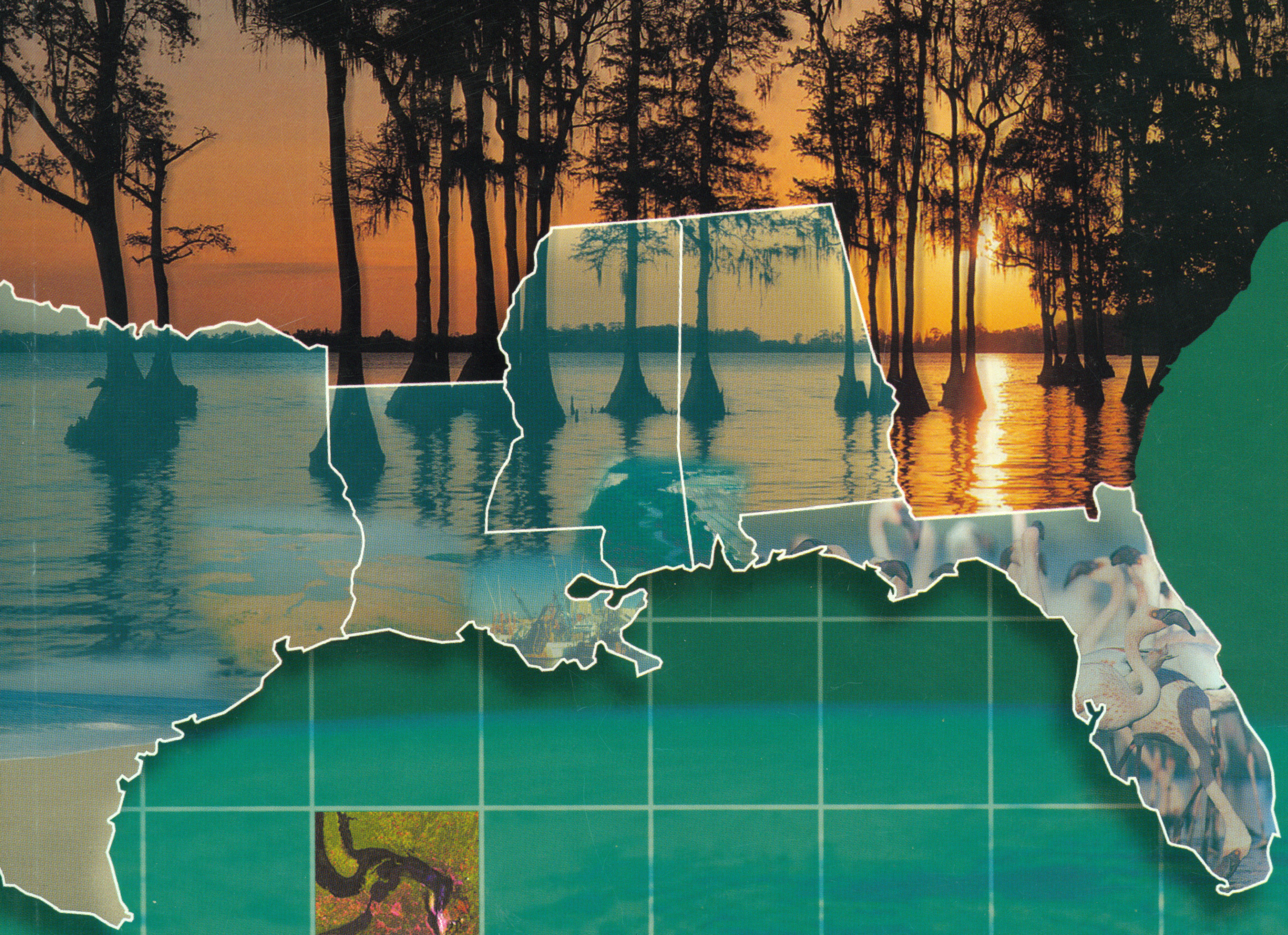
Integrated Assessment of the Climate Change Impacts on the Gulf Coast Region



Gulf Coast Region

Findings of the Gulf Coast Regional Assessment

Zhu H. Ning
R. Eugene Turner
Thomas Doyle
Kamran Abdollahi

June 2003

INTEGRATED ASSESSMENT OF THE CLIMATE CHANGE IMPACTS ON THE GULF COAST REGION

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Part I

Gulf Coast Regional Climate Change Assessment

Chapter 1

Gulf Coast Regional Assessment History

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1.1 Introduction

The Gulf Coast region includes five Gulf Coast states. The specific territories covered in the assessment are the Gulf Coastal Plains and coastal waters of southern Texas, southern Louisiana, southern Mississippi, southern Alabama, and western Florida (Fig. 1). The Gulf itself has a surface area of 1.63 million square kilometers (630,000 square miles) and a watershed area of 4.69 million square kilometers (1.81 million square miles) in the United States. This region is one of the nation's largest ecological systems and is closely linked to a significant portion of the nation's economy. Energy, fisheries, agriculture, forests, and tourism rank among the most significant sectors of the Gulf Coast region's economy. The Gulf has five of the nation's top ten fishing ports. Gulf ports handle one half of the nation's import-export tonnage and the Gulf produces 72% of the nation's offshore petroleum production. The Gulf Coast region relies on many natural resources to fuel many important sectors of its economy.

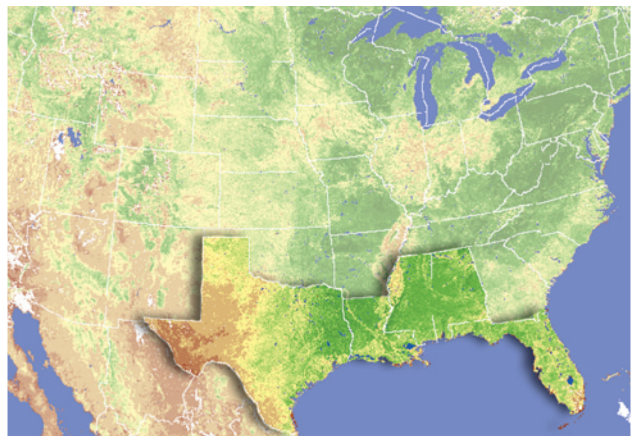

Figure 1. The Gulf Coast region defined by the first National Assessment.

1.2 The Regional Assessment Workshop

To start the regional assessment, the regional assessment team, sponsored by the USEPA, led the region by hosting the Gulf Coast Regional Climate Change Workshop and Public Forum on February 25-27, 1998 (Fig. 2) The workshop participants identified the distinctive regional characteristics and potential consequences of climate variability and change. The workshop participants identified numerous issues of regional concern. Coastal ecosystems, forests, water and air quality, fisheries, commerce, industry, and energy, were the key sectors that they considered vulnerable to climate change. Chapter 2 section 7 of this publication summarizes the key findings of these key sectors/issues at the workshop.

Significant technical contributions to the Workshop were provided by the Workshop Steering Committee members, who represented Southern University, the USGCRP, the White House Office of Science and Technology Policy (OSTP), the National Wetland Research Center (NWRC), Science and Engineering Alliance (SEA), Southern Regional Climate Center (SRCC), National Center for Atmospheric Research (NCAR), NASA, USDA Forest Service, Louisiana State University (LSU), Florida State University (FSU), and Tulane University.

The main purpose of this Workshop was to examine the regional vulnerabilities to climate variability and change and to obtain information that could be aggregated across regions to support the national climate change assessment. The specific objectives of the Workshop were to

(1) Identify current stresses or issues of concern in the region;
(2) Examine how greater climate variability and climate change might interact with the current stresses;
(3) Discuss information needs to further the assessment process;
(4) Identify possible coping mechanisms and define a regional research agenda; and
(5) Design regional follow-up assessment activities.

