Louisiana to Alabama) and eastern (Florida). Despite little variation in terrain, the Gulf Coast supports a diversity of freshwater, coastal, and upland terrestrial ecosystems.

Credit: Amanda Wait/DG Communications

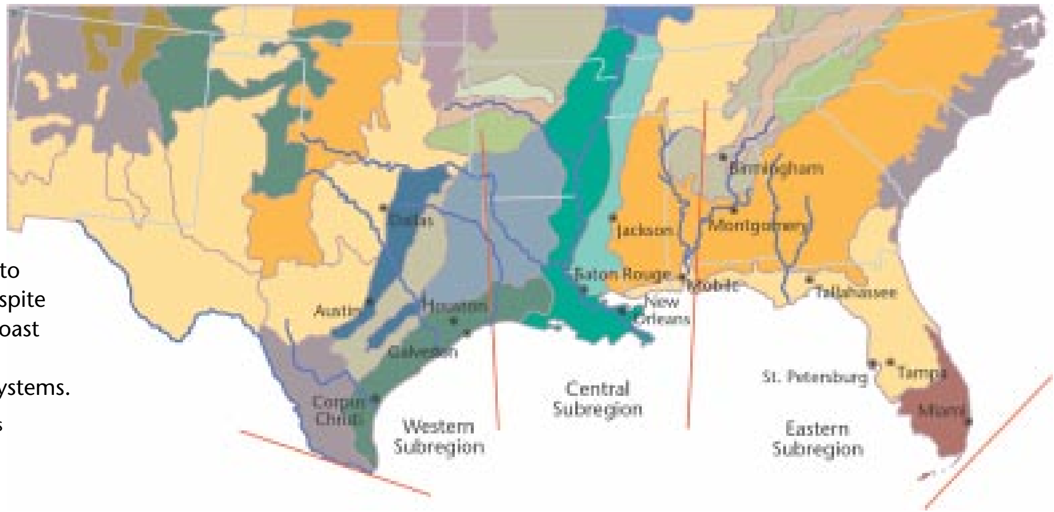
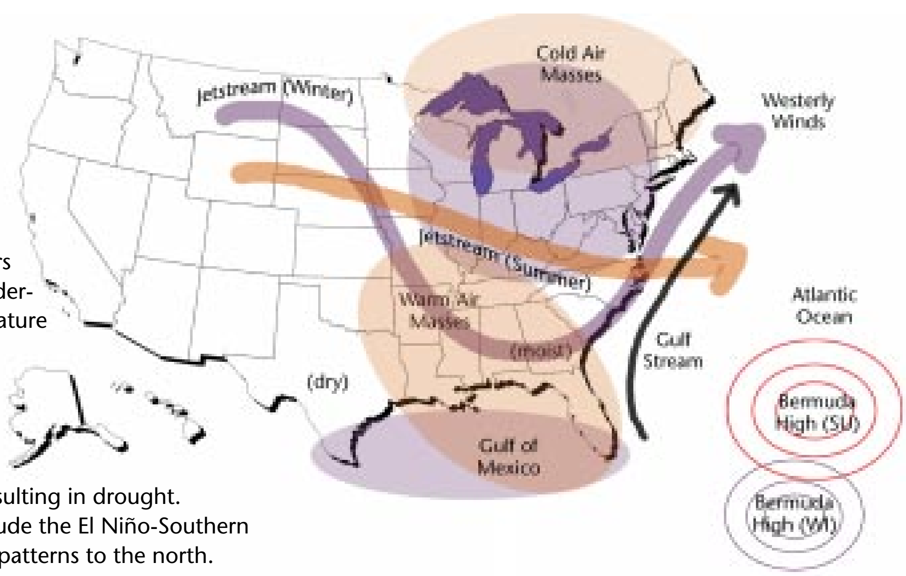


FIGURE 2
Water Control Structure
from page 3

The natural landscapes, waterways, and ecological processes of the Gulf Coast have been significantly altered by human activities, including water control structures such as this pump station in South Florida. The station is part of one of the world's largest water management systems, built by the US Army Corps of Engineers, to protect the urban areas of South Florida from flooding and to support agriculture while simultaneously draining nearly 65 percent of the original Everglades and fundamentally changing its character.

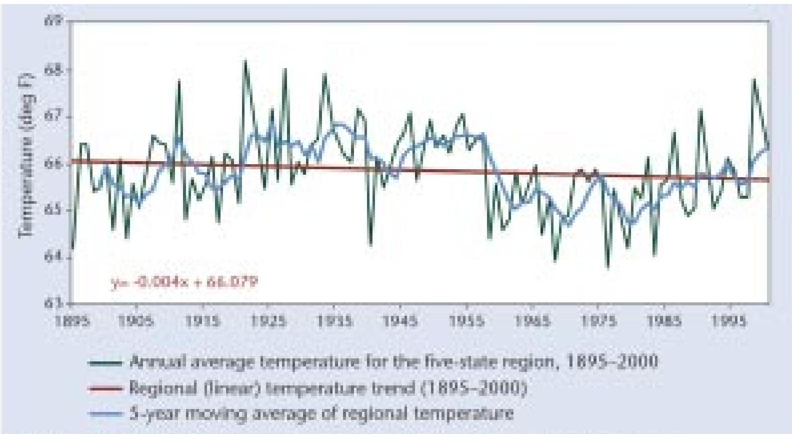
Photo Credit: South Florida Water Management District

FIGURE 3
Influences on Gulf Coast Climate
from page 5



The Gulf Coast region is substantially wetter than the climate of other locations at this latitude because moist air flows in from the Gulf of Mexico, Caribbean Sea, and Atlantic Ocean. The region enjoys mild winters occasionally punctuated by cold air masses from the north that bring low temperatures and freezing conditions. Summers tend to be hot and humid, with rainfall brought by thunderstorms and tropical storms. Another influential climate feature is the Bermuda High pressure system, which controls the duration of the wet season in South Florida. During the winter, the Bermuda High is small and located south and east of Florida; in the spring, it expands and moves northward. If the Bermuda High does not move north in the summer, then the wet season rains are delayed, resulting in drought. More remote influences on the climate of the region include the El Niño-Southern Oscillation cycle (not depicted) and continental weather patterns to the north.

Credit: Amanda Wait/DG Communications



Source: Derived from state temperature data available at the US National Climatic Data Center, Asheville, N.C.

FIGURE 4

Gulf Regional Average Temperature (1895–2000)

from page 6

While air temperatures warmed over most of the United States during the 20th century, they cooled slightly on average in the Gulf region. Such regional differences are not inconsistent with the global warming trend. In addition, climate varies from year to year and decade to decade as shown in these temperature curves. The five Gulf Coast states experienced a warm period between the 1920s and 1949 and then substantial cooling until the late 1960s, when temperatures again began to rise. This warming has been less than the previous cooling, hence the slight downward trend of the regional average for the 20th century.

FIGURE 5

The Hydrologic Cycle

from page 10

Gulf Coast ecosystems are connected by the flow of water, from the uplands to the coast. Any change in the hydrologic cycle underlying this connection will affect both natural and managed ecosystems and the goods and services they provide. This hydrologic cycle depiction illustrates how water availability and flow is a function of both a changing climate *and* human activity. A changing climate will affect rainfall, evaporation, transpiration, surface and subsurface runoff, and groundwater recharge. Human activities—such as creating impervious surfaces, using surface and groundwater for human demands, and altering river channels and deltas—also greatly impact the water cycle.

Credit: Melissa Drula, Annie Bissett/DG Communications

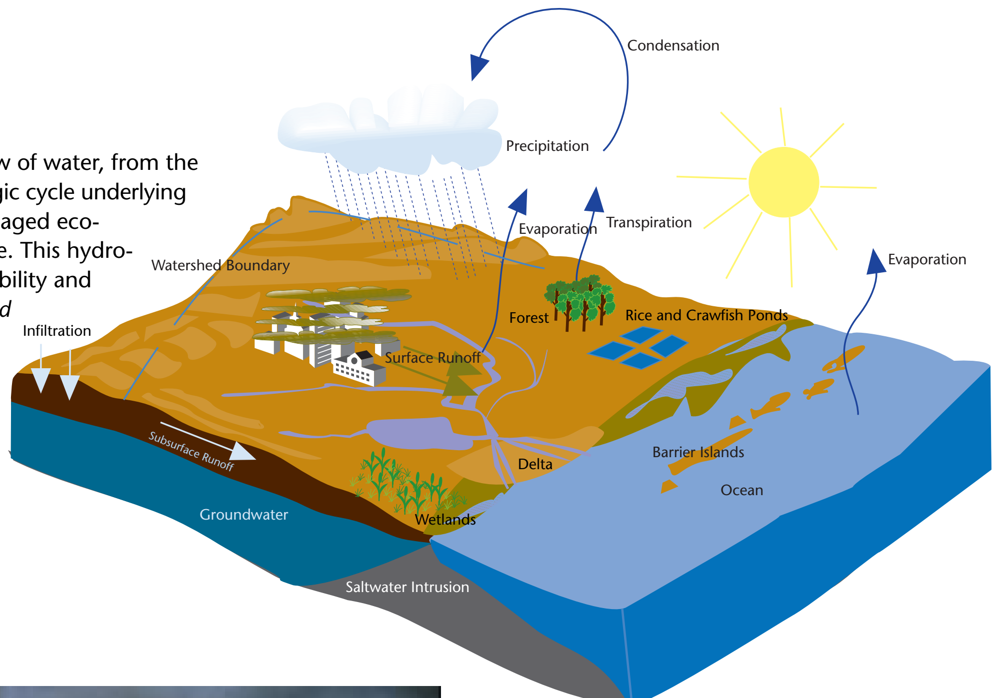


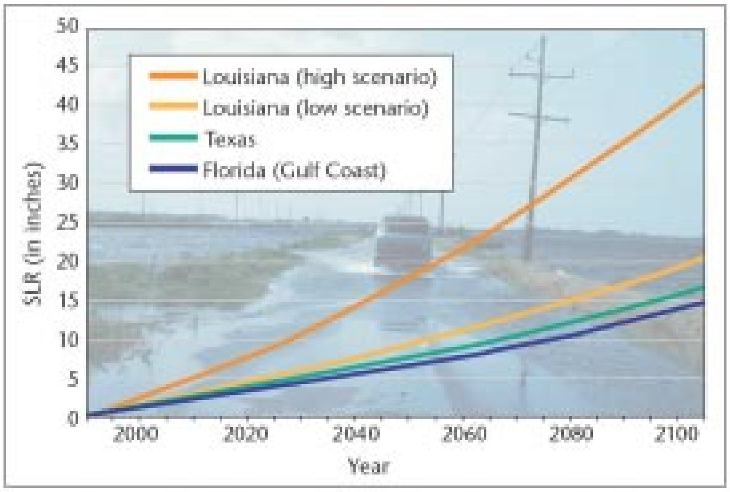
FIGURE 6

Wilfire

from page 11

Wildfires have shaped many of the region's ecosystems. Grasslands and prairies are maintained by wildfires and some natural forests also depend on them for regeneration. Yet timber production and homes located at the community/forest boundary face great risks from wildfires. If rainfall decreases and/or evaporative moisture loss increases with global warming, the likelihood of wildfires occurring will increase.

Photo Credit: South Florida Water Management District



Note: Model runs produced by Tom Doyle (US Geological Survey) are based on midrange SLR scenarios and average regional subsidence figures as described in the text.

FIGURE 7

Relative Sea-Level Rise Scenarios for the Gulf of Mexico

from page 11

Climate models project that sea-level rise (SLR)—already occurring along the Gulf Coast—will continue at a faster rate over this century and beyond, increasing coastal erosion and flooding during normal high tide as well as during severe storms. Sea-level rise projections are shown here for different parts of the Gulf of Mexico, with two different scenarios for Louisiana due to its wide range of land subsidence rates. By the late 1990s, this road—the only land access to the rural community of Isle de Jean Charles in Terrebonne Parish, Louisiana—was regularly flooded by wind-driven tides, forcing the local government to raise the road several feet at a cost of $2 million.

Photo Credit: Denise Reed

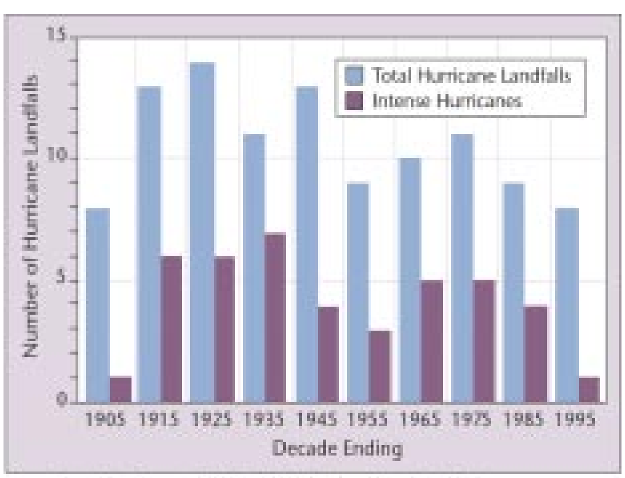
FIGURE 8

Damage from Hurricane Andrew

from page 12

In 1992, Hurricane Andrew brought widespread destruction to Florida and the Atlantic seaboard with damages estimated at about $27 billion. Damages from future storms are likely to be aggravated by sea-level rise, and the costs can be expected to be substantially higher because more coastal development already lies in harm's way. Should global warming increase the intensity of hurricanes, the impacts on people and property in coastal communities are likely to increase.

Photo Credit: South Florida Water Management District



Source: adapted from Bove et al. (1998); © 1998 American Meteorological Society, reproduced with permission by AMS.

FIGURE 9

Gulf Landfalling Hurricanes by Decade

from page 12

Hurricane activity varies from decade to decade and is correlated with the El Niño-Southern Oscillation cycle. The 1990s ushered in a period of greater hurricane activity that is unrelated to human-induced climate change, and the number of intense hurricanes (categories 3–5) is projected to increase over the next 25 years. During El Niño events, the probability that hurricanes will make landfall in the southeastern United States goes down, while the probability increases during La Niña events. With global warming, hurricane *intensity* (maximum wind speeds, rainfall totals) may increase slightly, although changes in future hurricane *frequency* are uncertain.