More than 200 scientists, policy makers, stakeholders, industry representatives, state, regional, and national experts attended the Workshop. Minorities, African Americans, Asians, Hispanics, and Native Americans, in the region were well represented. In addition, the Workshop included participants from the Canadian Ministry of the Environment, and international scientists and students.

The Workshop was extensively covered by the media. A total of eight newspaper articles, four TV news reports, and four radio news reports were generated. Based on the Workshop results, a report has been compiled by the project directors and the breakout session leaders. The report (USGCRP, 1998a) reflected the scope, participation, program, recommendations, and findings. It also includes transcripts of the presentations made by some of the plenary speakers and keynote speakers. The Workshop Steering Committee provided an opportunity for the participants to enhance their contribution through a peer-reviewed compendium published in addition to the Workshop final report. It included articles on climate change and related research findings, climate projections (modeling efforts), and overviews on crucial issues.

The Workshop was an important part of this nation's effort to improve understanding of the present and potential consequences of climate variability and change, both detrimental and beneficial, and to provide a context for understanding these consequences in relation to the pressures created by other long-term stresses on the environment and society. We used the findings and recommendations to adjust the direction of the assessment research program and to support the national assessment activities organized by the USGCRP and the international assessment activities organized by the IPCC. The Workshop helped the regional participants to increase their understanding of what is known, unknown, and uncertain related to the potential consequences of climate variability and change for the Gulf Coast region. The Workshop also provided helpful information to those who protect and utilize our nation's natural resources, who provide for our food, fiber, and economic resources, and who would determine local, national, and international policies.

Figure 2. A session at the Gulf Coast Regional Climate Change Workshop.

1.3 The Regional Assessment Research, Education, and Outreach Activities

The regional team began an integrated assessment of potential consequences of climate change for the Gulf Coast region after the conclusion of the Workshop. Of those sectors/issues the participants identified, the regional assessment research team, due to time and resource constraints, chose two for further work: coastal ecosystems, and maritime (bottomland) forest resources. Case Studies and major findings of the further assessment into those two issues are summarized in Part II and Part III of this publication. The overall goal of the integrated assessment effort was to analyze and evaluate potential consequences of climate variability and change for the region in the context of other pressures on the people, environment, and natural resources. Specific objectives were to

1. Select and apply climate scenarios/models, ecosystem models, and socio-economic trends scenarios to regional data bases,
2. Assess climate change impacts on sectors within the region with emphasis on coastal ecosystems and maritime (bottomland) forests,
3. Identify coping strategies and research needs, and

4. Undertake outreach efforts to stakeholders especially minority communities, small limited resource farmers, minority farmers, small forest woodland owners, and socially and economically disadvantaged communities.

The regional assessment recognized the interrelationship between the physical or natural environment and human activities. This relationship balances the environmental and economic attributes of a region by linking the goals of environmental protection and economic development. Ecological, economic, social, and cultural values related to coastal ecosystems and maritime forests were incorporated into the assessment process. The process also included climate scenarios, ecosystem models, and socioeconomic trends. Assessment of these two key issues was performed through a range of illustrative and supportive case studies. The case studies approach added substance to the assessment. Case study results also provided sound and scientific data to support the impact projections and analyses. Each case study was of importance to answer questions related to key issues. The title and the content of each chapter of this book is based on the topic and the results of each case study conducted.

The lead institution, Southern University and A&M College (SU), is an 1890 land-grant Historically Black College and University (HBCU). Southern University is the largest institution within the nation's historically black university system with 5 campuses and is optimally positioned to serve African American and other minority communities in the Gulf Coast region. To promote regional participation, this assessment was accomplished by the joint efforts of Southern University, Louisiana State University, National Wetland Research Center, and Alabama A&M State University (an HBCU).

Outreach and stakeholder involvement were also a fundamental component of the assessment. The stakeholder network that was initially established through the Gulf Coast Regional Climate Change Assessment Workshop was expanded. These stakeholders included policy makers, managers, planers, scientists, private business owners, farmers, fishermen, minorities, and low-income communities. Outreach meetings were hosted to obtain detailed information on key issues, concerns, coping strategies, and information needs.

The assessment provided answers to four questions: 1.What are the current environmental stresses and how are they likely to play out in the future without a change in climate or climate variability? 2. How will a change in climate or climate variability affect these environmental stresses? 3. How can people cope with climate variability and change in ways that help with other environmental stresses? 4. What research is needed to better estimate the consequences of climate variability and change?

1.4 Assessment Approach and Methodology

1. Setting the regional baselines and scenarios

A sound understanding of current conditions and future trends is necessary for the conduct of any climate change impact assessment. Therefore, the first step of the assessment was the establishment of regional baselines and scenarios.

Baselines for the regional climate, human environment, and natural environment, and possible future scenarios were established based on the Workshop participants' inputs, literature, and scientific data. The three baselines were established simultaneously in order to describe current conditions in the region. The established current condition provided information for the projection of future scenarios. The projected future climate scenario and human environmental scenario were synthesized to provide information for the projection of the natural environmental scenario. Information obtained from the baseline conditions and climate scenarios was used to assess the impact of climate change on the natural environment, human, society, and economy of the region.

2. Selection of two specific priority sectors: coastal ecosystems and maritime forests

This assessment investigated the implications from climate change on the natural environment of coastal ecosystems and maritime forests. The assessment of the impact on the natural environment provided information for understanding both the causes and impacts of societal responses to climate change. Also, the assessment of the natural environment was integrated with the assessment of the socioeconomic/human environment impact in order to provide a comprehensive understanding of the human dimensions of the change.

3. Literature review of the current condition of selected ecosystems, their socioeconomical significance, and the potential climate change impacts on the selected ecosystems

An extensive literature review enabled the team to access information on the current condition of the selected ecosystems, their socioeconomical significance, and the potential climate change impacts on these selected ecosystems. The potential consequences and impacts of climate variability and change on the region's natural and socioeconomic/human environment was assessed by integrating the following: 1) background information on the region's natural and socioeconomic/human environment, in which its people live; 2) the region's historical climate; and 3) likely changes in its future climate.

4. Summarizing the literature review and incorporating case study results as quantitative examples to illustrate and support the qualitative and quantitative information

We accomplished the research and assessment activities through case studies. The case studies added substance to the assessment by providing sound scientific data to support the impact predictions and analyses. Each case study was designed to answer questions that relate to a key issue. The specific ecological systems and locations of the case studies were chosen based on their representativeness of the Gulf Coast region. Through these case studies, team members have:

- Established baseline conditions,
- Described the role of natural and human environment in the regional economy,
- Summarized the effects of current climate variability and change,
- Predicted future effects of climate variability and change,
- Analyzed the impact of human activity,
- Provided a qualitative assessment of the consequences on the region's economy,
- Developed management/adaptation/coping strategies, and
- Defined future research needs.

5. Conducting a qualitative assessment of the socioeconomic implications of the projected ecological changes in these sectors through case studies

The major source for making the qualitative assessment was the current literature. Team members presented the results of projected socioeconomic impacts from the case studies to stakeholders at meetings and gathered information on the socioeconomic impacts that the local community is currently experiencing and feel they could experience in the future.

6. Generating, through case studies and outreach activities, an array of adaptation strategies that merit further investigation

The results of analytical work, outreach activities, and the outcomes obtained in steps 1-5 provided the information and input to accomplish step 6. In the process of accomplishing step 1-5, the assessment team members assessed the vulnerability of people in response to the consequences of climate change, and developed coping strategies based on these consequences and related vulnerabilities. Through the case studies and the sectional assessment, scientists obtained a better understanding of what is known and what is unknown. Based on the findings, the future research needs were identified.

7. Defining coping strategies and future research needs based on the work described above and stakeholders input

In the process of accomplishing this assessment, two symposia, two meetings, one roundtable, two summer institutes, and numerous seminars were organized. These venues provided the stakeholders a variety of fora for discussing coping strategies and research needs. The stakeholder input reflected the real needs of the people in this region. Questionnaires were distributed to obtain a broad input for the public on coping strategies and research needs.

Coping strategies and research needs were synthesized from the several activities and evaluated for consistency across activities and for feasibility. Candidate coping strategies were analyzed with respect to institutional constraints and other potential barriers to their implementation. Research needs were analyzed with respect to their compatibility with existing research programs and ranked by priority of the needed research results.

8. Integration of information/results into regional assessment publications

Assessment results were combined and integrated prior to publication. Volunteers, identified as technical experts, conducted extensive technical peer review of the regional assessment publications for scientific and technical accuracy and validity. Provisions were also made for including general comments from stakeholders. The review procedures were coordinated by the assessment Team Leader. The Team Leader provided a central distribution and receiving point for written reviews. The Team Leader was also responsible for responding to and documenting the responses to written review comments. (see Appendix 1 for documented peer review process)

REFERENCE

USGCRP 1998. Gulf Coast Regional Climate Change Workshop Report, complied by Zhu H. Ning and the regional assessment team members for the USGCRP, can be found at http://www.nacc.usgcrp.gov/regions/gulfcoast.html

Chapter 2

Physical and Natural Environment of the Region

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2.1 Introduction

The specific territory covered by the regional assessment encompasses the Gulf Coastal Plains and coastal waters of southern Texas, southern Louisiana, southern Mississippi, southern Alabama, and western Florida **(Fig. 1).** Wetlands are a typical landscape in the Gulf Coast area. Wetlands include areas where the water table is usually at or near the surface or where the land is covered by shallow water. These habitat types are abundant in the Gulf of Mexico. Wetlands may be forested, such as swamps and mangroves, or nonforested, such as marshes, mudflats, and natural ponds. Large areas of nonforested wetlands are found in coastal Texas, Louisiana, and Florida. Recent state estimates of coastal wetlands acreage (both forested and unforested) are: Alabama (121,603 acres); Florida (2,254, acres); Louisiana (3,910,664 acres); Mississippi (64,805 acres); and Texas (412,516 acres) (Ringold and Clark, 1980).

2.2 Physiogeographic Descriptions of the Gulf Coastal States

The physiogeographic descriptions of five Gulf Coastal states in this section are based on information obtained from Duncan, et al, 1995, The World Book Encyclopedia, 1998, and the New Encyclopedia Britannica, 1998.

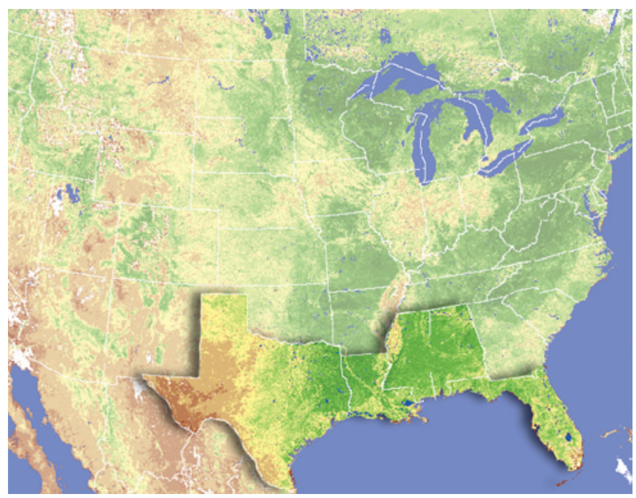

Figure 1. The Gulf Coast region defined by the National Climate Change Assessment.

Alabama

Most of southern Alabama lies less than 500 feet (150 meters) above sea level. The surface of the state rises gradually toward the northeast. Alabama has six main land regions: (1) the East Gulf Coastal plain, (2) the black belt, (3) the piedmont, (4) the Appalachian Ridge and Valley Region, (5) the Cumberland Plateau, and (6) the Interior Low Plateau **(Fig. 2).** The east Gulf Coastal plain is Alabama's largest land region. It covers the entire southern two-thirds of the state, except for a narrow strip of land called the black belt. In western Alabama, the plain extends

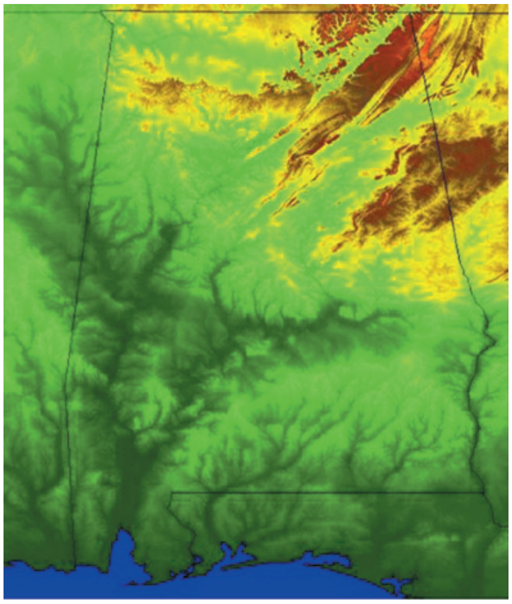

Fig. 2. Alabama territory covered by the Gulf Coast regional assessment.

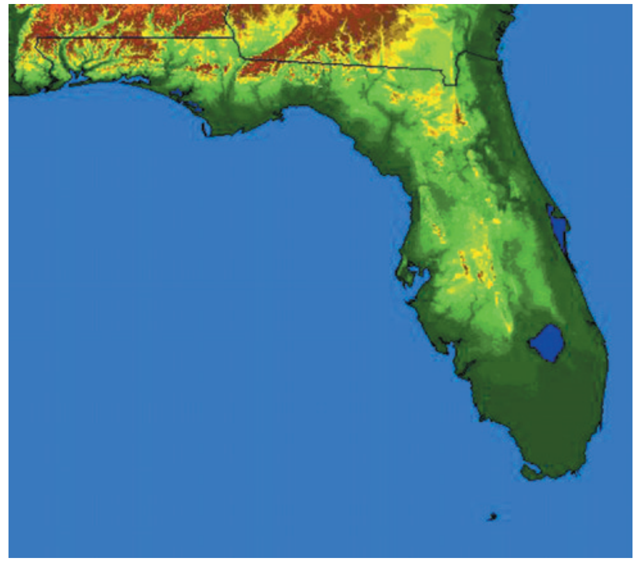

Fig. 3. Florida territory covered by the Gulf Coast regional assessment.

north almost to Tennessee. The plain has several sections. The low, swampy land of the Mobile River Delta makes up the southwestern section. The southeastern part is called the Wiregrass area. It is named for a tough grass that once grew there in pine forests. Today, the Wiregrass area is an important farming region. The northern part of the plain is often called the Central Pine Belt because many pine forests cover its low, rolling hills. In the western part of this section, the soils are gravelly and sandy, and are not good for growing crops.

The black belt is a narrow strip of rolling prairie wedged between the northern and southern parts of the East Gulf Coastal plain. The black belt was named for the sticky black clay soils of its rolling uplands. Early in Alabama history, farmers developed large plantations in this region. Boll weevils came to the black belt in 1915, and damaged the cotton crop. Some farmers then changed from growing cotton to raising livestock.

The piedmont in east-central Alabama, is an area of low hills and ridges separated by sandy valleys. The clay soils of these hills and ridges have been badly eroded. Most of the land is forested. Cheaha Mountain, the highest point in Alabama, rises 2, 407 feet (734 meters) on the northwestern edge of the Piedmont.