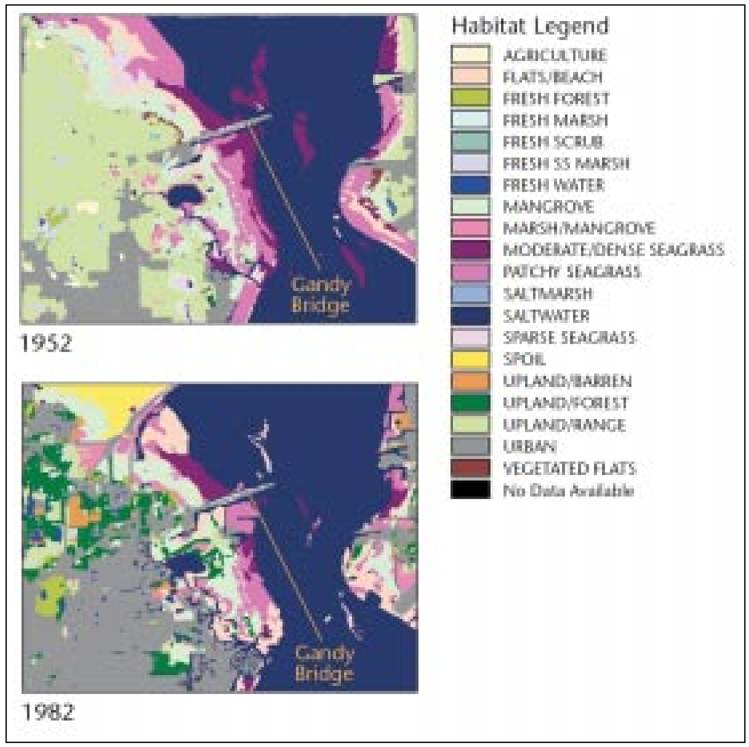
FIGURE 10

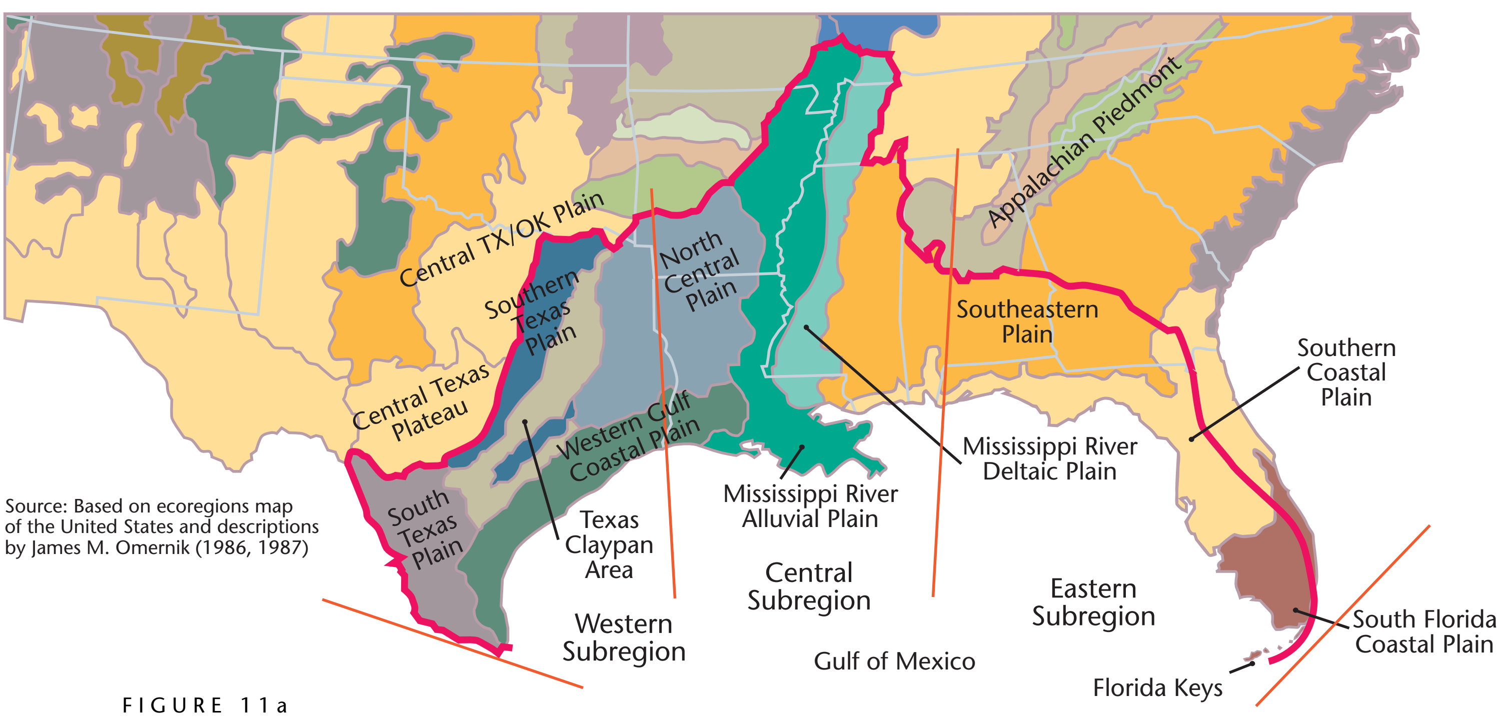
Land-Use/Land-Cover Change, St. Petersburg-Tampa Area, Florida (1952–1982)

from page 13

To accommodate the rapid population growth in the Gulf states, especially in Florida and Texas, and coastal areas more generally, urban centers expand into surrounding natural habitats and agricultural areas, as shown in this pair of maps of the St. Petersburg-Tampa area. As more land is developed for human uses, plants and animals lose their habitats, and potential migration corridors—needed to adapt to climate change—are obstructed.

Credit: US Geological Survey, Gulf of Mexico Integrated Science Program





Source: Based on ecoregions map of the United States and descriptions by James M. Omernik (1986, 1987)

FIGURE 11a

Ecoregions of the Gulf Coast

from page 15

Despite little variation in terrain, the Gulf Coast region hosts a diversity of ecosystems that evolved on upland, alluvial (material deposited by flowing waters), and coastal landscapes under the influence of temperate and subtropical climates. Upland ecosystems include temperate hardwoods, pine flatwoods (or barrens), scrub forests, and prairies. Freshwater wetlands and aquatic ecosystems encompass swamps, freshwater marshes, lakes, rivers, and springs. The near-shore areas include barrier islands, mangroves and salt marshes, seagrasses, estuaries and bays, and coral reefs. The five case studies—shown in Figure 11b and highlighted in this report—represent some of the diversity of ecosystems and the species richness of the region.

Credit: Amanda Wait/DG Communications

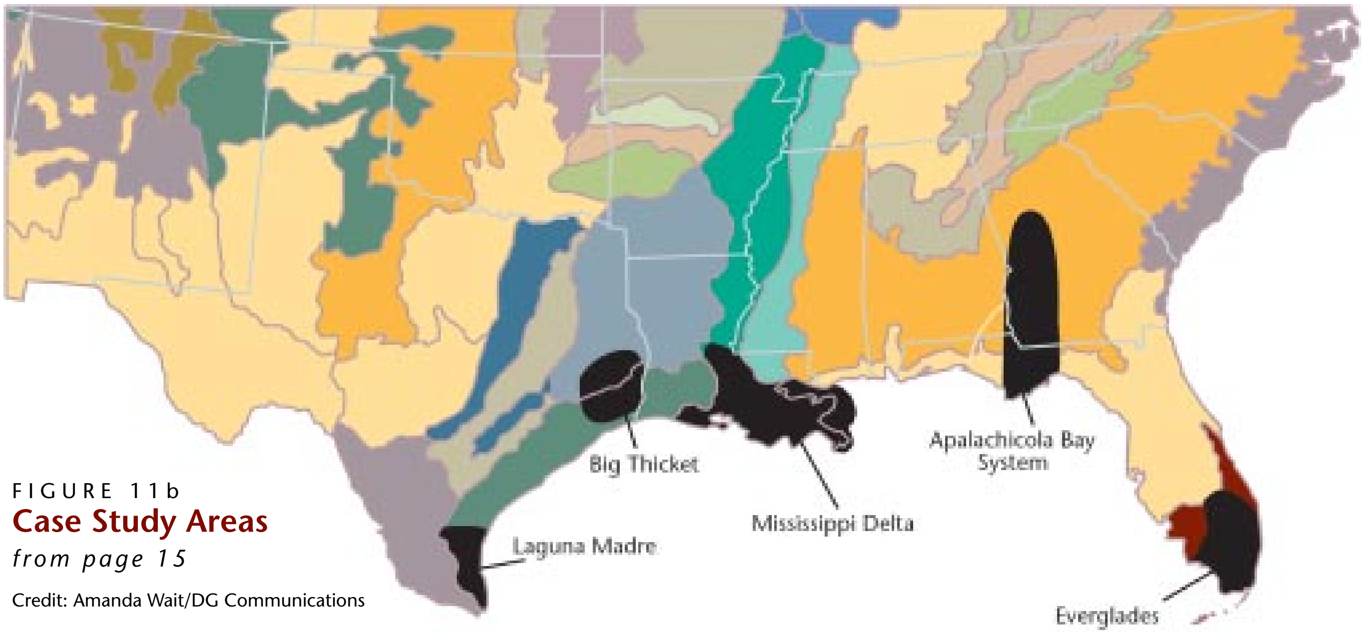


FIGURE 11b
Case Study Areas
from page 15

Credit: Amanda Wait/DG Communications

FIGURE 12
Pitcher Plant Bog
from page 16

The lower coastal plains—which extend about 60 miles inland from the coast and run from the western edge of North Florida to the eastern border of Mississippi—were once a continuous moist pine barren commonly known as Gulf Coast pitcher plant bogs. Only three percent of these habitats remain today, serving as home to unique carnivorous plants (well over half of the approximately 45 North American species occur in the Gulf Coast), as well as the endangered pine barrens tree frog, the odd flightless grasshopper, and a unique spittlebug.

Photo Credit: Robert Twilley

FIGURE 13
Hardwood Hammock
from page 16

Hardwood hammocks are typical habitats in South Florida. Made up of dense stands of trees, these hammocks are slightly elevated "islands" created by the flow of water in the middle of sloughs (the deeper and faster-flowing center of broad marshy rivers). Many tropical tree species such as mahogany and cocoplum grow alongside temperate species such as live oak, red maple, and hackberry. Due to their elevation, hammocks rarely flood, and they are protected from fire by natural moats formed when acids from decaying plants dissolve the limestone around them.

Photo Credit: Susanne Moser

FIGURE 14
Whooping Cranes
from page 17

The Whooping Crane—the rarest of the world's 15 crane species—historically wintered along the Texas Gulf coast, and nonmigratory populations occurred in Louisiana and possibly other areas in the southeastern United States. The Aransas-Wood Buffalo population in Texas is one of only three wild populations remaining. Habitat loss, pollution in their wintering grounds, and vulnerability to natural and human-caused disturbances continue to threaten this magnificent bird.

Photo Credit: Gwenn Hansen

FIGURE 15
Black Mangroves
from page 17

As global warming increases average temperatures, the freeze line will also move northward. Black mangroves, quite sensitive to freezing temperatures, are moving northward and establishing themselves more firmly on the Louisiana coast—one biological indicator that warming is already underway.

Photo Credit: Robert Twilley

FIGURE 16

Typical Agricultural Crops

from page 18

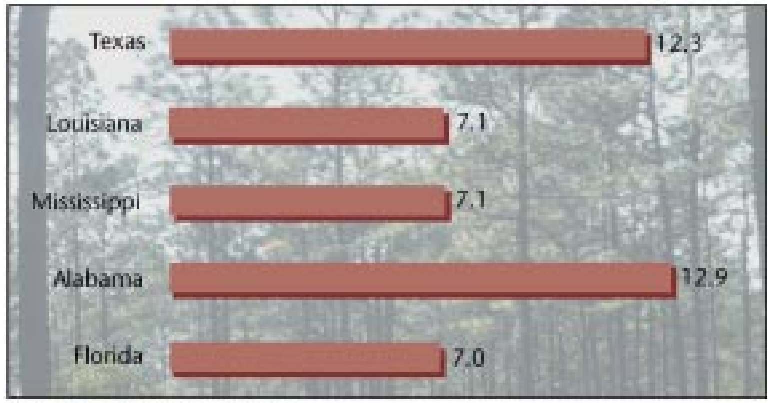
The Gulf region is well suited for agriculture, with the five states combined producing $28 billion—or 14 percent—of total agricultural value in the United States in 1997. Citrus, sugarcane, peanuts, rice, and cotton are among the leading crops. Only with sufficient water during the growing season, from rainfall or irrigation, will yields be maintained in the future.

Photo Credits: US Department of Agriculture (citrus, peanuts, rice), South Florida Water Management District (sugar), Susanne Moser (cotton).

FIGURE 17

Value of Gulf Forest Industries (1996) (in $billion)

from page 18



Source: US Department of Commerce (1999)

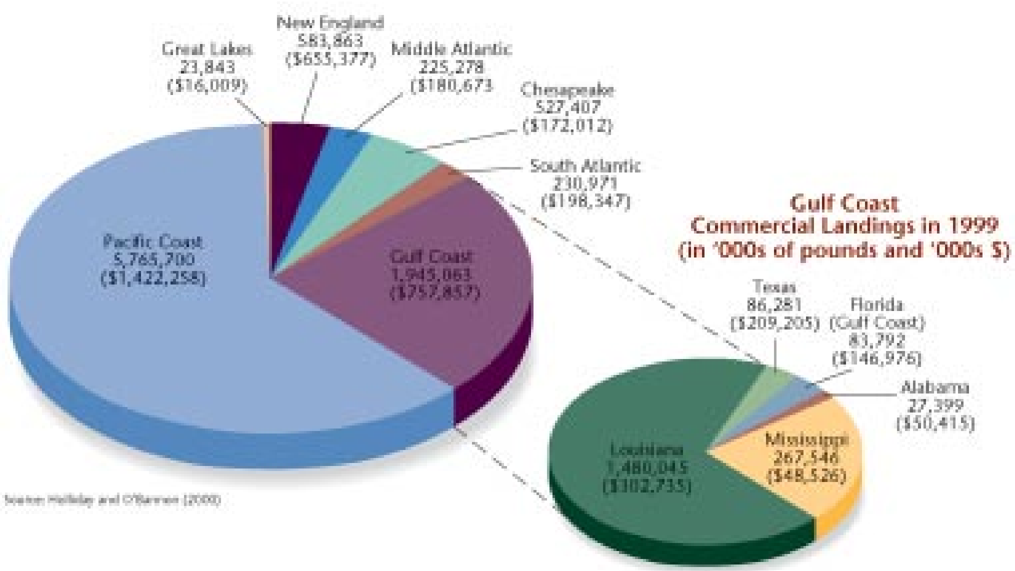
In 1996, the five Gulf states accounted for $46.4 billion of the national timber production. Alabama and Texas together produced about 10 percent of the national inventory and more than half of Gulf Coast production. Major changes in forestry can be expected in the future, although projections are difficult to make because the direct impacts from climate change will interact with shifts in global timber markets. If the drier climate scenario plays out, savannas and grasslands would expand at the expense of forests, particularly in the uplands of the Gulf Coast, and fires would become more frequent. Wetter climate conditions, on the other hand, would increase the productivity of hardwoods at the expense of softwoods and would leave the region's forests more vulnerable to pests such as the Southern pine bark beetle.

Photo Credit: Robert Twilley. Chart: Amanda Wait/DG Communications

FIGURE 18

Fishery Landings (1999)

from page 19



The rich waters of the Gulf of Mexico yielded 1.95 billion pounds of fish and shellfish in 1999, worth more than $758 million dockside. The Gulf Coast has the largest and most valuable shrimp fishery in the United States, and in 1999 the region produced 78 percent of the total national shrimp landings. Many of the harvested fish and shellfish depend on fragile coastal wetlands as nurseries and essential habitat. Continuing wetland loss—projected to increase with global warming over the 21st century—will undermine this valuable sector of the Gulf economy.

Credit: Amanda Wait/DG Communications

FIGURE 19

Oil Rig in the Gulf of Mexico

from page 20

The economy of the Gulf Coast is perhaps best known for its rich energy resources. Approximately 95 percent of the oil and 98 percent of the natural gas produced on the outer continental shelf comes from the central and western regions of the Gulf of Mexico. While reducing emissions from the production and refining of these fossil energy resources would directly reduce the risks of global warming, it is critical to find ways to cut emissions without undermining the economic vitality of the region.

Photo Credit: Robert Twilley

FIGURE 20

Recreational Fishing on Kissimmee River, Florida

from page 20

Alluvial and shoreline ecosystems—such as swamps and marshes—support wetland wildlife, including waterfowl, alligators, and fur-bearing animals. A growing ecotourism industry depends on these ecosystems for recreational activities such as hunting, fishing, hiking, canoeing, and birdwatching.

Photo Credit: South Florida Water Management District

FIGURE 21a

Open Prarie

from page 22

The remaining areas of the once-vast coastal prairies that extended from the Carolinas to South Texas are threatened by both urban sprawl and invasive species, particularly the Chinese tallow tree. Once established, the tree transforms a diverse coastal prairie (top) into a biologically impoverished forest within 30 years (bottom). It is not yet known what role climate change will play in prairie invasions, but the combination of climatic and human stresses on ecosystems frequently renders habitats more vulnerable to invasion. Already, the Chinese tallow tree has become an abundant invader in the understory of many Gulf Coast forests, and climate-related disturbances such as hurricanes tend to accelerate its invasion and establishment. In addition, drier conditions with fewer flooding episodes as projected by some climate models appear to favor Chinese tallow at the expense of native species.

Photo Credits: Evan Siemann

FIGURE 21b

Invasion by Chinese Tallow Trees

from page 22

FIGURE 22
The Big Thicket
from page 24

The Big Thicket National Preserve, which incorporates more than 97,000 acres of public lands and waters, is internationally recognized for its splendid biological diversity, encompassing bald cypress swamps, as well as upland pine savannahs and sandhills. The preserve is home to a variety of endangered species such as the red-cockaded woodpecker and brown-headed nuthatch.

Photo Credit: US National Park Service

FIGURE 23
Perry Lake, Alabama
from page 25

Freshwater ecosystems such as Perry Lake or nearby Cahaba River in Alabama are particularly vulnerable to climate-related changes in the water cycle, including changes in rainfall, runoff, and groundwater (aquifer) recharge. Potentially diminishing rainfall and groundwater recharge rates due to global warming would have serious consequences for freshwater ecosystems, especially when combined with human activities such as drainage of more wetlands for flood control, reductions in groundwater outflow caused by upstream water-management systems, and increased water usage by agricultural, industrial, and urban interests.

Photo Credit: Randall Haddock, Cahaba River Society, Birmingham, Ala.