The Appalachian Ridge and Valley Region is an area of sandstone ridges and fertile limestone valleys. It lies northwest of the piedmont. The region has coal, iron, oil, and limestone—the three basic minerals used in making iron and steel.

The Cumberland plateau, also known as the Appalachian plateau, lies northwest of the Appalachian Ridge and valley region. The surface varies from flat to gently rolling land. It reaches a height of about 1,800 feet (549 meters) above sea level in the northeast. The land slopes to about 500 feet (150 meters) where it meets the east gulf coastal plain in the southwest.

The interior low plateau lies in the northwestern part of the state. Much of the land is in the valley of the Tennessee River.

Florida

Florida is part of the Atlantic-Gulf Coastal plain, a large land region that extends along the coast from New Jersey to southern Texas. Within Florida, there are three main land regions (1) the Atlantic Coastal plain, (2) the East Gulf Coastal plain, and (3) the Florida uplands **(Fig. 3).**

The Atlantic coastal plain of Florida covers the entire eastern part of the state. It is a low, level plain ranging in width from 30 to 100 miles (48 to 160 kilometers). A narrow ribbon of sand bars, coral reefs, and barrier islands lies in the Atlantic Ocean, just beyond the mainland. Long shallow lakes, lagoons, rivers, and bays lie between much of this ribbon and the mainland.

Big Cypress Swamp and the Everglades cover most of southern Florida. The Everglades include 2,746 square miles (7112 square kilometers) of swampy grassland. Water covers much of this region, especially during the rainy months.

The Florida Keys makes up the southernmost part of the state. These small islands curve southwestward for about 150 miles (241 kilometers) off the mainland from Miami. Key largo is the largest island.

The East Gulf Coastal plain of Florida has two main sections. One section covers the southwestern part of the peninsula, including part of the Everglades and Big Cypress Swamp. The other section of Florida's East Gulf Coastal plain curves around the north edge of the gulf of Mexico across the panhandle to Florida's western border.

The East Gulf Coastal plain is similar to the Atlantic coastal plain. Long, narrow barrier islands extend along the Gulf of Mexico coastline. Coastal swamps stretch inland in places.

The Florida uplands are shaped somewhat like a giant arm and hand. A finger of the hand points down the center of the state toward the southern tip of the peninsula. The uplands separate the two sections of the East Gulf Coastal plain from each other and separate the northern section from the Atlantic Coastal plain.

The uplands region is higher than Florida's other land regions. But its average elevation is only between 200 and 300 feet (61 and 91 meters) above sea level. Lakes are common in the Florida uplands. Many of these lakes were formed in sinkhole-cave-ins where a limestone bed near the surface was dissolved by water action. Pine forests grow in the northern section of the uplands.

The northern part of the Florida uplands extends from the northwestern corner of the state along the northern border for about 275 miles (443 kilometers). Its width varies from about 30 to 50 miles (48 to 80 kilometers). This section has fertile valleys and rolling hills of red clay. The southern part of the Florida uplands is a region of low hills and lakes. It covers an area about 100 miles (160 kilometers) wide and about 160 miles (257 kilometers) long.

Louisiana

Most of Louisiana was once part of an ancient bay of the Gulf of Mexico. The Mississippi and other rivers flowing from the north brought huge amounts of silt to the bay. This action over thousands of years built up the land area to its present size. Louisiana has three main land regions. All are part of the fertile low land that lies along the Gulf Coast of the United States **(Fig. 4.).** These regions are (1) the East Gulf Coastal plain, (2) the Mississippi alluvial plain, and (3) the West Gulf Coastal plain.

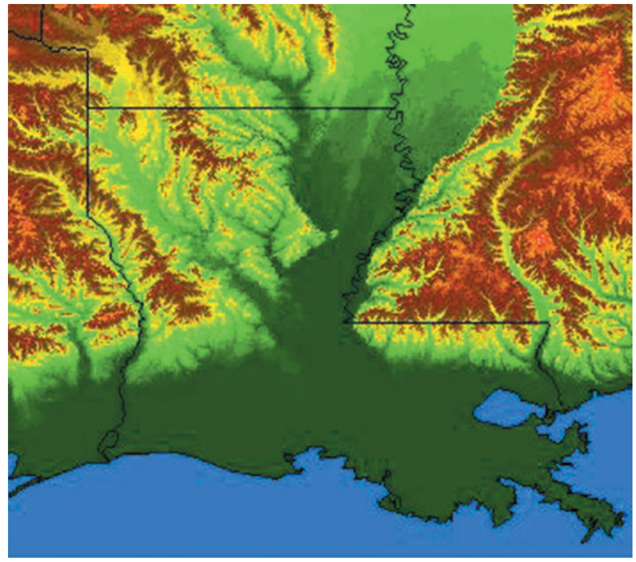

Fig. 4. Louisiana territory covered by the Gulf Coast regional assessment.

The East Gulf Coastal plain in Louisiana covers the area east of the Mississippi river and north of lake Pontchartrain. It rises gradually from marshes in the west and south to low, rolling hills in the north.

The Mississippi alluvial plain lies along the lower Mississippi river. In Louisiana, it reaches from the Arkansas state line to the Gulf of Mexico. Broad, low ridges and hollows parallel the river as it winds down the plain. The high fields atop the ridges are called frontlands. The frontlands slope away from the river to the backlands, which are great stretches of clay and silt. The backlands have several ancient channels of the Mississippi, far from its present course. The Mississippi Delta was formed of silt brought to the river's mouth. It covers about 13,000 square miles (33,700 square kilometers)-about a fourth of Louisiana's total area. The delta has the state's most fertile soil.

The West Gulf Coastal plain includes all Louisiana west of the Mississippi alluvial plain. At the southern end of the plain, low sand ridges called barrier beaches lie along the Gulf of Mexico. Behind these beaches, marshes stretch inland for about 20 miles (32 kilometers). Beneath the marshes and the coastal and offshore waters are large underground formations called salt domes. These domes cap great deposits of salt. Pools of natural gas and petroleum are trapped along the sides of the salt deposits. Sulfur is sometimes found in the top of the domes between the salt and the upper crust.

North of the marshlands, the gently rolling Louisiana prairies-about 60 miles (100 kilometers)

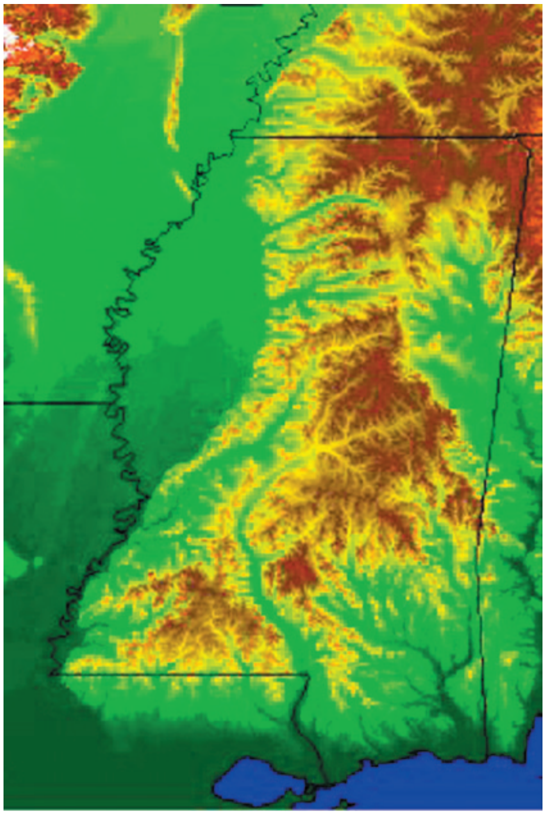

Fig. 5. Mississippi territory covered by the Gulf Coast regional assessment.

wide-reach westward across the plain to Texas. North of the prairies, the land rises gradually as it stretches toward Arkansas. The highest point in Louisiana is 535-foot (163-meters)Driskill Mountain, about 40 miles (64 kilometers) from the Arkansas line.

Mississippi

Mississippi has two main land regions: (1) the Mississippi alluvial plain, and (2) the east Gulf Coastal plain **(Fig. 5).**

The Mississippi alluvial plain covers the entire western edge of the state. It consists of fertile lowlands and forms part of the 35,000-square-mile (90,600-sequare-kilometer) alluvial plain of the Mississippi River. The region is quite narrow south of Vicksburg. North of the city, the plain spreads out and covers the area between the Mississippi and the Yazoo, Tallahatchie, and Cold Water rivers. Floodwaters of the rivers have enriched the soil of the region with the deposits of silt. The fertile soil of the Mississippi alluvial plain is famous for its large cotton and soybean crops. Most Mississippians call this region the Delta.

The east Gulf Coastal plain extends over all the state east of the alluvial plain. Most of the region is made up of low, rolling, forested hills. The coastal plain also has prairies and lowlands. Yellowish-brown loess (soil blown by winds) covers the region in the west. Most Mississippians call these deposits the cane, bluff, or loess hills. The Tennessee River hills rise in northeastern Mississippi. They include the highest point in the state, 806-foot (246-meter) Woodall Mountain. The Pine Hills, often called the Piney Woods, rise in the southeastern part of the region. They are covered largely with longleaf and slash-pine forests.

The main prairie is called the black belt or black prairie because its soil is largely black in color. This long, narrow prairie lies in the northeast section of the state. The black belt stretches through 10 counties. Livestock graze there, and corn and hay grow well on the farmlands of the black belt. Small prairies also lie in the central Mississippi, east of Jackson. Along the Mississippi Sound, lowlands stretch inland over the southern portion of the region.

Texas

Texas has five main land regions. These are, from east to west: (1) the Gulf Coastal plains, (2) the prairie plains, (3) the rolling plains, (4) the Great Plains, and (5) the basin and range region **(Fig. 6).**

The Gulf Coastal plains of Texas are part of the fertile lowland that lies along the entire gulf coast of the United States. They range in elevation from sea level to about 300 feet (91 meters) above sea level. A subtropical region extends along a large part of the coast.

The southernmost part of the coastal plains consists of the fertile Rio Grande Valley. Just north of this valley lies the Middle Nueces Valley, part of the Nueces Plains. The two valleys are famous for their winter vegetables and fruits. The region along the coast from the Rio Grande Valley to Louisiana has rich soils. Cotton and several types of grain thrive in this region.

The northeastern part of the plain is a timberland with thick forests of oak, pine, sweet gum, and other trees. This area is often called the piney Woods. Major lumber and paper companies own most of the land. Farmers in this area raise beef and dairy cattle and poultry. The region has many large mineral deposits

The prairie plains lie west of the forest belt of the coastal plains. The prairie plains feature alternating belts of rugged hills and rolling hills. The rugged

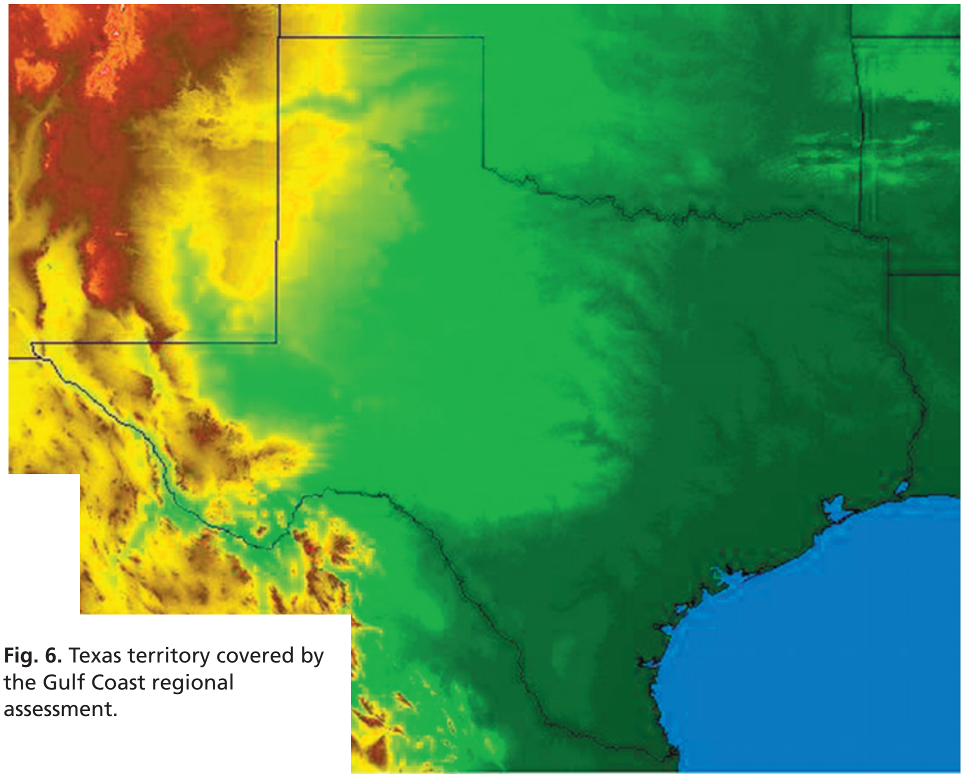

Fig. 6. Texas territory covered by the Gulf Coast regional assessment.

hills are covered with oak and hickory forests. The region includes the fertile Black Waxy prairie. The prairie has rich soils for farming.

The rolling plains are a hilly area west of the prairie plains. The areas' elevation increases as it approaches the Great Plains to the west. The region has scattered belts of fertile farmland and rich petroleum deposits.

The Great Plains reach westward from the prairie plains and the rolling plains into New Mexico. They form part of the series of treeless plains that extends northward through the western United States into Canada. The Great Plains of Texas rise from an altitude of about 700 feet (213 meters) above sea level in the east to over 4,000 feet (1,200 meters) above sea level in the west.

A large part of the Great Plain region lies within the Texas Panhandle, the part of the state that juts northward alongside new Mexico and Oklahoma. The western part of the Panhandle is called the Liano Estacado (staked Plains) or the high plains. This treeless grassland is a high plateau. The Liano Estacado has many irrigated cotton, grain sorghum, and wheat farms. The southern part of this area lies above an underground region called the Permian Basin. The state's largest petroleum and natural gas deposits are in the Permian Basin.

The Edwards Plateau forms the southern part of the Great Plains. Its surface is mainly bare limestone bedrock, but it is dotted with shrubs and sparse grasses. Thick grasses grow in the plateau's river valleys and basins. In the eastern part of the Plateau, the land becomes irregular, forming what is called the Texas Hill Country More sheep and goats are raised in the Edwards Plateau than in any other part of the United States.

The basin and range region, commonly called the Trans-Pecos Region, make up the westernmost part of the Texas. It includes high, partly dry plains that are crossed by spurs of the Rocky Mountains. These spurs include, from north to south, the Guadalupe, Davis, and Chisos Mountains. The peaks that do not form continuous ranges are called Lost mountains. Farmers use the level sections mainly for raising cattle, with some irrigated agriculture on the plains along the Rio Grande. Many beautiful mountain gorges are along the upper Rio Grande, which forms the region's western border. Santa Elena canyon, in Big Bend National Park, is one of the area'smost spectacular gorges.