FIGURE 24
Swamp Forest Impacted by Saltwater
from page 26

The combination of sea-level rise and less freshwater runoff from land lead to saltwater intrusion into once vibrant coastal estuaries. This example from Falgout Canal in Louisiana illustrates the problem, which could become more serious with climate change. This navigation canal dredged in the 1960s allowed salt water into a freshwater swamp, resulting in dead cypress trees surrounded by brackish marsh vegetation.

Photo Credit: Denise Reed

FIGURE 25
Brown Marsh in Coastal Louisiana
from page 26

Should climate change lead to more droughts in upland and coastal areas, reduced flow of freshwater into these coastal ecosystems would harm estuaries, bays, and lagoons. The 25-month drought in coastal Louisiana that extended through summer 2000, along with reduced river flow into the marsh area, contributed to severe dieback of some 100,000 acres of marsh.

Photo Credit: Greg Linscombe, Louisiana Department of Wildlife and Fisheries

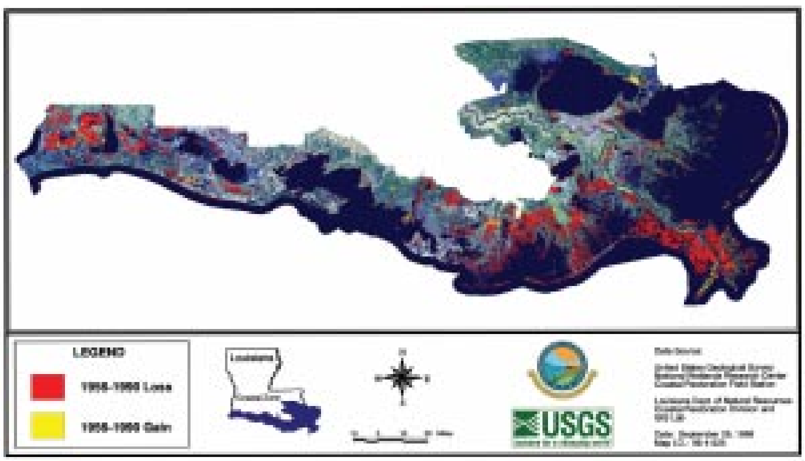


FIGURE 26
Louisiana Coastal Land Loss (1956–1990)
from page 43

More than 12,000 square miles of coastal wetlands were once part of the Mississippi River delta, representing nearly 40 percent of the total coastal salt marsh in the continental United States. These wetlands are disappearing at an average rate of 25 square miles per year or about 50 acres per day. The normal ecological processes that built and nourished these vast wetlands have been profoundly disrupted by human intervention—construction of dams, levees and channels in the river, and the conversion of more than 80 percent of forested wetlands to farms and cities. The combined effects of sea-level rise and human alterations to sediment supply will continue the current wetland loss rates for the next 20 years. Later in the 21st century—as temperatures increase more—loss rates are likely to increase.

Credit: US Geological Survey, National Wetlands Research Center (1998), MAP 98-4-525

FIGURE 27
Kemp's Ridley Sea Turtle
from page 46

The endangered Kemp's Ridley sea turtle—shown here emerging from egg-laying in the beach sands of Padre Island National Seashore, Texas—is one of six sea turtles found in the Gulf Coast region. Sea turtles are threatened primarily by human activities such as disturbance or destruction of nesting sites, artificial lighting along developed beachfronts, entrapment in fishing nets, water pollution, and being hunted for their eggs and leather. Further loss of nesting habitats due to beach erosion from accelerating sea-level rise will substantially reduce their prospects for survival.

Photo Credit: US Geological Survey

FIGURE 28
Isles Dernieres
from page 47

Louisiana's Isles Dernieres is a low-lying island chain that serves as home to brown pelicans, other shorebirds, and a host of fishery species. These islands also serve as "hurricane protection" for coastal communities, oil and gas facilities, and seaport infrastructure on the mainland. Yet these invaluable islands are severely threatened by human interference with natural coastal processes such as sea-level rise, local land subsidence, sediment transport and hurricane- and storm-driven waves and overwash. Since the late 1990s, over $30 million has been spent to restore the height and width of these protective islands.

Photo Credit: Denise Reed

FIGURE 29a/b
Healthy and Unhealthy Corals
from page 47

Healthy coral reefs (top) are among the most beautiful and biologically diverse ecosystems on the planet. In the past few decades, however, unprecedented declines in the condition of coral reefs in the Gulf of Mexico have been detected including extensive coral bleaching due to higher temperatures (bottom), growth of algae on reefs, loss of the dominant algae-grazer (a sea urchin), and pervasive overfishing of reef species. The shallow waters surrounding the South Florida reefs make them especially vulnerable to the higher ocean water temperatures that are expected to accompany climate change in the Gulf.

Photo Credits: Mike White, Florida Keys National Marine Sanctuary (top/healthy); S. Miller, NOAA, Office of Oceanic and Atmospheric Research, National Undersea Research Program (bottom/bleaching)

FIGURE 30
Pitcher Plant
from page 48

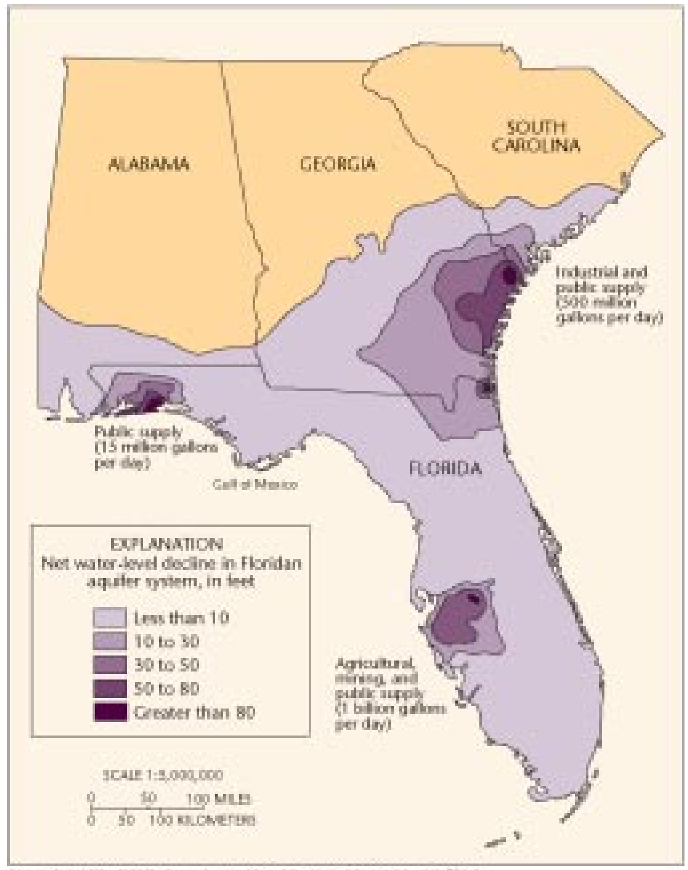
The endangered green pitcher plant is a perennial herb that lives on decaying insects and leaves that fall onto its leaves. Although 31 of the known remaining 34 populations occur in Alabama, protecting the habitat of this endangered species is hampered by a lack of state protection laws. Pitcher plants live in mixed oak or pine flatwoods, seepage bogs, and along stream banks, and fire appears to help maintain their habitat, whereas reduction of streamflow and moisture affect their habitat negatively. Increased residential, agricultural, and forestry development, fire suppression, and climate-driven alteration of its little remaining habitat further threaten this unique plant. Photo Credit: Henry Gholz

FIGURE 31

Declines of Regional Water Levels Due to Withdrawal from the Floridan Aquifer (predevelopment to 1980)

from page 51

Drawdown of underground water reservoirs to meet human demands combines with sea-level rise to increase saltwater contamination of aquifers, particularly near the coast. Large groundwater withdrawals in the coastal zones of Florida (e.g., Pensacola and Tampa) or Alabama (e.g., Gulf Shores) have already increased salinity in wells. These problems are common in coastal aquifers across the Gulf region and are likely to increase with growing population and accelerating sea-level rise.



Source: J. A. Miller (1990), Groundwater Atlas of the United States, Map HA 730-G

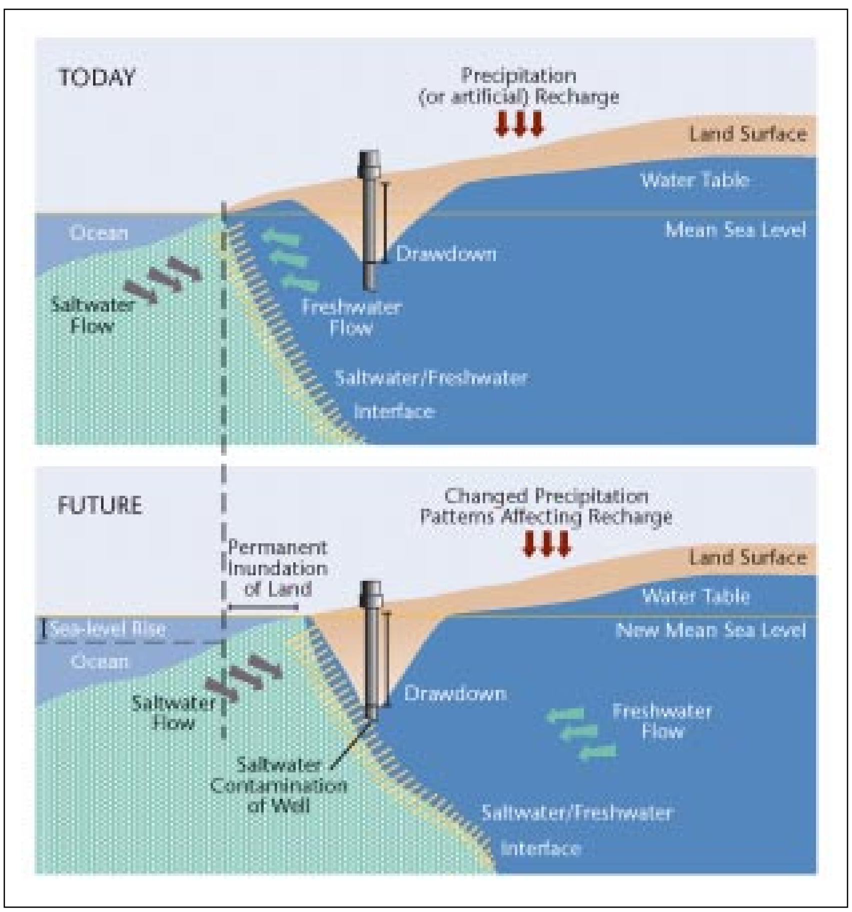


FIGURE 32

Aquifer Drawdown and Saltwater Intrusion

from page 51

As sea level rises, salt water penetrates coastal aquifers more deeply. Fresh water drawn from wells near the coast can thus be contaminated by saltwater—a risk increasing with growing human water demand, increasing drawdown, potentially reduced groundwater recharge, and sea-level rise.

Credit: Amanda Wait/DG Communications

FIGURE 33

The Everglades

from page 52

Decades of managing water primarily for urban and agricultural uses has put the Greater Everglades critically at risk. Climate changes and accelerating sea-level rise will cause shifts in plant and animal communities and increased success of invasive species. Other significant impacts could result from more intense hurricanes or from more frequent or intensive droughts, which would increase the risk of major wildfires. Restoration efforts that do not account for climate-related changes are likely to leave the Everglades less able to adapt to a warmer world.

Photo Credit: Susanne Moser

FIGURE 34

Shrimp Trawler

from page 54

Family-owned shrimp trawlers alongside large commercial fishing operations are as much a part of the coastal landscape as crawfish ponds and aquaculture tanks. The fishing and fish farm industries are particularly vulnerable to changes in freshwater availability, increases in salinity due to saltwater intrusion into coastal ground- and surface water, and water quality declines in coastal areas, as well as to losses of marsh, mangrove and seagrass habitat.

Photo Credit: Thomas Minello, National Marine Fisheries Service

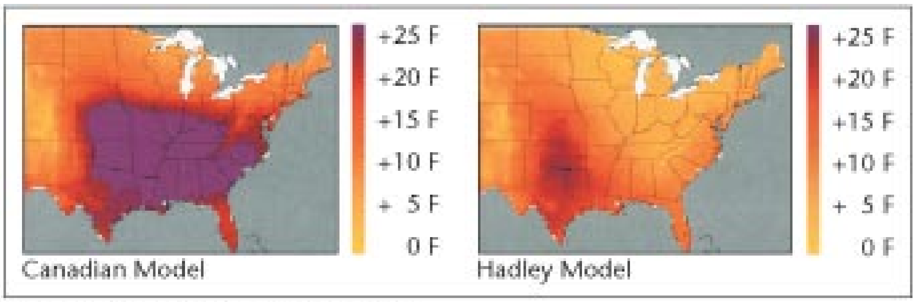
FIGURE 35

Erosion Damage from Tropical Storm Frances (1998)

from page 55

Tropical Storm Frances hit the Texas coastline in 1998, causing severe erosion damage to houses along the shorefront, such as those shown here on the west end of Galveston Island. With accelerating rates of sea-level rise, even minor storms in the future could wreak major havoc, damaging houses, infrastructure, and industrial facilities. Over time—short of significant and sustained increases in investment in shorefront protection—second and third-row homes will become oceanfront property.

Photo Credit: Susanne Moser



Source: National Assessment Synthesis Team (2001), based on models produced by NOAA's National Climatic Data Center

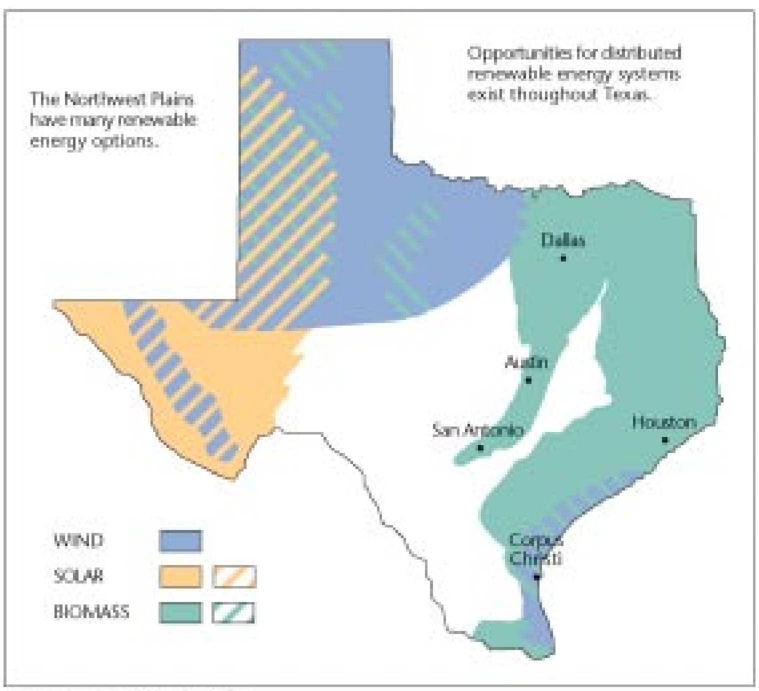
FIGURE 36
July Heat Index Change by 2100
from page 56

The July heat index is projected to increase with global warming more in the South than in any other region of the United States. Urban areas such as Dallas, Houston, Baton Rouge, Birmingham, and Tampa are especially vulnerable to more frequent heat waves and a resulting increase in heat-related illnesses and deaths. In each of these cities, deaths attributed to extreme heat conditions average about 28 per year, and this rate could more than double to 60 to 75 deaths per year with a 3°F warming of average summer temperatures. Vulnerability to heat-related stress depends largely on people's ability to protect themselves from temperature extremes —for example, on whether they can afford air conditioning—and on their pre-existing health condition.

FIGURE 37
Windmill
from page 62

Many environmental, economic, and public health benefits can result from reducing the combustion of fossil fuels and the emissions of heat-trapping gases that accompany fossil fuel burning. One way to reduce fuel consumption is to increase use of alternative energy sources such as wind power. This Zond Z-40 550 kW wind turbine is located on a wind farm in West Texas (Fort Davis), one of a growing number of wind farms throughout the state.

Photo Credit: Brian Smith, courtesy of the US Department of Energy/National Renewables Energy Laboratory



Source: Texas State Energy Conservation Office

FIGURE 38
Renewable Energy Potential in Texas
from page 62

Texas has a variety of clean energy resources—wind, solar, biomass, and geothermal. The state has begun to develop some of this supply, and it has the market power to help spread the use of renewable energy. Other Gulf states can also increase and further diversify their energy production with renewables such as solar, hydro, and biomass, and thereby reduce their production of greenhouse gases.

Credit: Texas State Energy Conservation Office

FIGURE 39

Improving Irrigation Technology

from page 63

Pivot irrigation, as shown here on a cotton field in Mississippi, is widely used, but other water-conserving technologies are available. Exploring these options is essential if we are to help natural and managed ecosystems better adapt to a changing climate. In the face of a changing climate, for example, the cost-benefit analysis applied to human activities such as agricultural irrigation should be reassessed. The potential benefits of sustained or increased agricultural yields or prevention of saltwater intrusion into surface waters must be weighed against potential negative side-effects such as further draw-down of groundwater resources, increased salinization of soils, or withdrawal of essential fresh water from natural ecosystems. Technically feasible solutions are available to adapt to and mitigate climate change, and the cost of these solutions is frequently lower than the cost of doing nothing.

Photo Credit: US Department of Agriculture

FIGURE 40

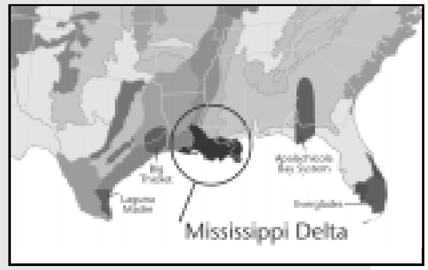
Beach Replenishment

from page 66

Typical responses to the landscape changes associated with rising sea level have included building seawalls and other hard structures to hold back the sea, raising the land and replenishing beaches—as shown here in Corpus Christi, Texas—or allowing the sea to advance landward and pulling human development back from the shoreline in an ad hoc manner. Each of these options can be costly, both monetarily and in terms of lost landscape features, habitats, buildings, and infrastructure. Beach replenishment, while avoiding some of the negative side-effects of shoreline hardening, will be required more frequently as faster sea-level rise increases coastal erosion. The most affordable option is likely to require long-term planning for an inevitably rising ocean.

Photo Credit: Texas General Land Office, Coastal Projects Division

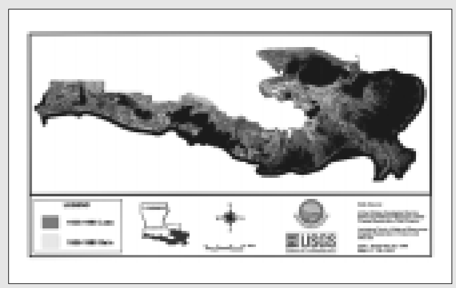
CONTROLLING A RIVER: THE MISSISSIPPI RIVER DELTAIC PLAIN



Over the past century, the nearly 1.3 million square mile watershed of the Mississippi River has experienced major environmental changes, including conversion of more than 80 percent of forested wetlands to agriculture and urban areas, channelization, dam construction, and leveeing of the river. The lower Mississippi deltaic plain has also been engineered by construction of flood-control levees and massive structures that keep the river from switching channels and also restrict sediment and freshwater supply to river flood plains (Figure 26).

This has been especially damaging to the region's wetlands. The more than 12,000 square miles of coastal wetlands associated with the Mississippi River delta represent nearly 40 percent of the total coastal salt marsh in the conterminous United States. These wetlands are disappearing at an average rate of about 25 square miles per year or about 50 acres per day, and more than 1,000 square miles of freshwater wetlands in Louisiana have already been lost or converted to other habitats.[86] Only about 20 percent of the original 37,500 square miles of bottomland hardwood forests and swamps in the lower Mississippi River valley remain today.

FIGURE 26
Louisiana Coastal Land Loss (1956–1990)



See page 37
for full-size color image of this figure

Some of these wetland losses are due to delta subsidence (sinking), which results in relative rates of sea-level rise of up to 0.39 inches per year.[24] Although subsidence is a natural process, human interference with river and sediment flow and withdrawal of groundwater have exacerbated it. Adequate inflow of fresh water and sediment is critical for sustaining existing wetlands and expanding delta landscapes along the coast.

One of the most critical climate-change issues for the delta is how future rates in sea-level rise will affect the already highly altered and rapidly degrading coastal wetlands of Louisiana. Landscape models project that the combined effects of increased sea-level rise and human alterations to sediment supply will continue the current wetland loss rates in the Terrebonne and Barataria Basins until 2018. These simulations demonstrate that from 1988 to 2018 the region will lose nearly 900 square miles of coastal wetlands to open water, threatening navigation and the industrial, agricultural, and fisheries sectors of the regional economy.[87] Future wetland loss rates could increase as sea-level rise accelerates in the latter part of the 21st century. Although hurricanes can play a positive role in wetland development by remobilizing sediments and assisting in building marsh substrate, channelized coastal landscapes such as Louisiana's allow storm surges to move farther inland, increasing saltwater penetration into interior freshwater marshes. Sea-level rise will exacerbate this disturbance whether or not hurricanes and storms become more frequent or intense in the future.

Major changes in the upper and lower watersheds of the Mississippi-Atchafalaya river system have also increased the likelihood of low-oxygen conditions in Gulf waters. Wetland destruction has removed the watershed's nutrient-buffering capacity; river channelization for flood control and navigation has shunted fresh water to the continental shelf; and major increases in nitrogen fertilizer washed into the Mississippi River Basin have quadrupled nitrate concentrations in the river system. On the Louisiana continental shelf, hypoxia can extend over as much as 8,000 square miles, depending on the amount of freshwater discharge, which controls the addition of nutrients and the stratification of shelf waters. Climate model studies predict a 20 percent increase in discharge from the Mississippi River watershed, which could lead to an expanded hypoxic or "dead zone."[88] This delta region—with big population centers such as New Orleans—represents one of the most vulnerable regions of the Gulf Coast, an area where the combined effects of engineered and altered landscapes, natural subsidence, and climate change will have tremendous consequences for human well-being, natural resources, and biodiversity.

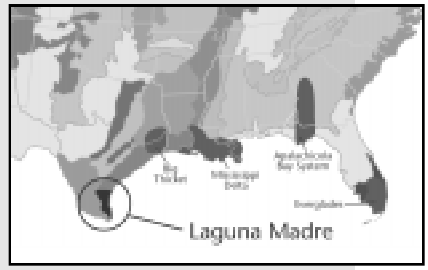
If increased drought reduces freshwater flows, the result will also be reduced nutrient inputs, slower flushing of nutrients and contaminants, and alterations in estuarine food webs. While nutrients such as nitrogen are critical for plant growth and ecosystem functioning, too much can increase algal growth and other problems such as hypoxia and anoxia. Again, the interaction of climate-related changes with other human pressures is critical: in relatively pristine watersheds with fewer sources of nutrients and contaminants, impacts on estuaries may be less severe than in developed areas, such as the heavily industrialized and urbanized Tampa and Galveston Bays, which have numerous point and nonpoint sources of nutrients and contaminants. In addition, many of these estuaries receive deposits of nutrients and contaminants from the atmosphere. These factors can combine to degrade water quality in estuaries and to threaten fisheries and human health through such changes as increased harmful algal blooms and accumulation of toxic metals. As in freshwater wetlands, plant growth in coastal wetlands could increase with higher concentrations of CO_2. Studies of mangroves have shown enhanced produc-tivity with elevated CO_2 concentrations. But again, productivity gains due to increased CO_2 concentrations may be countered by other climate-driven changes.

> Changes in surface runoff would impact coastal ecosystems and fisheries by changing water quality and the mix of species.

Changes in surface runoff patterns—either decreases due to drought or increases caused by freshwater influxes during floods—will also impact coastal ecosystems by changing the salinity and perhaps shifting the mix of plant and animal species in the community. However, the complex interactions of climate and human activities that influence the quantity and quality of freshwater runoff illustrate that the outcome depends at least as much on how water is managed as on climate-induced changes in rainfall.

An extensive levee system has reduced flooding from the Mississippi River into adjacent wetlands by channeling freshwater flows directly to the shallow continental shelf off the Louisiana and Mississippi coasts. During periods of high river discharge, a large mass of oxygen-poor bottom water can form in the northern Gulf of Mexico as the fresh water forms a stratified layer above the denser salt water and delivers more nutrients into the Gulf.[89] These river discharges are affected by climate far upstream in the watershed, in the western and midwestern United States. Climate-change projections for the Ohio River basin, for instance, suggest there will be higher

SALTY BALANCE: THE LAGUNA MADRE AND THE SOUTH TEXAS COASTAL PLAIN



The Laguna Madre, the only hypersaline lagoon in the United States, is part of the South Texas Coastal Plain, which extends inland from the western Gulf of Mexico as a gently sloping prairie of short grasses, mesquite trees, thorny brush and prickly pear cactus. Much of the plain is used as rangeland, with some cropland and improved pasture. Two major river systems encircle this semi-arid region of South Texas: the Nueces River to the north and the Rio Grande River to the south. These rivers provide the only continuous sources of surface fresh water for the cities and estuarine systems of South Texas.

The Laguna Madre formed between the mainland and Padre Island, which at 130 miles is the longest barrier island in the United States. At its widest, Padre Island measures 3 miles across and has dunes that rise 25 to 40 feet behind wide sandy beaches on the Gulf side. The upper Laguna Madre exchanges water with Baffin Bay, the "saltiest" bay in the United States. Tidal currents in the lagoon are weak, circulation is sluggish, and residence times of water masses are long. During exceptionally dry periods, high salinity may cause fish and other animals to leave or die. The lagoon also suffers periodic large fish kills due to severe freezes. The shallowness of the lagoon and the long distances to deep water worsen the conditions that can lead to fish mortality.

The South Texas Coastal Plain supports unique ecosystems and wildlife, including barrier island dunes and beaches, Tamaulipan brushlands, Laguna Madre seagrasses, intertidal wind flats, Baffin Bay, and the Rio Grande delta. Some areas are biologically diverse, such as Padre Island, which hosts more than 600 species of plants, and the Tamaulipan brushland with more than 600 vertebrate animal species and 1,100 plant species, including an endemic oily oak tree species. Padre Island beaches serve as nesting grounds for endangered Kemp's ridley sea turtles and threatened green sea turtles (Figure 27). The Laguna Madre accounts for 75 percent of Texas's seagrass habitat, which supports many rare and endangered species and provides vital nursery grounds that sustain a bountiful commercial harvest of shrimp, blue crabs, red drum, spotted sea trout, and southern flounder. The threatened green sea turtle, once abundant enough to support commercial harvest in South Texas, feeds on submerged turtle grass rooted in the lagoon bottom. At the Laguna Atascosa National Wildlife Refuge, the endangered aplomado falcon has recently been reintroduced. The banks of the Arroyo Colorado and nearby thorny chaparral uplands shelter ocelot, jaguarundi, indigo snakes, horned lizards, chachalaca, green jays, kiskadee flycatchers, and other unusual animals.

The most important human impacts on this region over the past 30 years have been water diversion and flood-control projects, brushland clearing, pollution, continued dredging of the intracoastal waterway, and the pressures of population growth. The lower Laguna Madre, for instance, has lost about 60 square miles of seagrass cover due to reduced water clarity since the 1960s. Extensive agriculture has fragmented and reduced the areas of native terrestrial ecosystems. And both the

FIGURE 27
Kemp's Ridley Sea Turtle

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northern and southern ends of Padre Island have been developing rapidly as resort and residential real estate. In addition, the large number of people now living in "colonias" without sewage treatment contributes to the contamination of ground and surface waters and poses a human health problem. This is exacerbated by untreated wastewater from Mexican municipalities released into the Rio Grande.

In addition to human impacts, parts of the Rio Grande watershed have experienced severe drought since 1993, and low flow has exacerbated water quantity and quality problems. Also, a lengthy, unprecedented brown tide (*Aureoumbra lagunensis*, a type of toxic algal bloom) has persisted in the Laguna Madre since 1990. The bloom began in association with high salinities and a nutrient pulse from a fish kill caused by a 1989 freeze.[91]

Global warming will compound these human pressures on Laguna Madre, in some case improving, in others worsening the situation. For example, if future climate change brings a prolonged and more intense wet season in this region, the reliability of rainfall and soil moisture could improve. The gentle slope of South Texas prairies helps the land retain rainfall and runoff. In wet periods, freshwater ponds form in swales over clay soils, water is stored in sandy soils, wildlife and native plants increase their productivity, and salinity is moderated in the Laguna Madre and Baffin Bay. If rainfall decreases in the future, however, it would not take much of a reduction in moisture to spur increased desertification. Moreover, models project that all types of coastal wetlands in Texas would decline with less freshwater delivery to the estuaries, thus exacerbating wetland losses already occurring. Over the long term, such coastal wetland losses would diminish estuarine-dependent fisheries.[92]

Warmer winters are especially important from an ecological point of view. A northward shift of the freeze line would bring dramatic effects to the Coastal Bend and upper Laguna Madre, allowing southerly biotic communities to expand northward and, due to fewer disturbances from frost, mature and develop more complex ecosystems over time. Already, without a fish kill in the Laguna Madre since 1989, mean fish size increased and predation patterns appear to have changed, altering community interactions.[93]

discharge from the Mississippi River in the future, particularly during El Niño events.[90] Increases in precipitation and water flows would exacerbate the already serious problems of eutrophication and stratification that create the hypoxic "dead zone" in the Gulf, while a drier upstream climate would reduce the size of the near-shore hypoxic zone.

Interactions of sea-level rise with hurricanes and other severe storms have been dominant factors shaping the coastal terrain for the last several thousand years.[16,94] Barrier islands typically move toward the mainland as sea level rises through a process of beach erosion on their seaward flank, overwash of sediment across the island during storms, and deposition of the eroded sediment in the quieter waters of the bay. The rate of this natural migration (roll-over) depends on the rate of sea-level rise and the frequency and severity of storms and hurricanes. Human development disrupts overwash and sediment movement, but storms and sea-level rise continue. The result is erosion of the beach face and nearshore areas. The vulnerability of barrier islands and island communities to increased erosion is already evident along the Gulf Coast in areas like Dauphin Island, Alabama, or Isles Dernieres, Louisiana (Figure 28).

Even if coastal ecosystems can keep up with present and future rates of sea-level rise, the combined impacts of sea-level rise, episodic hurricanes, and human interference with natural barrier processes threaten the survival of coastal ecosystems in the long run. For example, mangrove forests that are stressed by hurricane wind damage are limited in their ability to produce peat, and this keeps the forests from accumulating substrate and growing vertically to keep pace with sea-level rise. Extended seawater flooding then kills the trees and either slows restoration or causes a total loss of habitat.

In the Gulf, rising ocean temperatures will alter coral reef ecosystems. Coral growth is generally restricted to average water temperatures between 72°F and 86°F, and winter temperatures below 64°F affect corals adversely.[95] Currently, summer sea-surface temperatures in South Florida occur near the maximum temperature tolerance of many corals.[95,96] These species face heat stress during episodes of elevated temperature, such as those that accompany El Niño events.[97] The past few years have seen unprecedented declines in the condition of coral reefs in the region, including often extensive coral bleaching, growth of algae on reefs, loss of the dominant herbivore (a sea urchin), and pervasive over-fishing of reef species (Figure 29).[95,98] The shallow waters of the South Florida reefs will make them especially vulnerable to future episodes of higher sea-surface temperatures that are expected to accompany climate change in the Gulf Coast. In the tropics and subtropics, higher temperatures and changes in rainfall often coincide, meaning that nearshore marine organisms may have to cope with fluctuations in salinity while they are stressed to their limits of heat tolerance.[99]

Coral reefs may also be at risk from increases in atmospheric CO_2 concentrations, which will eventually reduce the alkalinity of surface waters. This in turn would decrease the calcification rates of reef-building corals, resulting in reefs with weaker skeletons, reduced growth rates, and increased vulnerability to erosion during severe tropical storms.

Climate-induced changes in ocean temperatures might also alter circulation patterns in the Gulf of Mexico and Caribbean Sea.[100] If so, South Florida could see changes in coastal and marine ecosystems, since it lies at a critical intersection of the Loop Current and the Gulf Stream. The interaction between these major circulation systems controls the distribution, recruitment, and survivability of coastal marine fish and invertebrate communities of the Florida Keys and other areas of South Florida.[101] These currents also influence the residence time of water in nearshore environments and the transport of sediments and nutrients along the coast to Florida Bay.