2.3 Land use

Table 1 and 2 provided summary of land use information of the five Gulf Coastal states.

Table 1 Land Cover/Use, by State: 1992.

[in millions of acres (1,940,000 represents 1,940,000,000)]

States	Total surface area[a]	Non-federal			
		Total	Developed[b]	Rural Land	
				Total	Crop land
United States	1,937.7	1,480.9	91.9	1,389.0	382.0
Alabama	33.1	31.2	2.0	29.1	3.1
Florida	37.5	30.4	4.6	25.8	3.0
Louisiana	30.6	26.4	1.8	24.6	6.0
Mississippi	30.5	28.0	1.3	26.7	5.7
Texas	170.8	163.7	8.2	155.5	28.3

a, includes water area not shown separately.
b, includes urban and built-up areas in units of 10 acres or greater, and rural transportation

Source: U.S. Census Bureau, Statistical Abstract of the United States 1999.

Table 2 National Forest System Land By States: 1997.

[in thousands of acres (e.g., 231,884 represents 231,884,000)]

State Total	Gross area within unit bounaries[a]	National forest system land[b]	Other lands within unit boundaries
United States	231,808	191,785	40,023
Alabama	1,290	665	625
Florida	1,418	1,147	271
Louisiana	1,025	604	421
Mississippi	2,312	1,158	1,154
Texas	1,994	755	1,239

a, Comprises all publicly and privately owned land within authorized boundaries of national forests, purchase units, national grasslands, land utilization projects, research and experimental areas, and other areas.
b, federally owned land within the “gross area within unit boundaries.”

Source: U.S. Census Bureau, Statistical Abstract of the United States 1999.

2.4 Water Resources

Table 3 provided summary of water resources information.

Table 3 Land and water area of states and other entities: 1990.

State	Total area		Land area		Water area			
					Total		Inland	Coastal
	Sq.mi.	Sq.km.	Sq.mi.	Sq.km.	Sq.mi.	Sq.km.	Sq.mi.	Sq.km.
United States								
Alabama	52,237	135,293	50,750	131,443	1,486	3,850	968	519
Florida	59,928	155,214	53,937	139,697	5,991	15,517	4,683	1,308
Louisiana	49,651	128,595	43,566	112,836	6,085	15,759	4,153	1,931
Mississippi	48,286	125,060	46,914	121,506	1,372	3,553	781	591
Texas	267,277	692,248	261,914	678,358	5,363	13,890	4,959	404

Source: U.S. Census Bureau, Statistical Abstract of the United States 1999.

Alabama

Navigable rivers flow through almost every part of Alabama. The Mobile River and its tributaries flow south to the Gulf of Mexico. They form the most important river system in the state. The Alabama and the Tombigbee, Alabama's longest rivers, meet about 45 miles (72 kilometers) north of Mobile and form the Mobile River. The Chattahoochee River forms much of the border between Alabama and Geogia. The Tennessee River (Fig. 7) is the most important river in northern Alabama. It flows west across almost the entire width of the state. However, Alabama has no large natural lakes, and dams on rivers have created many artificial lakes.

Florida

Florida has many rivers, such as Escambia river, Yellow river, Apalachicola river, Suwannee river, and more. There are abundant creaks and lakes as well. Among all five Gulf Coastal states, Florida has the largest water area.

Louisiana

The waters of all the rivers in Louisiana find their way to the Gulf of Mexico. The Mississippi, of course, is Louisiana's most important river. Other important rivers in the state include the Atchafalaya, Black, Calcasieu, Ouachita, Pearl, Red, and Sabine.

Mississippi

Mississippi has many rivers and lakes. The nation's most important river, the Mississippi forms most of the state's western border. Its floodwaters, in earlier times, often deposited silt on the land and helped make the land fertile.

The state has several main river basins. The rivers of the western and north-central basin drain into the Mississippi River. These rivers includes the Big Black River and the Yazoo River with its tributaries, the Coldwater Big Sunflower, and Tallahatchie rivers. Rivers of the eastern basin drain into the Gulf of Mexico. They include the Pearl, Pascagoula, and Tombigbee. Many of Mississippi's lakes are artificially created reservoirs.

The Mississippi River has formed many oxbow lakes, mostly north of Vicksburg. Mississippi also has many slow-moving streams called bayous. Some of the bayous connect the lakes with the rivers in the Delta. Others link the inland waterways with the Gulf of Mexico.

Texas

The Rio Grande, Texas' largest river, is one of the longest and most historic rivers in North America. Other Texas rivers include the Brazos, Canadian, Colorado, Guadalupe, Neches, Nueces, Pecos, Red Sabine, San Antonio, and Trinity. Most of the state's rivers flow in a southeast direction into the Gulf of

Mexico. In the dry western parts of Texas, many streams have water only after a rainstorm.

2.5 Soil

Alabama

There are four main soil zones found in Alabama. In the far north, the Tennessee Valley contains the dark loams and red clays that add vivid dashes of color to the landscape when exposed. Farther south lie the varied soils of a mineral belt, and these are succeeded by the rich limestone and marl soils of the Black Belt. Along the coast of Alabama there are sandy loams and deep porous sands.

Louisiana

The soils of Louisiana have been one of the state's priceless resources; nearly one-third of the total land area is covered by the rich alluvium deposited by the overflowing of its rivers and bayous. Muck and peat soils are found within the coastal marshes, while the bottom soils of the Mississippi and Red river valleys are other alluvium and loessial, or windblown, soils. Within the uplands, or hills, there are more mature soils that are less fertile.

Florida

In general, Florida's soil consists of sand, sandy loam, claylike marl, peat, and muck, but more than 300 soil types have been mapped. Six broad soil-vegetation regions may be described.

Texas

There is immense variation in the types of Texas soil. The Piney Woods region of east Texas has a gray and tan topsoil that covers the red subsoil usually within a foot or two of the surface. The soil along the upper and middle Texas coast is black clay or loam, with lighter-coloured sandy soil on coastal islands, bars, and spits. The soil of the southern Texas coast and inland to the Rio Grande is sandy, like that of east Texas, but is less eroded and leached.

The Blackland Prairie, a belt of fertile black clay to the west of the Piney Woods, extends southwesterly from the Red river to San Antonio. The soil of the Grand Prairie region, just to the west of the Blackland Prairie, is more rocky and resistant to erosion.

The Cross Timbers, a forest region with light-colored, slightly acid, sandy loam soil, stretches across the prairies of northern Texas, enclosing part of the Grand Prairie. Red sandy and dark clay soils are found in the Llano Basin, in the center of the state. The Edwards Plateau has thin, stony soil with a limestone bedrock.

Most of the soils of the western North Central Plains are red or tan-colored and sandy, but some black clay is found in the region. The High Plains, just to the west, has dark brown to reddish clay loams, sandy loams, and sands. In the Trans-Pecos region are found reddish brown sandy soil in the mountains and grayish brown to reddish brown clay soil in the basins.

The rich fertility of the soils first attracted settlers to Texas. Much of the soil was lost through wasteful farming and ranching practices in the 19th and the early 20th centuries, but since the 1930s efforts by federal and state governments have done much to promote soil conservation in the state.

2.6 Coastline

Alabama

Alabama's general coastline extends for 53 miles (85 kilometers) along the gulf of Mexico. The tidal shoreline, which includes small bays and inlets, is 607 miles (977 kilometers) long.

Mississippi

Mississippi has a coastline of 44 miles (71 kilometers) along the Gulf of Mexico. With bays and coves, it has a total shoreline of 359 miles (578 kilometers). The largest bays include Biloxi, St. Louis, and Pascagoula. The nation's longest sea wall protects about 25 miles (40 kilometers) of coastline between Biloxi and Point Henderson at Pass Christian. Other coastal towns include Bay St. Louis, Gulfport, and Ocean Springs Deer Island is near the month of Biloxi Bay, and a chain of small islands lies off the coast. They include Cat, Horn Ship, and Petit Bois islands. Mississippi Sound separates them from the mainland.