FIGURE 28
Isles Dernieres

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FIGURE 29a & 29b
Healthy and Unhealthy Corals

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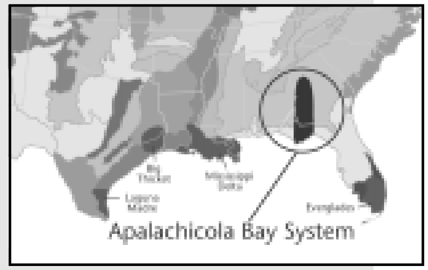
for full-size color images of this figure

RUNNING DRY: THE PANHANDLE REGIONAL ECOSYSTEM (ALABAMA-FLORIDA)



Florida's largest river, the Apalachicola, together with the Chattahoochee and Flint Rivers in Georgia and Alabama, are known collectively as the ACF river system. Together they drain more than 19,000 square miles of watershed that starts in the lower piedmont plateau and flows through the flat coastal plain to form a delta at the shoreline of the Florida panhandle.[101] The Apalachicola Bay at the mouth of the river system is characterized by zones of extreme salinity fluctuation controlled by the combined effects of river flow, seasonal winds, tides, and the shape of the river basin.

Ecosystems in the Apalachicola drainage basin include upland forests, swamps, marshes, and flood-plain wetlands. The sections of the watersheds from the Florida panhandle to Mobile Bay support some of the richest biodiversity in all of North America. The flora of the drainage basin includes 117 plant species, including 28 threatened and 30 rare species. Nine plant species are found only in the panhandle region, while 27 are found only in the general Apalachicola area.[102] The floodplain forests of this region are habitat to more than 250 species of vertebrates, excluding fish, and represent one of the most important animal habitats in the Southeast.[102] Moreover, the highest density of amphibian and reptile species in the United States occurs in the upper watersheds. Two species of birds, the ivory-billed woodpecker and Bachman's warbler, are considered extinct (Figure 30). The barrier islands in this region provide important habitat for Gulf migratory birds. The AFC river system is also known for its diversity of fish, with 85 species.[103] Some species are restricted to the river basins in this central Gulf Coast region, including the striped bass, which occurs only in the Apalachicola River.[104]

FIGURE 30
Pitcher Plant

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Increased demands for water by large upstream cities such as Atlanta have promoted engineering and water-management projects that now divert freshwater resources from the AFC river system. In addition, agriculture extracts well over 300 million gallons per day for irrigation, largely from the Flint River. Massive water consumption by the households and industries of the metropolitan Atlanta region results in minimal upstream storage and marked reductions of water downstream of the city. In addition, the water released back into the system from Atlanta is reduced in quality. Small flows from reservoirs are released to dilute urban wastes, mostly from the Atlanta area, in order to achieve minimally acceptable water quality. Further reductions in reservoir water levels would threaten a multimillion-dollar recreational industry in this watershed.

The current regulation of river flows by reservoirs and by intensive water withdrawals has eliminated much of the floodplain and the dynamic habitats it provided for plants and animals. While human consumption of fresh water is expected to continue to increase, thus likely leading to further reductions of freshwater flow in the Apalachicola Bay system, future rainfall and streamflow are uncertain. Increased moisture may help to alleviate the risk of drying out the area, while additional climate change-related reductions in rainfall and streamflow would markedly reduce the plant and animal productivity and threaten the unique biodiversity of this ecoregion.[105]

CHAPTER
Four

Consequences of a Changing Climate for Ecosystem Goods and Services

The ecological impacts of climate change will have important implications for the goods and services that ecosystems provide to society. As the previous chapter indicates, climate-driven changes must be viewed in the context of human pressures and land-use changes that are already stressing ecosystems. Below we focus on the consequences of climate change for water, air, land, and coastal resources, as well as for the health and well-being of human populations.

Water Resources

Current and growing demands on freshwater resources by cities, farms, and industries leave the Gulf Coast vulnerable to even slight changes in the seasonal or geographic distribution of fresh water. Changes in the supply and distribution of rainfall could have significant impacts on the productivity of agriculture, aquaculture, and forestry, as well as on industrial, recreational, and transportation activities.

Despite the uncertainty about how global warming will affect future Gulf Coast water supplies, the trend in human population growth in the region makes it highly likely that human consumption of water resources will increase. If climate change results in reduced runoff and lower groundwater levels in the spring and summer, the consequence could be an eventual shortage of water to satisfy the growing and competing human demands. In the Floridan aquifer system, increases in water withdrawals for public supply and agriculture have already resulted in declines in groundwater levels (Figures 31 & 32).

The increasing drawdown of surface and underground water reservoirs could combine with sea-level rise to increase saltwater contamination of aquifers, particularly near the coast and in most of South Florida. For example, large groundwater withdrawals in the coastal zones of Baldwin and Mobile counties in Alabama, which include the Mobile Bay and Gulf Shores regions, have increased salinity in wells (Figure 32). Drinking water supplies taken from the Mississippi River for coastal communities such as New Orleans are frequently threatened by saltwater intrusion caused by a combination of sea-level rise, land subsidence, and periodic low river flows. Groundwater rationing is already being implemented periodically during dry conditions in urban regions of Texas, Alabama, and Florida.

An increase in local subsidence and sinkhole formation has also been associated with growing groundwater and natural gas withdrawals. Sinkholes are natural features of limestone geology. However, activities such as dredging, constructing reservoirs, diverting surface water, and pumping groundwater can accelerate the rate of sinkhole expansion, resulting in the abrupt formation of collapse-type sinkholes. Drought can exacerbate the frequency of collapse of these sinkholes, so under the scenario of a drier future climate in the Gulf Coast, this risk would increase.

One of the largest users of surface water in Alabama is thermoelectric power generation. Higher water temperatures could reduce the efficiency of power plant and other industrial cooling systems and make it increasingly difficult to meet regulatory standards for acceptable downstream water temperatures, particularly during extremely warm periods. These problems would be compounded if a warmer climate also becomes drier, resulting in decreased runoff, particularly in areas that are also affected by rising sea levels.

FIGURE 31
Declines in Aquifer Levels

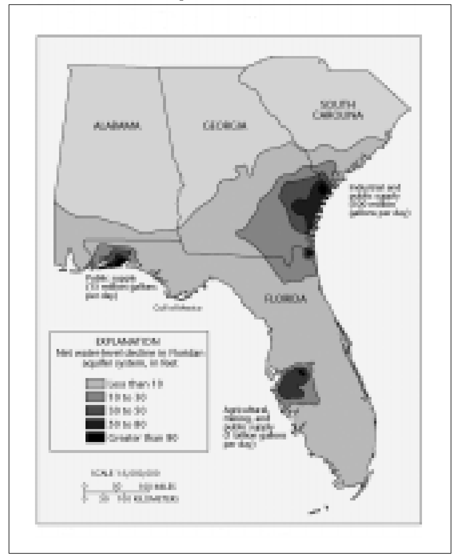

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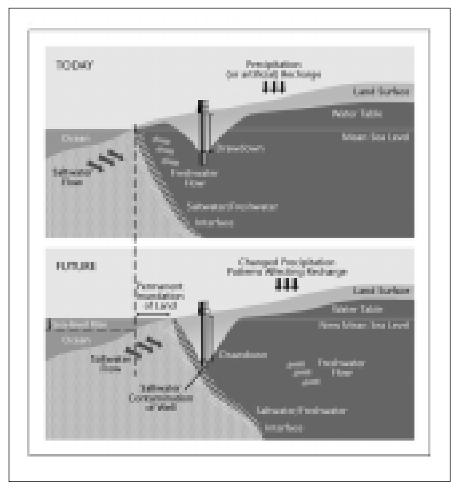
FIGURE 32
Aquifer Drawdown and Saltwater Intrusion



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Agriculture and Forestry

Agriculture and forestry in the Gulf Coast rely heavily on adequate freshwater resources, and the greatest impacts of climate change would be felt through the combination of decreased soil moisture (due to warmer temperatures and possibly reduced rainfall) and reduced water availability for irrigation.

Based on both climate scenarios considered here, drier conditions are possible for the cropland areas in the immediate coastal zone, particularly in southwest Texas, the lower Mississippi Delta, southern Alabama, and the Florida Panhandle.[106] In the drier climate scenario, cotton, soybean, and sorghum productivity would drop without irrigation, while there would be only modest decreases in the production of hay. Citrus production may shrink moderately in Florida. According to model studies, rice yields in Louisiana could decrease by the year 2030 and then possibly increase by 2090, assuming that water is available for increased irrigation.[107]

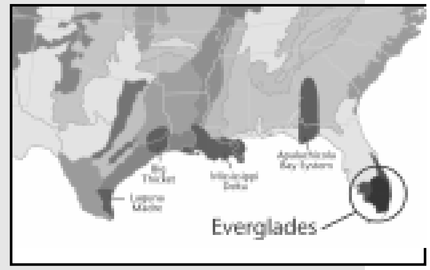
Fertilization of crop growth by higher atmospheric carbon dioxide (CO_2) is unlikely to compensate completely for projected increases in water demand associated with warmer temperatures. In model-based studies, potential yields at higher CO_2-concentrations are realized only with increased irrigation.[106] Thus, increased demand for water by other sectors is likely to amplify negative impacts of warming on agriculture.[106]

Vegetation models using the drier climate scenario project an expansion of savannas and grasslands at the expense of forests, particularly in the uplands of the Gulf Coast.[108] These changes in plant communities would be influenced not only by reduced soil moisture but also by increased fire frequency. If such shifts from forests to dryland vegetation are realized, the results could be dramatic by the end of the 21st century.

> The greatest impacts of climate change on agriculture and forestry would be felt from a combination of decreased soil moisture and reduced water availability for irrigation.

Although the amount of water available will greatly influence long-term changes in forest composition across the region, forest management can change the composition and productivity of forest stands locally over relatively short periods. For example, soil nutrient availability largely controls the productivity of the even-aged plantation stands that now dominate

DRYING OR DROWNING THE "RIVER OF GRASS"?—THE SOUTH FLORIDA REGIONAL ECOSYSTEM



The predrainage landscape of South Florida was a mosaic of habitats connected by fresh water. The water flowed in rivers, streams, and shallow sheet flows across the gently sloping landscape below Lake Okeechobee, through sawgrass interspersed with tree islands and tangled mangrove forests, to shallow estuaries, and out to the coral reefs off shore.[109] Wading birds, alligators, sawgrass plains, mangroves, and tropical hardwood hammocks are still among the most recognizable features of this landscape.[110] The Everglades wetlands once extended over 3 million acres[111] within a total South Florida wetland system of 8.9 million acres, which included the Big Cypress Swamp, the coastal mangrove communities, and Florida Bay.[112]

The natural evolution of this landscape mosaic has been driven by the slow relative rise in sea level over the past 3,200 years, as well as extreme episodic events—in particular, fires, freezes, tropical storms, hurricanes, floods, and droughts.[17] The large variability in rainfall from year to year can bring excessive flooding in some years and drought in others. However, this natural year-to-year variability, along with the normal seasonal variability in rainfall, is a major contributor to the high productivity and biodiversity of these wetlands (Figure 33).[112]

The same episodic events that control the natural landscape also affect human populations. To protect the growing population from severe storms and to support agriculture (especially the sugar industry), South Florida developed one of the world's most extensive water-management engineering systems.[113] These engineering efforts have caused a change in the timing and supply of clean water flows, reducing the Everglades to a degraded remnant that continues to decline.[114] The natural variability of surface water flows has been altered dramatically, so that now in very wet years, massive amounts of fresh water are discharged through canals and via enormous pumps into a few coastal estuaries. The historical sheet flows of water that used to occur along other parts of the coast have been reduced substantially, commonly resulting in saltwater intrusion and occasionally in hypersaline conditions in systems such as Florida Bay.

FIGURE 33
The Everglades

See page 40
for full-size color image of this figure

As a result of the water-management system, the Greater Everglades is an endangered ecosystem whose sustainability is critically at risk.[115] While a great deal of uncertainty remains about the specific impacts to be expected from climate change, global warming is likely to exacerbate the effects of human stressors on the Greater Everglades ecosystem. Among the impacts that can be expected are ecosystem shifts due to sea-level rise and increased success of invasive exotic species. Other major effects could result from more frequent or more intense hurricanes or from more frequent or intensive droughts, which would increase the risk of major wildfires.

The greatest risks the Everglades face from climate change, however, may well be accelerated sea-level rise and the damaging impacts of elevated storm surges. Since the flow of water is the most critical factor in the survival of the region's unique mosaic of habitats, any changes in water balance will certainly affect this unique and valuable landscape. An enormous restoration process recently approved by Congress, the Comprehensive Everglades Restoration Project (CERP), however, does not take into account either sea-level rise or potential shifts in water flow driven by climate change.

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the forestlands of the Southeast, and most of these stands are now routinely fertilized. By selecting different species (or even genotypes) and controlling stand density (through planting and thinning, fertilization, changes in rotation length, and use or prevention of fire), human management will continue to exert the dominant control over the makeup and productivity of forests in the region. This also implies that management practices can be used to adapt to an altered physical environment. However, extreme, long-lasting droughts could still have a negative impact on these managed systems, given their generally shallower fine roots (which leave them more sensitive to soil water deficits) and high canopy leaf areas (which increase evapotranspiration), relative to more open, natural stands of trees.

Forest managers, as well as an increasing number of other landowners, are well aware of the natural role of fire in southern pine forests and would prefer increasing use of prescribed fires to reduce fuel loads and wildfire risks.[116] However, the structure of younger managed forest stands, with continuous tree canopies near the ground and high accumulation of fuels, prohibits the use of prescribed fire during the first decade or so of the typical plantation cycle. The costs and legal liabilities of attempting to manage fire, even in older stands, apparently still outweigh the risks of losses through wildfire, since most forest plantations are still not burned. This situation will lead to increased risk of wildfire if the climate becomes more favorable to fire in the future. During the summer of 1998, drought resulted in more than 2,500 fires that burned roughly 500,000 acres in Florida, destroying valuable timber and damaging roughly 350 homes and businesses (see Figure 6).

> While economic forces are typically the dominant factors controlling the productivity of agriculture and forestry, yields may increase due to higher CO_2 levels if water resources are not limited.

Economic forces have historically been major drivers of changes in the relative distribution of agriculture and forestry. Since most of the forests, along with croplands, are on privately owned land, market forces strongly affect land use.[117] Projected impacts of climate change on the productivity of forests and agricultural areas could lead to reallocation of land uses as landowners adjust to changing economic conditions. For instance, the wetter climate-change scenario projects increased hardwood productivity at the expense of softwoods, resulting in decreased revenues in the latter during the next couple of decades.[118] This shift would cause a slight decline in the amount of forestland, particularly in the Gulf Coast region. Given the current trend of increasing pine plantations in upland regions of Mississippi, Louisiana, and Alabama, an increase in regional rainfall could mean that future conversions of cropland to forestland would either continue at current trends or at slightly lower rates than without climate change. However, under the drier climate-change scenario, conversion of forests into some other land use, such as rangelands, seems significantly more likely.

Warmer average temperatures and milder winters will also result in a higher incidence of damage by agricultural and forestry pests such as the Southern pine bark beetle, which caused over $900 million in damage to southern US pine forests between 1960 and 1990.[119] Milder winters without frost will allow the larvae of several types of pest to produce more generations per year. While moderate water stress can actually increase plants' resistance to plant-feeding pests, severe stress can increase the susceptibility of forests and crops to infestation by pests. Already, agriculture in the Gulf and other Southeastern states consumes 43 percent of the insecticides and 22 percent of the herbicides used by US farmers, even though the region has only 14 percent of the nation's cropland.[106,120] This heavy use of restricted chemicals across the Gulf Coast landscape reinforces concerns about water use and water quality and how climate change may affect both in the future.

Fisheries and Aquaculture

As mentioned earlier, shrimp, blue crab, and menhaden fisheries in the Gulf of Mexico are consistently among the highest valued commercial fisheries in the United States.[54] Assessing the consequences of climate change for these fisheries is complex because of potentially competing effects of temperature, water availability and flow, and impacts on wetlands. Increases in sea-surface temperatures, for example, could enhance the annual yield of shrimp in the Gulf of Mexico. Warmer water and higher growth rates would increase productivity of some commercially valuable, estuarine-dependent marine species, and productivity could be further enhanced over time if wetlands were able to migrate inland in response to sea-level rise (a rather uncertain prospect).[121] However, any enhanced fisheries productivity is likely to be temporary because of other long-term effects on fishery habitat. The annual yield of shrimp in the Gulf of Mexico, for example, declines when the annual discharge of the Mississippi River goes up, expanding the size of the dead zone on the Louisiana shelf.[122] Impacts on coastal marshes in Texas and Louisiana, which serve as nurseries, also affect fisheries production.[123] Rapid sea-level rise and warmer winter temperatures are likely to negatively impact these habitats. If long-term reductions in freshwater flow into estuaries and rapid sea-level rise result in a net loss of coastal marsh area, these fisheries will most likely decline.[124]

FIGURE 34
Shrimp Trawler

See page 40
for full-size color image of this figure

In the semi-arid Laguna Madre of Texas (see box, p.45), the lack of fresh water and highly saline shorelines both limit the development of marshes. If global warming extends this low-rainfall climate pattern northward, the existing intertidal marshes will diminish in area because of shoreline retreat and enlarged salt barrens landward. Such loss of marsh habitat is unlikely to be compensated for by mangroves or seagrasses and would cause fishery yields to decline below historic levels. Significant declines have already been observed in shrimp and blue crab commercial yields in South Texas bays and the Laguna Madre during the drought and warm winter conditions of the 1990s.[125] Also, densities of small fishes, shrimps, and crabs have recently been observed to be lower in Laguna Madre seagrass beds, compared with coastal areas elsewhere in the Gulf of Mexico.[34]

> Increased groundwater salinity resulting from more droughts and saltwater intrusion could negatively impact the region's aquaculture industry.

The large aquaculture industry in Louisiana and Mississippi places high demands on freshwater reserves, particularly groundwater (Figure 34). In most of the Gulf Coast states, about 50 percent of aquaculture ponds use groundwater. In Louisiana, 75 percent use groundwater. Increased groundwater salinity resulting from more frequent droughts and saltwater intrusion could negatively impact the region's aquaculture industry. During the two-year drought from 1999 to 2000, salt contamination of surface and shallow groundwater limited crawfish farming in southwest Louisiana, leading to economic devastation of many crawfish-farmers.

Climate change is also likely to affect the recreational and sport fishing industry. Increased temperatures are unlikely to directly harm most target species since they exist in already warm environments. However, runoff affects freshwater habitats and any reduction in runoff would limit the capacity of these aquatic ecosystems to support fishing activity. Thus, both coastal and freshwater fisheries of the Gulf Coast are vulnerable to potential changes in the flow and availability of water in the 21st century.[127]

Coastal Communities

Much concern about climate change has focused on the potential of more frequent extreme weather events having the greatest direct economic and human health impacts in the United States. The Gulf Coast is particularly vulnerable in this regard.[128] Of the top 15 most notable* weather disasters in the United States, 9 occurred in Gulf Coast states.[129] The top three states in the nation in terms of average annual losses from hurricane, flood, and tornado damage are Florida ($1.7 billion), Louisiana ($966.9 million) and Texas ($909.4 million), with Mississippi following in seventh place ($463.5 million) and Alabama in eighteenth ($185.0 million).[130]

> A growing population in coastal areas leaves more people and property at greater risk from climate change.

The most significant impacts will result from hurricanes and floods, especially as sea level increases, with additional impacts from droughts and thunderstorm-related hazards (hail, tornadoes, and lightning). The number of such events and amount of losses steadily increased from 1949 to 1994, based on statistics from both the insurance industry and the Federal Emergency Management Agency.[131] While national economic losses show an increasing trend, from a few hundred million dollars annually in the late 1970s to $2.5–$21.9 billion annually from 1989 to 1997, trends in the frequency and intensity of tropical storms and hurricanes do not show a consistent parallel increase.[132] However, intense rainfall events (more than 2 inches in a 24 hour period) have increased in frequency.[3] This suggests that the increasing losses are primarily due to societal changes, including a growing population in high-risk coastal areas, and lifestyle and demographic changes that leave more people and property at greater risk.[133]

Against the backdrop of increasing societal vulnerability to hazards, how might trends in weather-related hazards change in the future? A recent review of studies has confirmed that extreme events such as floods and droughts are indeed increasing, but not uniformly across the globe or the United States.[134] The observed evidence is consistent with the general predictions of climate models, which suggest more extreme weather events as a result of global warming.

The number of intense hurricanes making landfall has decreased over the period 1944 to 1996, even while economic damages have soared.[135] Rapid population growth and development in vulnerable coastal areas are primary reasons behind this increase in damages.[136] For example, damages associated with Hurricane Andrew in 1992 were estimated at about $27 billion, nearly three times the costs of any other weather-related event in the Southeast in

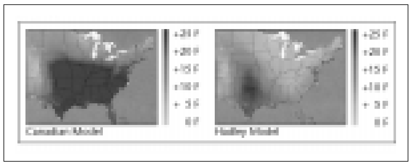
FIGURE 35
Erosion Damage from Tropical Storm Frances (1998)

See page 40
for full-size color image of this figure

* "Notable" was a function of economic losses, death toll, event magnitude, and meteorological uniqueness.

the past decade. Should global warming increase the number or intensity of hurricanes, the impacts on people and property in coastal communities are likely to be severe, especially when aggravated by sea-level rise. But even without an increased frequency or intensity of storms, future storm damages are likely to rise substantially just because of the increased amount of development in harm's way (Figure 35). Predictions of future wave and storm surges accompanying severe hurricanes (categories 3–5) indicate that significant wave heights (between 3 and 6 feet) will occur as far inland as New Orleans, if barrier islands and wetlands are lost as buffers.[137] The ravages of Hurricane Andrew in 1992 on Florida and Hurricane Georges in 1998 on coastal Alabama, Mississippi, and Louisiana, or even Tropical Storm Frances on Texas in 1998 should serve as a telling wake-up call to Gulf Coast inhabitants.[138]

FIGURE 36
July Heat Index Change by 2100



See page 41
for full-size color image of this figure

So far, no trend has been detected in the frequency, duration, or magnitude of droughts in the United States.[139] The most severe droughts in the Mississippi River Basin occurred in the 1930s and mid-1950s, with other major water deficits occurring in the early 1990s[139] and again in 2000. However, projecting future water deficits requires analyzing more than rainfall and other indicators of available moisture. It requires consideration of increased demand on surface and groundwater resources and also the consequences of engineered water systems. As discussed earlier, water demand is increasing in the Gulf Coast region, and higher temperatures will increase evapotranspiration. Whether or not these trends will amount to increasing water deficits depends both on yet-uncertain rainfall changes and on water management. The potential damage that prolonged moisture deficits can bring, given current water consumption in the Gulf Coast, became evident during 2000 with losses estimated at $4 billion to agriculture and related industries.[140]

Public Health

Weather-Related Public Health Issues

The July heat index is projected to increase the most in southern states (Figure 36), and Texas is particularly vulnerable to increased frequencies of heat waves, which could increase the number of heat-related deaths and the incidence of heat-related illnesses. Urban areas such as Dallas and Houston are especially vulnerable to these extreme events, as is Tampa. In each of these cities, deaths attributed to extreme heat conditions average about 28 per year, and this rate could more than double to 60 to 75 deaths per year with a 3°F warming of summer temperatures. Vulnerability to heat-related stress depends largely on people's ability to protect themselves from temperature extremes, that is, on whether or not they can afford air conditioning. Also, the elderly, the very young, and those whose health is already compromised are most prone to illness during heat waves.[141]

Heat-related deaths per year in Dallas and Houston could more than double with a 3°F warming in summer temperatures.

Air quality issues associated with a changing climate include changes in near-surface ozone (smog), particulate pollution, visibility, and pollen counts. Climate change is likely to produce conditions that enhance ground-level ozone formation. Increased concentrations of air pollutants will be particularly evident, for instance, in the Houston-Galveston area, which is one of several Gulf Coast cities currently classified as an area of "severe" non-compliance with federal air quality standards. Ground-level ozone has been shown to aggravate respiratory illnesses such as asthma, reduce lung function, and induce respiratory inflammation.[142] Even modest exposure to ozone can cause healthy individuals to experience chest pains, nausea, and pulmonary congestion.[142] In much of the nation, a warming of 4°F could increase ozone concentrations by about 5 percent.[143]

Upper and lower respiratory allergies are influenced by humidity. Even as little as a 2°F warming, along with wetter conditions, could increase respiratory allergies due to increased pollen counts in Mississippi and Louisiana.[142,144]

Water-Related Public Health Issues

Changes in water availability and flow will influence the prevalence of diseases and waterborne pathogens, especially in densely populated areas. Such changes are typically associated with extreme events and hotter temperatures, which can lead to expanded habitat for and infectivity of disease-carrying insects and an increase in the potential for transmission of diseases such as malaria and dengue fever.[145] Gulf Coast states are cited as particularly vulnerable to these changes; indeed both malaria and dengue fever vectors have already increased markedly, even during the droughts of recent years.[146] Vulnerability to climate-change and water-related health risks is particularly severe in areas where water supply and quality, waste-disposal systems, and in some cases even electricity for heating and cooling, are already substandard (as for example in the "colonias" of South Texas).[147]

> Changes in water availability and flow—typically associated with extreme events and hotter temperatures—will influence the prevalence of diseases and waterborne pathogens.

Although mosquitoes are abundant in many areas of the Gulf Coast, factors other than climate strongly affect the risk of mosquito-borne disease outbreaks. Infrastructure, sanitary, and public health improvements have led to a reduction in cases of dengue fever in Texas from 500,000 in 1922 to only 43 between 1980 and 1996.[148] The ability of the health care system to reduce our health risks in the face of climate change is thus an important consideration in any projections of vulnerability during the 21st century.

Besides the water- and temperature-dependent impacts on disease-carrying insects, a variety of human health risks stems from disease organisms that reside in coastal waters. Those risks can be exacerbated by warmer temperatures and increased rainfall. They include human infections that are acquired by eating contaminated fish and shellfish and diseases acquired during the recreational use of water.[149] Gastrointestinal diseases, respiratory diseases, and skin, ear, and eye infections can all result, and some of these can be fatal, particularly to children, the elderly, and immune-compromised people. Microorganisms associated with diseases in coastal water occur naturally (e.g., *Vibrio vulnificus*, as well as toxic algae and red-tide dinoflagellates) and can enter waterways through the disposal of human and animal wastes.

Changes in temperature, rainfall, and ENSO cycles, together with human factors such as water and sewage management, will determine the distribution of human health risks along the Gulf Coast, both in geography and timing. In Florida, 30 percent of the population uses septic tanks, which contribute about 210 million gallons of waste every day. Those wastes contain microbes that can reach groundwater and nearby surface water bodies. Over the past decade, surveys of indicator bacteria and human intestinal viruses in fresh water and nearshore coastal waters demonstrate that water quality in many of Florida's canals and tributaries has been impacted by wastewater from nearby residential areas. In addition, the contamination is related directly to rainfall, stream flow, and water temperature. Increased rainfall events associated with El Niño in southwest Florida are statistically related to a decrease in water quality. A high incidence of intestinal viruses in nearshore waters and canals has been detected during strong rain events such as those that occurred during the 1998 El Niño. Rainfall has also been linked to a decrease in coastal water quality (measured using bacteria levels) over the past 25 years in the Tampa Bay region. Overall, between 70 percent and 95 percent of the sites surveyed along the west coast of Florida to the Florida Keys tested positive for human intestinal viruses, including coxsackie, Hepatitis A, and the Norwalk viruses, which are associated with diarrhea, aseptic meningitis, and myocarditis, respectively.[150]

Along Louisiana's coast, viral and bacterial contamination of shellfish has repeatedly caused illness (neurotoxic poisoning etc.) and closed important fisheries. The protozoan *Perkinsus marinus* is the most important pathogen threatening the Gulf's significant oyster industry.[151] Prevalence of *P. marinus* has been related to salinity and temperature, with low temperatures and salinities usually limiting infection and higher temperatures and salinities typically increasing it. Long-term climatic changes could produce shifts in salinity and temperature that favor *P. marinus* prevalence and disease. Centers of infection have been found along the central to northern Texas coast in Galveston Bay, the Barataria Bay area of Louisiana, and Tampa Bay.[151]

Warmer coastal waters and nutrient pollution can also increase the intensity, duration, and extent of harmful algal and cyanobacterial (formerly, blue-green algae) blooms, particularly in Florida and Texas. These blooms damage habitat and shellfish nurseries and can be toxic to both marine species and humans. About two-thirds of the Texas coastline was closed to shellfish harvesting in 1996 because of contamination by an unusually large bloom of marine algae, or red tide. In summer 2000, a red tide bloom along the beach at Galveston caused the closing of recreational and commercial operations.

CHAPTER
Five

Meeting the Challenges of Climate Change

Climate change is likely to have a number of disruptive impacts on Gulf Coast ecosystems, as discussed above, especially in light of ongoing human pressures on the environment. They vary in the degree of scientific certainty (see box, p.60), however, we believe that in order to prevent or minimize the negative impacts and to profit from the potential benefits of climate change, people and policymakers in the region can and should take action now.

We outline here three basic strategies for protecting ecosystems and maintaining ecological goods and services in the face of a changing climate:

- **mitigation,** which involves reducing the pace and magnitude of global warming and thus minimizing climate-driven ecosystem change
- **minimization,** which involves reducing the human drivers of habitat destruction and species loss
- **adaptation,** which involves changing the way we do business in order to minimize the severity of climate-change impacts and enhance the ability of ecosystems and Gulf Coast communities to cope with climate change

Together, these approaches can reduce the region's vulnerability to the impacts of climate change and yield significant ecological, economic, and health benefits, even in the absence of major climate disruption.* We consider them a prudent and responsible approach to ensuring stewardship of the Gulf Coast's invaluable ecological resources. Because much of the land in the region is privately owned, strategies for dealing with climatic and human drivers of ecosystem change must involve private landowners as well as governmental agencies and other sectors of society.

Mitigating the Climate Problem

The primary goal of mitigation is to reduce the magnitude of climate stressors that induce ecosystem change. Reducing greenhouse-gas emissions can be seen as a type of "insurance policy" that aims at directly reducing the risks of global warming. Clearly, in the Gulf Coast, where the fossil-fuel industry is the biggest economic sector and where greenhouse-gas emissions are among the highest in the nation, it is critical to find ways to reduce greenhouse-gas emissions without reducing the economic

* The vulnerability of a system to climate change is a function of its sensitivity to changes in climate and its ability to adapt. See note 3.

HOW CONFIDENT CAN WE BE ABOUT CLIMATE-CHANGE IMPACTS ON GULF COAST ECOSYSTEMS?

The climate change assumptions that underlie the assignment of confidence levels include

- an increase of 3–10°F in air temperature over the next 100 years
- a concurrent increase in coastal and inland water temperatures
- a 13-inch average sea-level rise
- an unchanged frequency of severe storms, including hurricanes (except for continued decadal changes in storm frequency such as the projected return to higher storm activity in the Gulf Coast region in the next decade), but possible slight increase in hurricane intensity
- still uncertain changes in the direction and magnitude of water availability

The assigned confidence levels reflect both the level of certainty in climate-change projections and the expected ecosystem response to those changes. In addition, the climate-change impacts are viewed against the backdrop of expected continued increases in population and land-use changes.

Confidence Levels

Potential Impacts on Gulf Coast Ecosystems	High Confidence	Medium Confidence	Lower Confidence
Across All Systems	Increased competition for fresh water among natural, urban, and agricultural ecosystem uses Enhanced spread of invasive species and decrease in native biodiversity Increase in human health effects from heat extremes	Subtropical vegetation moving into central warm temperate region unless hindered or otherwise destabilized by human alterations of the landscape	Major ecosystem changes in wetland, agricultural, and forest ecosystems under drier climate conditions
Upland Ecosystems	Increased pests such as pine bark beetles impacting forests, agriculture, and residential areas, especially under moist climate conditions	Increased forest disturbance from fires, storms, and other physical stressors, and changes in community composition Increased agricultural productivity due to CO_2 fertilization where water is not a limiting factor; reduced where water is a limiting factor and pests increase	Under drier conditions, reduced forest productivity; expansion of grassland vegetation from west to east; shift in moist to dry forests, and from dry forests to savannah vegetation Under drier conditions, fire frequency and intensity may increase, benefiting prairie systems, but negatively affecting production forests and wildlife

Confidence Levels

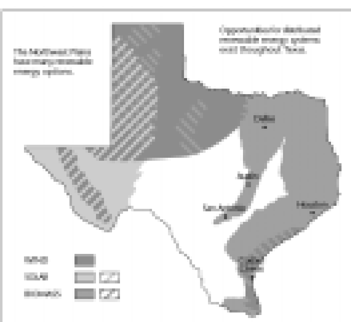
Potential Impacts on Gulf Coast Ecosystems	High Confidence	Medium Confidence	Lower Confidence
Freshwater Wetlands & Aquatic Ecosystems	Increased salinization of groundwater resources Decrease dissolved oxygen in lakes and streams due to higher water temperature	With reduced stream flow in small regional rivers, decrease in productivity of down-stream ecosystems Higher urban runoff impacting water quality and fisheries of lakes and estuaries	Increased flooding of natural systems and floodplains in urban areas
Coastal and Marine Ecosystems	Habitat losses in wetlands not able to migrate inland, accumulate substrate as sea level rises, or adapt to increased salinity and water levels Increased flooding associated with storm surges due to sea-level rise Erosion and eventual loss of barrier islands unable to migrate landward Saltwater intrusion into coastal aquifers Reduced growth and stability of coral reefs due to increased sea temperatures and other stressors	Declining estuarine water quality due to combined changes in runoff and contamination from agricultural and urban sources Increased salinity of estuaries dominated by local runoff and droughts Increased incidence of marine and waterborne pathogens under both climate scenarios Change in frequency and duration of stratification and hypoxia on the continental shelf off the Mississippi River delta as a result of changes in nutrient-laden runoff	Increased stress in tidal marshes in regions becoming drier With reduced streamflow from local rivers and increased salinity of estuaries, reduced wetland habitat, changes in estuarine food web, and long-term declines in marsh-dependent fisheries With reduced streamflow from local rivers, reduced aquaculture productivity; with increases, increased aquaculture productivity

* "Confidence" refers to the level of "scientific certainty" and is based on expert understanding and judgment of the extant scientific literature supporting likely ecosystem impacts of certain climate-related changes. The focus here is on impacts on ecosystems and their goods and services, assuming plausible climate scenarios for the region. Note that the level of confidence is NOT synonymous with the degree of ecosystem vulnerability to climate change, nor to the relative economic or social importance of any particular change.