Louisiana

Louisiana has a general coastline of 397 miles (639 kilometers) along the Gulf. But the marshy coast has been made extremely uneven by silt deposits. As a result, Louisiana's tidal shoreline-including bays, offshore islands, and river months- is 7,721 miles (12,426 kilometers) long. Salt water from the Gulf of Mexico enters the coastal waters through canals. It kills many of the freshwater marsh plants that help hold coastal soils in place, and as a result, large amounts of these soils are washed away. About 50 square miles (130 square kilometers) of Louisiana's coastal land erodes annually.

Florida

The coastline of Florida is 1,350 miles (2,173kilometers) long divided into Atlantic Coast and the Gulf Coast. The Atlantic coast has 580 miles (933 kilometers) of shoreline. The Gulf coast is 770 miles (1,240 kilometers) long.

Texas

The general coastline of Texas is 367 miles (591 kilometers) long along the Gulf. The tidal shoreline, including bays, offshore islands, and river mouths, is 3,359 miles (5, 406 kilometers) long. A series of narrow sand bars, enclosing shallow lagoons, lies along the Texas coast. These sand bars help protect the coast from ocean storms and huge, destructive waves called tsunamis. The Texas coast has 27 artificially created ports, that were once filled by silt left by the many streams emptying into the Gulf of Mexico. When they were filled by silt, only small vessels could use them. By removing the silt and deepening the harbors, engineers built 12 deepwater pots and 15 ports for barges and small ships.

2.7 Current Stresses

The following regional key sectoral issues were identified by the Gulf Coast Regional Workshop (Ning and Abdollahi, 1999, USGCRP, 1998a)

2.7.1 Coastal Ecosystems

The potential impacts of climate change are of great practical concern to those interested in Gulf Coast region's **wetland** resource. The Northern Gulf Coast area is of greatest risk in the U.S. because of its low-laying habitats with easily eroded substrates. The IPCC and the World Meteorological Organization (IPCC, 1997 and WHO, 1996) have identified coastal wetland as an ecosystem most vulnerable to direct, large-scale impacts of climate change, primarily because of their sensitivity to increase in sea-level rise.

The Gulf Coast is a region prone to rapid subsidence of an order of magnitude greater than the Atlantic and Pacific coastal zones. The Governor of Louisiana's representative at the workshop referred to this region as the "Poster Child of Vulnerability". Accelerated **sea-level rise** of any predicted rate, high or low, will only exacerbate the impacts of the existing rate of sea-level rise on this highly vulnerable coastal region.

Gulf Coast ecosystems continue to be impacted by stresses of altered **watershed dynamics** and **flood** control measures. Changing climate conditions which impact flow regimes in other regions (such as the Upper Mississippi River watershed) are also felt along the Gulf Coast. Gulf Coast states have experienced an increase in total annual rainfall during this century. This increase is associated with more intense rainfall events, which alter both the timing and delivery of freshwater to coastal wetlands and estuaries. The State Climatologist for Louisiana stated that intense spring rainfall events have doubled in frequency since 1971, while the number of summer events during that period were half as frequent. In addition to these climatic changes, **flood control measures** and impoundment alter surface water flows and impede the sediment flux that is necessary to sustain the development of river deltas. The extraction of freshwater for municipal purposes and irrigation, along with landscape fragmentation in the coastal zone has altered the balance of freshwater and tidal flows. Several Gulf Coast estuaries and wetlands are slated for engineered restorations (e.g. fresh water diversions along the lower Mississippi River and the Everglade's surface water restoration).

Rising sea level and deteriorating landforms allow **saltwater to intrude** further inland and to mix with surface and groundwater supplies. Changing the salinity patterns of Gulf Coast wetlands threatens stability of freshwater ecosystems and survival of two important shellfish resources — oysters and shrimp. Fertilizers, herbicides, and pesticides applied on agricultural crops in watersheds that feed coastal marshes and estuaries also pose a real concern. The cumulative impact of water removal and replacement, whether for municipal or industrial purposes, involves a reduction in the quality of water interring downstream wetlands. Urban floodwaters that are pumped across levees also introduce significant contaminants of unknown fate into adjoining wetlands.

Frontal passages and hurricanes account for most of the acute effects that lead to coastal changes of barrier islands and wetlands. Even relatively mild winter storms create fetch dynamics in coastal bays and estuaries that can cause significant impacts.

The invasion of non-indigenous species of flora and fauna alters the structure and balance of coastal systems to the exclusion, in some cases, of native species. The **loss of habitat** for resident wildlife is also of concern. The Gulf Coast spans the transition zone between temperate and sub-tropical climates and species distribution, which adds to its biological diversity as a region. Climate changes and conditions may foster the rate of spread of exotic species. Some notable exotic species include *Melaleuca, Salvinia,* Water hyacinth, Eurasian millfoil, Brazilian pepper, Chinese tallow tree, gecko, and zebra mussel.

2.7.2 Forests

Climate variability is already a prime stress and is related to the many summer storms of both sub-tropical and convection driven origin. Forests are affected by numerous thunderstorms of high intensity as well as tropical storms and the associated high winds. The high rainfall during short periods associated with these storm leads to **flooding** and waterlogged soils. Plant growth is impacted. Reduced root growth and increased incidence of windthrow are not uncommon problems.

Along the coast and for some distance inland, **sea-level rise** is a major problem in the region. Natural sea-level rise is a product of warming temperatures and thermal expansion. Apparent sea-level rise is aggravated by subsidence caused from the organic soils and the losses of sediment influx as drainage patterns have been altered for human use in coastal areas. Sea-level rise exacerbates drainage of rivers and streams resulting in flooding and **saltwater intrusion** that severely alter the coastal ecosystems. Freshwater swamps are being killed by saltwater intrusion and bottomland hardwoods are being killed by alteration of flood timing and duration. Changes in species composition, changes in wetland boundaries, and complete loss of terrestrial ecosystems to open water areas have occurred. Such changes have also been associated with increased numbers of pests and success of new pests in the region.

Although high rainfall is common, the Gulf Coast region also experiences its share of **droughts.** Droughts in recent years have caused much damage and loss of productivity. Plants growing in waterlogged soils have restricted root systems and once the soils begin to dry out, plants are unable to extract sufficient water from the soil. Wildland ecosystems under water stress often lead to insect and disease infestations, with a concomitant increase in the frequency and severity of wildfires. The release of sequestered carbon through uncontrolled wildfire can lead to major air pollution and to the buildup of radiatively important gases and particles in the atmosphere. In the summer, high temperatures provide additional stress through increased plant respiration, reduced photosynthesis, and direct-heat-caused injury. In the winter, temperature fluctuation and the sudden onset of freezing temperatures result in biological miscues and loss of productivity. The negative impacts on flower and fruit production are most noticeable.

Ozone and other **air pollutants** are problems in many areas of the Gulf Coast region. Foliar damage, reductions in photosynthesis, and associated reductions in growth have been shown to occur. These problems are becoming more serious in the Gulf Coast region.