FIGURE 37
Windmill

See page 41
for full-size color image of this figure

FIGURE 38
Renewable Energy Potential in Texas



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vitality of the region (see Figure 19). Fortunately, according to a growing number of studies by governmental agencies as well as independent research institutions, climate protection and other environmental benefits can be achieved simultaneously with economic gain.[152]

Texas, with the highest annual emissions of greenhouse gases of any state in the United States, is responsible for a significant share of the global burden of CO_2.[153] While emissions from other Gulf Coast states are smaller, crude oil and natural gas production, the petrochemical industry, and reliable supplies of energy are critically important to the whole region. Against this backdrop, it is remarkable how many opportunities for environmental, economic, and public health cobenefits can arise from reducing the consumption of fossil fuel and the emissions of heat-trapping gases. In Texas and Florida, for instance, where a number of cities currently fail to meet air pollution limits, reducing emissions from fossil-fuel burning could help meet federal clean-air standards.[153,154] Gulf Coast states have an immediate opportunity here to develop implementation plans to meet those standards while also reducing global warming pollutants.

Moreover, both Florida and Texas have ample opportunities to contribute to and benefit from the development of clean energy technologies and alternative energy markets (Figure 37). Florida produces only small amounts of fossil fuel but depends heavily on petroleum and electricity, and thus on energy imports. Fossil-fuel consumption is greatest for transportation and for electricity production. In light of its rapidly growing population, support of tougher federal vehicle fuel-efficiency standards, efforts to reduce vehicle miles traveled, and the development of renewable energies such as solar would be most effective.[155] Through the international Cities for Climate Protection Campaign, a number of communities—such as Alachua, Broward, Delta, Hillsborough, Miami-Dade, and Orange Counties in Florida; Miami Beach, Riviera Beach, and Tampa, Florida; New Orleans, Louisiana; and Austin, Texas—are already tackling emission reductions. They are, for example, improving energy efficiency, supporting small-scale use of renewable energy, reducing vehicle miles traveled, cutting waste, and taking other landscaping and planning measures.[156] These can serve as models to other Gulf Coast communities, as does the gubernatorial initiative on energy conservation in Alabama.

Texas has a variety of clean energy resources—wind, solar, biomass, and geothermal. The state has begun to develop some of these and has the market power to help spread their use (Figure 38).[157] The industrial, transportation, and building sectors have significant potential for reducing emissions by switching from coal and oil to natural gas and by using already available technologies to achieve energy efficiencies.[153] With its strong technology and knowledge-based economy, Texas could also make a significant contribution by further developing such technologies for marketing regionally, nationally, and globally.

Texas recently passed an electricity-restructuring bill that tries to assure a bigger role for clean energy sources in meeting the state's energy needs. The state's Natural Resource Conservation Commission decided in fall 2000 to develop an inventory of greenhouse-gas emissions and a plan to address the emissions problem.

> Reducing greenhouse-gas emissions can be seen as a type of "insurance policy" that aims at directly reducing the risk of global warming.

Louisiana is already switching most of its energy production from oil to natural gas and has begun to develop solutions to climate change. The state has recognized four critical opportunities to reduce global warming pollutants: increasing energy efficiency wherever possible, promoting its natural gas resources, promoting and developing renewable energy resources, and improving the state's transportation systems.[158]

In addition, forest conservation, afforestation, and reforestation provide largely unexplored opportunities to reduce atmospheric CO_2, as do agricultural land-use practices that help sequester carbon in soils.[159] While some current agricultural and forestry operations already help to sequester carbon, it is natural forest protection and reforestation that can make a noticeable contribution to the region's mitigation strategies. Such activities can also yield important ecological benefits if biodiversity and other environmental considerations are taken into account. In summary, these examples highlight the modest but important beginnings and opportunities emerging throughout the Gulf Coast states.

Minimizing Human Impacts on the Environment

The second important strategy, immediately available to Gulf Coast states, is to reduce the impact of human drivers of habitat disturbance and destruction. Already stressed ecosystems typically are more vulnerable to additional stressors, such as those associated with climate change.

The litany of pressures from an increasing population include suburban sprawl and habitat fragmentation (see Figure 10), increased use of surface and groundwater resources, diminished water quality, engineering of river flows and runoff, land-use practices such as pest control and fire suppression, and development of barrier islands, wetlands and other ecosystems for human use. In addition, there are market-driven pressures on agriculture to increase yields with high chemical inputs, on fisheries to overharvest, and on forestry to replace diverse natural forests with plantations of a fast-growing species for increased yields.

While these types of land and resource uses currently yield enormous economic benefits to the Gulf Coast, implementing "best practices" can minimize their ecologically harmful side effects. For example, progressive zoning initiatives that integrate different land uses over a smaller area can protect natural resources and open space from suburban sprawl.[160] Best practices can also improve the management of agricultural and aquatic ecosystems to achieve goals such as water conservation and reduced farm runoff (Figure 39). Furthermore, critical evaluation should be given to the role of federal and state subsidies that promote the development and reclamation of certain ecosystems that are also particularly vulnerable to climate change, such as coastal marshes, flood plains, and wetlands.

> Implementing "best practices" can minimize the ecologically harmful side effects of land and water resource use.

FIGURE 39
Improving Irrigation Technology

See page 42
for full-size color image of this figure

Adapting to Climate Change

Finally, Gulf Coast residents, planners, land managers, and policymakers can take actions now that will minimize the potential impacts of global climate change and leave the region better prepared to deal with an uncertain future. Clearly, climate change magnifies the problem environmental managers face all the time: how to balance the uncertainty of environmental changes against the certain costs involved in making management changes. Moreover, the time horizon and geographic scale of human management of ecosystems or natural resources does not necessarily match the natural cycles and processes in these systems. Ecosystems may react with time lags to climatic and human pressures. Thus, we always face the risk of over- or underadapting to climate change. One of the best ways to deal with this irreducible uncertainty in environmental management is to adopt learning-oriented, flexible approaches that include monitoring, periodic review, assessment and adjustment of previous decisions in light of new information—a strategy known as adaptive management.

In the immediate future, the principal targets for adaptation in the Gulf Coast should include

- those natural and managed ecosystems facing the greatest risk of losing their environmental assets or natural resources to climate change
- those decisions that affect land and water management in the long-term
- those climatic changes that are most likely to occur

That does not mean discounting plausible but currently less certain climate changes that could be enormously important in the future. Instead, adaptation measures should be examined for their feasibility under either drier or wetter climate conditions in the future.

Given these targets, the following areas seem most important for consideration in current policy-making, planning, and management decisions.

Adaptation in Water Resource Management

Adaptation options in water resource management are among the most important, since so many Gulf Coast ecosystems and economic activities are potentially at risk if climate change reduces water resources. However, because future water scenarios are uncertain, the greatest emphasis now must be placed on increasing water management flexibility rather than on planning for only a wetter or only a drier future. For example, the prospect of extended periods of drought punctuated by more extreme rainfall and flooding events—a scenario much of the region has already experienced in recent years—would most likely produce significant public pressure for short-sighted but long-lasting measures such as channelization, reservoir construction, levees, etc. Past experience in the Gulf Coast and elsewhere has shown that such "solutions" more often exacerbate rather than alleviate the problem over the long term.

> Water districts could begin now—without commiting to any particular future climate scenario—to review their policies, rules, and decision-making procedures and identify and improve those that restrict their flexibility and adaptive capacity.

The key to increasing water management flexibility is to be able to address year-to-year and seasonal water variability and weather extremes as they occur. Hence, water districts could begin now—without committing to any particular future climate scenario—to review their policies, rules, and decision-making procedures and identify and improve those that restrict their flexibility and adaptive capacity. For example, current rules for freshwater use for specific purposes would limit water management options under different climate scenarios. In addition, Gulf Coast communities and districts could review and produce water plans to address their water needs during drought-of-record conditions, and identify water-management strategies for periods when streamflows, reservoir storage, and groundwater levels are 50 and 75 percent below normal. Water plans should also identify increasing water demands that are driven solely by population growth and increasing water demands from relevant water users such as agriculture, urban areas, and industries. Texas mandated such an assessment in a 1997 amendment to the Texas Water Code. This legislation changed water planning in Texas from a statewide to a regional activity where water supply, storage, and use of streams, river basins, reservoirs, lakes, and groundwater aquifers must now be documented for improved management decisions.[161]

Another useful measure has been enacted in Florida. The state established a regulatory and taxation authority based on watershed boundaries, which allows districts to manage at the appropriate scale to address water-cycle changes.

Regular opportunities arise in the normal life cycle of water-management infrastructure to replace, repair, and if necessary relocate systems to address saltwater intrusion problems, and to reduce public health risks from septic systems by investing in modern sewage and wastewater treatment systems (see Figure 32). However, such opportunities to adapt to changing environmental conditions are frequently missed without a greater awareness of climate change and growing human demands on water systems.

Finally, most of the water-management systems of the Gulf Coast region have been developed to remove excess water and prevent flooding rather than to store water for use during periods of reduced precipitation. One central goal of the Comprehensive Everglades Restoration Project is to limit the present discharge of fresh water to the sea by increasing storage in wetlands for future needs. This approach should be examined throughout the region to increase adaptability to either a wetter or drier future.

> Forest managers can prepare for a changing climate by adjusting species, soil fertility, spacing, rotation length and fire management.

Adaptation in Agriculture and Forestry

Farmers are already accustomed to making season-to-season adjustments in their farming operations, and thus they may be able to respond to changes in long-term environmental conditions by choosing more favorable crops, cultivars, and cropping and irrigation systems. For example, changes in planting and harvesting dates for one crop or shifts to different crop varieties might maintain or increase yield under different climatic conditions. Given the diversity of crop-management options and the uncertainty about soil moisture and the availability of irrigation water in the future, farmers in the Gulf Coast region could benefit from improved information on weather and climate forecasting, such as access to improved ENSO forecasts.[162] In addition, farmers need to become aware of how their land-use practices contribute to larger regional issues of water quantity and quality, since they are important participants in meeting the challenge of climate change in the region.

Potential strategies for foresters include changes in genetic stock and silvicultural systems that can increase water use efficiency or water availability. Improved techniques in sustainable land management should include better information on the likelihood of fire, pests, drought, storms (hurricanes), and other natural disturbances.[106] Forest management offers opportunities to adjust species, genotypes, soil fertility, spacing, rotation lengths, and fire management to accommodate some of the expected consequences of climate change. Strong consideration of the implications of climate change for sustainable forestry is important, given increasing demand for forest products in coming decades.

Forestry and agricultural land-use planning would also benefit from better communication and coordination, such as on decisions about the conversion of marginal lands. Land-use decisions affect carbon and nutrient sequestration, which can influence not only the atmosphere but also water resources. This is particularly important to consider in rehabilitation programs for certain types of forests, such as those that previously inhabited large alluvial plains of the Gulf Coast.[163]

Land-use changes have important feedback effects on climate by modifying the amount of carbon that is stored in terrestrial ecosystems and by modifying the local and regional climate.[3] Both natural and managed ecosystems in the Gulf Coast, but especially forests, currently store substantial amounts of carbon. The amount of carbon stored in ecosystems at any time in the future will depend on a variety of factors. The largest impact will occur as a result of changes in land use and underlying market forces. For example, the establishment of new forests on former agricultural land will increase ecosystem carbon content in proportion to the amount of woody biomass accumulated in trees, along with lesser amounts accumulating in the litter layer and soil. However, increased harvesting of forest plantations, or conversion of forests of any type to urban or other generally nonforested land uses, will lead to proportionate decreases in ecosystem carbon content.

Adaptation in Land and Biodiversity Conservation

Another critical area for climate-conscious planning and management is land and species conservation in the region. Species currently protected within park or conservation land boundaries may migrate out of these areas as the climate changes and lose the protection that ensured their survival. Constructing buffer zones through conservation easements and migration corridors may help these species and habitats to adapt.

Conversely, in the process of ecosystem restoration, it would be short-sighted and imprudent not to consider climate change and sea-level rise.[164] Louisiana, for example, through its Coast 2050 wetland-restoration plan has an opportunity to include these considerations.[165] The most prominent regional example is the unprecedented effort under way now for the ecological restoration of South Florida's Everglades (see box, p.52).[166] In 2000, Congress approved a federal funding bill of $7.8 billion for restructuring the water-management system and acquiring large tracts of land for water storage and nutrient removal.[167] The human-dominated nature of these hydrological and ecological systems will fundamentally affect their ability to adapt to climate change over the next century. The South Florida restoration scenarios were analyzed and the final proposed plan selected in the absence of any assessment of the implications of climate change.

FIGURE 40
Beach Replenishment

See page 42
for full-size color image of this figure

Adaptation in Coastal Communities

Sea-level rise is already occurring and virtually certain to accelerate in a warmer world. An assessment of potential land loss along the Atlantic and Gulf coasts due to sea-level rise has identified Louisiana, Florida, and Texas as having the most vulnerable lowlands. As sea level rises, the statistics used to identify the probability of coastal flooding will have to be reevaluated. A 50-year or even more frequent flood may become as severe as a 100-year flood. Currently, coastal insurance rates are not adjusted for the growing risk from sea-level rise and associated coastal erosion. In order to sustain actuarial soundness and adequately reflect the increasing risk, flood insurance rates (set at the federal level through the National Flood Insurance Program) would need to be adjusted regularly.[168] The Federal Emergency Management Agency estimated in 1991 that the number of households in the coastal flood plain would increase from 2.7 million to 6.6 million by 2100 under a sea-level rise scenario of 15.6 inches over 100 years.[169] While the total economic impact of such a sea-level rise is still uncertain, it is clear that much coastal development is at increased risk in this century.[168]

Typical responses to the landscape changes associated with a rising sea level in the past have included building seawalls and other hard structures to hold back the sea, raising the land and replenishing beaches (Figure 40), or allowing the sea to advance landward and retreating from the shoreline in an ad hoc manner. Each of these options can be costly, both monetarily and in terms of lost landscape features, habitats, buildings, and infrastructure.

Wise long-term planning can reduce some of these future costs. The direct impacts on coastal communities will become evident in two ways: either through gradual erosion and permanent flooding of coastal areas with resulting damage to buildings, infrastructure, and natural ecosystems, or through increasing damages during extreme events, such as coastal storms as the storm surge increases and the beach or wetland buffer is gradually lost.[168] Thus, adapting to sea-level rise involves reviewing the local and regional long-term plans (for example, in shorefront zoning and land-use plans, growth objectives, etc.) and the local and state policies and regulations in place for dealing with the immediate impacts of coastal floods, tropical storms, and erosion.

Florida's Southwest Regional Planning Council, for example, recently decided to include the threat from sea-level rise in its planning. Other environmental-protection measures already in place in Florida have the associated benefit of reducing some of the impacts of climate change. For example, the state has enacted stringent controls on construction seaward of a "coastal control line," reducing further degradation of the shoreline and barrier habitats.

Barrier islands serve a protective function for industrial installations, roads, and human settlements. Recent studies show that restoring degraded barrier islands in some parts of coastal Louisiana could reduce storm surge elevations by up to four feet in nearby coastal communities.[170] Communities from

Texas to Florida will have to adopt restoration strategies to maintain the important function that barrier islands provide.

Given the negative ecological and economic consequences of seawalls and other "shoreline hardening" structures in the long run, states have every incentive to prohibit such construction and to enforce setbacks and retreat when the encroaching sea comes too close to assure reasonable public safety. Meanwhile, they can sustain economic use of coastal areas for years to come by allowing carefully enforced hazard-conscious development of shorefront property. States and communities can also commit resources to buying land and preserving open space after shorefront property has been damaged beyond repair. In the past, this option has been inhibited by high coastal property values and limited local resources, but state funds have been established elsewhere to support such efforts. It is equally important to consider the continuing economic and environmental benefits that come from healthy beaches and habitat preservation for ecotourism and fisheries.

> Communities from Texas to Florida will have to adopt restoration strategies to maintain the protective function that wetlands and barrier islands provide.

Since many coastal communities rely on wetland-dependent fisheries for their economies and on wetlands directly as storm buffers, it is important to provide opportunities for the natural landward migration of coastal wetlands as sea level rises. This can be achieved through conservation or flowage easements financed and managed by governments, private landowners, or conservation groups.

Both shorefront and upland adaptation strategies are supported by the public trust doctrine, which allows local and state governments to enforce the public's right of access to submerged lands, and to wetland and beach preservation, even on private property. The Gulf Coast region derives enormous economic benefits from healthy coastal ecosystems. These benefits should be included in cost-benefit analyses of various coastal management options.

Adaptation to Other Climatic Hazards

In the past, Gulf Coast communities have responded to storms, floods, wildfires, and other disasters primarily through efforts to protect themselves while remaining in hazardous locations. These responses have led to major human alterations of landscapes, vegetation, and water flow, frequently resulting in further environmental degradation that vastly exceeded the consequences of the episodic event that provoked them. For example, partly in response to the devastating hurricanes and floods in the region in the early part of the 20th century, people constructed engineered water systems, levees, and seawalls. In many ways, the Gulf Coast is more prepared for dealing with too much water than with too little. Regional disaster-management efforts are well honed for floods and storms, but less so for droughts. With opposing climate scenarios for the region and continuing uncertainties about the future frequency of hurricanes and tropical storms, Gulf Coast states are well advised to review and enhance their preparedness for disasters related to heat waves, extended drought, and wildfires. This could include preparing emergency water-management plans for urban areas to ensure cost-effective reliability during low-supply times and for coastal areas where saltwater intrusion into coastal aquifers would be aggravated by low freshwater runoff. It could also include organizing small landowners into blocks large enough to develop prescribed fire plans to reduce wildfire hazards in the ever-expanding interface between the human-dominated urban and rural portions of the landscape.

Climate change–conscious hazard management should also include a review of insurance coverage in various segments of the population (such as floodplain residents) and sectors of the economy (such as farmers, small businesses, forest landowners). For example, after Hurricane Andrew, a number of insurance companies wanted to withdraw their coverage in the most immediate coastal areas in Florida, but were prevented from doing so by state law.[171] While insurance withdrawal from hazardous areas would reduce the liability of insurance companies and help sustain their economic viability overall, coastal residents would be left without insurance coverage and thus increasingly vulnerable to severe storms.

Education about Ecology and Global Warming

Finally, we need to raise awareness and understanding of global climate change in the Gulf Coast region. This can begin by educating people of all ages about the cultural and ecological heritage at stake. But it must also involve educating them about the fundamentals of ecology and climate, and what drives them to change. Many Gulf residents' livelihoods are inextricably linked to its natural resources, and visitors from around the world come to the Gulf to enjoy and learn about its ecological heritage. Raising people's awareness and understanding of climate change will help to mobilize public support for minimizing and adapting to climate change.

> Raising people's awareness and understanding will help mobilize public support for minimizing and adapting to climate change.

With the help of the region's science capacity, decision-makers can also improve their understanding and ability to identify those water, air, and land resources that are critical to maintain economic activity and environmental quality in the region. This may include developing inventories that track the incremental demands on, and use of, these resources as population increases and as market forces and land uses change. Such inventories would be an important component of adaptive management schemes for Gulf Coast natural resources, so that adjustments could be made when yet-uncertain climate changes manifest unequivocally in the future.

Appendix: Developing Climate Scenarios

Scientists use two basic tools for projecting future climate change, an activity better thought of as developing plausible future scenarios rather than forecasting the future. These tools include

- historical observations and trends that can be projected into the future
- mathematical models that capture the most important processes determining climate

Building on these two methods to generate plausible climate conditions and extremes, scientists use "what if" scenarios to examine the vulnerability of natural and human systems and the likely impacts of climate change.

Historical observations, such as those described in Chapter 1, help scientists identify trends in important climate variables such as temperature and rainfall and changes in important weather patterns and events such as the El Niño–Southern Oscillation (ENSO) cycle or hurricanes. Computer-based climate models use mathematical representations of the processes that govern atmospheric and oceanic circulation to project future climate variables such as rainfall, temperature, and seasonal changes in climate. General circulation models (GCMs) are the most sophisticated type of climate model. In this report, we use the outputs from two GCMs used for the *US National Assessment:* the Hadley Centre climate model[172] and the Canadian Centre climate model.[173] The scenarios that these two models generate are quite different and we view them as spanning a large fraction of the current climate-change projections.

Two of the most significant differences between climate models involve how they treat complex cloud processes and the interaction between the land surface and the atmosphere. Both are simplified compared with the real world, in part because current climate models overtax even the world's fastest computers. The differences in the way the models treat these complex processes are sufficient to cause different projections of surface warming, evaporation, and rates of rainfall. The differences also influence projected patterns of atmospheric circulation (e.g., the strength of the Bermuda High). However, neither model can be easily dismissed or said to be more or less likely than the other because each has different strengths and weaknesses and captures many features of global climate reasonably well. For the southeastern United States, the Hadley climate model generally depicts a warmer, wetter future climate, while the Canadian climate model depicts a hot, dry future climate.

Despite these significant differences, the projections agree on a number of points: Both models agree that temperatures will increase (more in the Canadian model than in the Hadley model), and both project an accelerating rate of regional sea-level rise. The models differ in their projections of changes in rainfall and runoff and consequently in soil moisture—all critical factors that affect water availability to ecosystems and people in the region. Because adequate water resources are critical to the well-being of both humans and ecosystems, we believe the most prudent approach is to assess the potential outcomes of both drier and wetter conditions and the ability of natural and managed systems to cope with change in either direction.

GCMs cannot project changes in small-scale climate features, such as hurricanes and thunderstorms, or secondary changes, such as fires. To include these features, we have supplemented the model results with a number of other published studies to analyze these other important climate-related drivers of ecosystem change.

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Steering Committee

A national steering committee provided guidance and oversight to ensure the scientific review and integrity of the report. The Steering Committee members were

Dr. Louis F. Pitelka *(Chair)*, Appalachian Laboratory, University of Maryland Center for Environmental Science, Frostburg, Md.

Dr. Mary Barber, Ecological Society of America, Washington, D.C.

Dr. Christopher Field, Carnegie Institution of Washington, Department of Plant Biology, Stanford, Calif.

Dr. Peter C. Frumhoff, Union of Concerned Scientists, Cambridge, Mass.

Dr. Geoff Heal, Columbia University, Graduate School of Business, New York, N.Y.

Dr. Jerry Melillo, Marine Biological Laboratories, Woods Hole, Mass.

Dr. Judy Meyer, University of Georgia, Institute of Ecology, Athens, Ga.

Dr. William Schlesinger, Duke University, Nicholas School of the Environment, Durham, N.C.

Dr. Steven Schneider, Stanford University, Department of Biological Sciences and the Institute for International Studies, Stanford, Calif.

Contributing Authors

Robert Twilley, the lead author of this report, is professor of biology and director of the Center for Ecology and Environmental Technology at the University of Louisiana at Lafayette. Most of Dr. Twilley's research has focused on understanding the ecosystem ecology and management practices of mangrove wetlands both in the Gulf of Mexico (from Florida to the Yucatan Peninsula) and throughout Latin America. Specifically, he works on the nutrient biogeochemistry of wetland and coastal ecosystems, and on coupled ecological and socioeconomic models of ecosystem management in places such as the coastal Everglades, Chesapeake Bay, Albemarle Sound (North Carolina), and coastal Louisiana including the Mississippi River estuary. Dr. Twilley received his Ph.D. in 1982 in plant and systems ecology from the University of Florida, studying mangrove ecosystems at Rookery Bay as part of his dissertation research. He co-edited *The Biogeochemistry of Gulf of Mexico Estuaries.* In 1993, Dr. Twilley directed the scientific advisory panel of the Coastal Restoration of Louisiana Initiative.

Eric Barron is distinguished professor of geosciences and the director of the Earth and Mineral Sciences Environment Institute at Pennsylvania State University. His areas of specialization include global change, numerical models of the climate system, and study of climate change throughout Earth's history. He received his Ph.D. in the study of oceanography and climate at the Rosenstiel School of Marine and Atmospheric Sciences at the University of Miami in 1980. For five years he worked on global climate modeling at the National Center for Atmospheric Research. He has been an active member of the advisory boards for earth sciences at NASA and NSF, including five years as chair of the science executive committee of NASA's Earth Observing System. He is past chair of the climate research committee of the National Research Council and currently chairs the NRC's board on atmospheric sciences and climate. He was a member of the synthesis team for the US National Assessment of Climate Change Impacts. He is a fellow of the American Geophysical Union and the American Meteorological Society, and provided the overview of climate models and climatic processes to this report.

Henry L. Gholz is professor of forest ecology in the School of Forest Resources and Conservation at the University of Florida. His primary scientific focus is on the carbon, water, and nutrient dynamics of forests in the southeastern United States. He is currently involved in a collaborative program to quantify the long-term regional carbon balance of northern Florida. He has been interim chair for the school and developed its agroforestry and tropical forestry programs. Currently on leave from the university, Dr. Gholz is directing the NSF's Long-Term Ecological Research Program. Dr. Gholz received his Ph.D. in forest science at Oregon State University in 1979. He served as an advisor to the US Agency for International Development while a AAAS fellow in 1994–95. He is a member of the NRC's standing committee on agricultural biotechnology, health and the environment. He contributed to the report sections on upland ecosystems, in particular forests, agriculture, and potential impacts on biodiversity in the Gulf region.

Mark Harwell is professor of marine ecology at the Rosenstiel School of Marine and Atmospheric Sciences and, since 1991, the director of the Center for Marine and Environmental Analyses at the University of Miami. His primary interest is in ecological risk assessment and ecosystem management. Before going to Miami, he was the associate director of the Cornell University Ecosystems Research Center. Dr. Harwell (with Jack Gentile) was a leader in developing the US EPA ecological risk assessment framework, including the concepts of ecological indicators and endpoints. He has led several large risk assessments, including on fuel spills in Tampa Bay, on the global change effects on Biscayne Bay, and on the Everglades restoration process. He chaired the US Man and the Biosphere Human-Dominated Systems Directorate and led its core project on ecological sustainability and ecosystem management. For ten years, he served on the EPA's science advisory board, including two terms as chair of the ecological processes and effects committee, working repeatedly on risk-related topics. Dr. Harwell led a five-year international study to assess the global environmental consequences of nuclear war, with emphasis on ecological responses to climate change. He is a member of the US Global Change Research Program's National Assessment coastal sectoral assessment team. Dr. Harwell has served as a member of the NAS board on environmental studies and toxicology and was recently elected a fellow of AAAS. In this report, he provided input on Florida's coastal ecosystems, biodiversity, and on risk and resource management issues.

Richard L. Miller is NASA's chief scientist at the John C. Stennis Space Center in Mississippi. His research interests include the role that river-dominated coastal margins play in the transport and fate of organic carbon, the application of remote sensing technologies to the transport of particles and the measurement of water column productivity, and the development of new technology for coastal ocean measurements. His work contributes to a better understanding of the global carbon cycle and the role of organic carbon in global climate change. Dr. Miller received his Ph.D. in 1984 from North Carolina State University. In this report, he contributed to the sections on climate change, ocean and coastal currents, and their connection to freshwater and sediment input from rivers and estuaries.

Denise J. Reed is a professor in the Department of Geology and Geophysics at the University of New Orleans. Her research interests include coastal marsh response to sea-level rise, the contributions sediments and organic material make to marsh soil development, and how these are affected by human alterations to marsh hydrology. She has worked in coastal marshes in northwest Europe, southern Chile and the Atlantic, Pacific, and Gulf coasts of the United States. She has been involved in restoration planning both in Louisiana and in California, and in scientifically evaluating the results of marsh restoration projects. Dr. Reed was a member of the coastal and marine resources sector team for the US National Assessment of Climate Variability and Change. She received her Ph.D. from the University of Cambridge, U.K., and has worked in coastal Louisiana since 1986. In this report, she contributed to sections on coastal ecosystem response and potential mitigation and adaptation strategies.

Joan B. Rose, an international expert in water pollution microbiology, is currently a professor in the College of Marine Sciences at the University of South Florida. Her research focuses on waterborne disease-causing agents, specifically viruses and protozoa, and technologies for detecting and controlling them. During the last five years, Dr. Rose has been developing microbial risk assessment approaches to model the adverse health effects associated with low-level contamination of drinking water. She currently serves on the water science and technology board of the National Academy of Sciences and on the board of life sciences. She has served on the EPA science advisory board on water filtration and coli bacteria testing and she has recently been invited to join the National Drinking Water Advisory Council. In 2000, *Water Technology* named Dr. Rose one of the most influential people in water in the 21st century. Recently, she was awarded the 2001 Clarke Water Prize. Dr. Rose received her Ph.D. from the University of Arizona in 1985. In this report, she contributed especially to the section on the water-related health concerns.

Evan Siemann is assistant professor in the Department of Ecology and Evolutionary Biology at Rice University. He researches how local environmental factors interact with post-invasion adaptation to determine the likelihood and severity of Chinese Tallow Tree *(Sapium sebiferum)* invasions into East Texas coastal prairie, mesic forests, and floodplain forests. He is also exploring the ecosystem-level impacts of exotic tree invasions into coastal prairies and is engaged in projects to control exotic plant and animal invasions into Texas ecosystems. Other research interests include fruit crop biochemistry, weed management in field crop systems, and the relationship between biodiversity and ecosystem services. Dr. Siemann received his Ph.D. in 1997 in ecology from the University of Minnesota. In this report, he contributed to sections on agriculture, forestry, terrestrial ecosystems, and biodiversity and species invasions.

Robert G. Wetzel is a professor in the Department of Environmental Sciences and Engineering in the School of Public Health at the University of North Carolina at Chapel Hill. The dominant theme that threads throughout his 15 books and over 400 scientific publications is the many connections between biota of upland and land-water interface regions and lakes and rivers. In particular, he works on the chemical and competitive biotic regulation of plants, animals, and microorganisms living in wetlands and open water. Dr. Wetzel has been a faculty member at Michigan State University, the University of Michigan, and until recently the University of Alabama. He has received numerous awards of excellence (e.g., Hutchinson Medal, Naumann-Thienemann Medal, elected member of AAAS and the Royal Danish Academy of Sciences). He is on the editorial board of 12 scientific journals and has served on over 200 boards and panels concerning the functioning and restoration of freshwater ecosystems. Dr. Wetzel received his Ph.D. from the University of California, Davis. In this report, he contributed to sections on the impacts of freshwater ecosystems and resources.

Roger J. Zimmerman is director of NOAA's National Marine Service Fisheries Laboratory (NMFS) in Galveston, Texas. Prominent NMFS issues in the Gulf concern management of shrimp and reef fish fisheries, protection and conservation of sea turtles and marine mammals, and the restoration of coastal wetlands. Dr. Zimmerman's expertise is in marine crustacean biology and estuarine ecology. At NOAA, he has served as scientist and advisor on such fisheries issues as impacts of sea-level rise, loss and restoration of coastal wetlands, delineation of essential fish habitat, effects of low oxygen in offshore waters, the ecology of commercially important shrimp and crab species, and management of estuarine systems. Since 1981, Dr. Zimmerman has also taught and advised students through Texas A&M University on estuarine ecology of the Gulf of Mexico. Dr. Zimmerman received his Ph.D. in biological marine sciences from the University of Puerto Rico in Mayaguez. In this report, he contributed to sections on coastal ecosystems, especially in Texas, and on fisheries.

Confronting Climate Change in the Gulf Coast Region

Prospects for Sustaining Our Ecological Heritage

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The Union of Concerned Scientists
Two Brattle Square, Cambridge, MA 02238-9105
Phone: 617-547-5552 • Fax: 617-864-9405

E-mail: ucs@ucsusa.org • Web: www.ucsusa.org

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The Ecological Society of America
1707 H Street NW, Ste. 400, Washington, DC 20006
Phone: 202-833-8773 • Fax: 202-833-8775

E-mail: esahq@esa.org • Web: esa.sdsc.edu