2.7.3 Water and Air Quality

The Gulf Coast shares a number of stresses that are currently creating problems for coastal areas due to a high rate of population influx and development along the coast. Many of the health stresses in the region relate to **contamination** of the marine environment as a result of development, agriculture (nitrogen flow), and **industrial pollution,** such as benzene and other organic chemicals from oil refining. This is of particular concern because the Gulf Coast has the highest concentration of petrochemical companies in the nation. Pollutants in water are a major problem in the region. With the potential of sea level rise, health is threatened by petrochemical plants. In addition to the chemicals released by the petrochemical companies, the Mississippi River carries the chemical pollutants of the Central U.S. to the Gulf Coast region. Extraction, refining, and transport of oil and petrochemicals all carry risks for the health of humans, wildlife and ecosystems. Extreme rains and flooding can enhance run-off of nutrients, pollutants and microorganisms. Heavy rains and high nutrient levels can increase algae blooms and add to the **"hypoxic zone"** in the Gulf of Mexico, currently the size of New Jersey.

In addition, there were a number of disease events in Florida in 1997, which affected both humans and plants. These included St. Louis encephalitis around Orlando and three crop pests: medfly in Dade county, citrus canker sore and tomato leaf virus carried by whiteflies.

The growth of major cities and the effects of this growth on air quality are major health concerns in the Gulf Coast region. Large cities such as Houston and New Orleans have major problems with air pollution, particularly tropospheric ozone (O_3). Pollution stagnation, such as occurred in Baton Rouge in 1990 and 1995, is dangerous and may be exacerbated by increased temperatures. Poor air quality contributes to health endpoints such as heat shock, asthma, respiratory disease, and allergies.

When air quality is bad, people often stay inside of the house where the air quality is worse than outside of the house. In addition, when temperatures increase, more people use air conditioners, adding to the pollution problems.

Diversion of water to serve the growth of the human population in large cities is a potential threat to the availability of clean water in the Gulf Coast region. The large population growth in Atlanta is currently threatening Gulf Coast water quality. Similarly, population growth and the diversion of water are also threatening the water quality of the Rio Grande River. To assess this problem, it is important to monitor key water systems and to determine the purpose for which water is being used.

2.7.4 Fisheries

Increased variability in precipitation has the potential to greatly impact coastal fisheries by affecting freshwater inflow to estuaries, which in turn would affect flushing rates, the location of the freshwater-saltwater interface, and the quality of coastal estuarine nursery areas for fish and shellfish. Further inland, increased variability in precipitation has the potential to negatively impact riverine fish resources.

Fishermen of the Terrebonne Fishermen's Organization expressed concerns about **coastal erosion and the loss of coastal marsh habitat,** which, in Louisiana, is mainly attributable to subsidence of deltaic deposits of the Mississippi River, and human alteration of coastal marsh. They are concerned that sea level changes associated with global climate change will exacerbate the current problems of coastal erosion. Even small rates of sea-level rise take on a special significance in coastal Louisiana.

There is currently little public understanding of the importance of coastal water and habitat quality to coastal fisheries. Coastal habitat quality is affected by factors like industrial and metropolitan development along the coastal zone, tourism and recreation, inland land use (natural vegetation cover versus agriculture or silviculture, fertilizer and pesticide use, animal husbandry, etc.), and atmospheric and hydrologic deposition of pollutants (e.g., inorganic nitrogen) from industry located far inland. The extent to which climate change will exacerbate or ameliorate stresses on fisheries associated with changes in coastal water and habitat quality depends on future trends of coastal zone development. Some sense of the minimum amount of undisturbed coastal habitat and minimally disturbed coastal habitat buffer needed to sustain current fisheries must be gained in order to project habitat needs under climate change scenarios.

In 1997 Louisiana fisheries contributed roughly $20 billion to the gross national product, employing about a million people. Marsh and other coastal habitats on which coastal fisheries depend play an important role as nursery grounds for many commercially important fish and shellfish species. Other commercially important fishes, whose life histories are not directly tied to coastal habitats, are dependent on fish and shellfish produced in coastal habitats.

All aquatic organisms have particular ranges of physiological tolerance to factors like temperature, salinity, pH and dissolved oxygen. In general, species are found only in habitats that meet all of their requirements for survival, growth, and reproduction. These requirements often differ with different life history stages (eggs, larvae, and adults), particularly in marine and estuarine species. A change to warmer water temperature in the Gulf of Mexico, for example, has the potential to restrict the zone of inhabitance of temperate adapted species (northward movement in the Northern Gulf of Mexico is limited by the coastline) and shift the zone of more tropical adapted species northward.

The same may be said for fishes in inland freshwater stream and lake habitats along the Gulf Coast. The species are generally temperature adapted, so any warming, or tendency toward warmer extremes than at present, has the potential to restrict their natural range. The ability of any of these species to migrate north or south is dependent on the range of stream sizes the species normally inhabits, and the presence of barriers to dispersal such as dams or natural physiographic features.

A critical problem in trying to predict how global climate change might impact populations of both coastal and inland fisheries is that very little is known about the specific tolerances and life history requirements of many of the species involved. Life history information is being gathered for many of the commercially important species by agencies such as the National Marine Fisheries Service and state fisheries departments. However, the information is not being gathered in a coordinated way, with a view toward future climate change. In cases where key life history information is being gathered (e.g., in the course of routine shrimp, ichthyoplankton and groundfish surveys), important information on conditions of capture is not being recorded or archived, the collections are not being precisely referenced as to geographic position, and the collections are not being archived. We need a comprehensive interagency review of information needs related to impacts of global climate change on coastal fisheries, a better coordination of ongoing fishery surveys with proper attention to the quality of the information being gathered, and improved databasing and archiving of information collected.

2.7.5 Commerce, Industry and Energy

Industries of the region can be divided into two broad categories: primary industries and support industries. Primary industries with the most impact on the economies of the Gulf Coast region (in no particular order) are oil and gas, agriculture and forestry, tourism and entertainment, fisheries and aquaculture, chemical, manufacturing, port transfer and shipping. A number of support industries with important roles in the region (in no particular order) are insurance, finance, real estate, construction, medical and health, public sectors, military, government, and retail.

Current climatic and non-climatic stresses can be related to the relevant industries. Some of these influences originate within the region, while others have global dynamics. Some general "stresses" are coastal land loss, saltwater intrusion, population growth, and education/training of the general population and available workforce. Specific effects on the primary industries include the following:

a. Oil and gas

Clearly, global energy markets, international emissions agreements, and national policy are major forces in shaping the demand for oil and gas products, and the ultimate mix of fuels used to meet the nation's energy needs. Also, the current age and inefficiency of capital equipment is one important stress in this industry as well as in the chemical and manufacturing industries. Weather plays a substantial role in determining demand for, hence the price of, various fuels. Another major stress on the oil and gas industries is the frequency and magnitude of major storms. In such cases, drilling activities in the Gulf are curtailed. While this stress is currently thought to play only a minor role, future increases in storm intensity and frequency associated with climatic change could be important.

b. Agriculture and forestry

Agriculture is particularly sensitive to climate variability and extremes. The dates of the first and last frosts dictate planting and harvesting schedules. Shifts in the length of growing season can benefit or harm agriculture. Some crops will likely benefit from the enhanced CO_2 and increased air temperatures. There may even be opportunities for double cropping (i.e., two growing seasons each year). The expected drying of the soil and increased magnitude of heavy precipitation events, on the other hand, may be damaging to the agricultural industry.

c. Tourism and entertainment

Weather in the Gulf Coast region has an important influence on tourism. For instance, it is generally known that the month of August can be quite hot and humid, discouraging tourists and encouraging residents to travel out of the region. The role of weather in tourism, however, is a two-way street. Many of the tourists visiting the region in winter months are from the northeast. If winters in the northeast are less severe, there will be less incentive for these individuals to flee to the south. Another important influence on tourism is the perception of health threats. One example is the recent outbreak of encephalitis in central Florida, that resulted in the evening closings of the Disneyworld parks. Even very small outbreaks of infectious disease can have major impacts on tourism.

d. Fisheries and aquaculture

Wetland loss is a current issue of great importance to the fisheries and aquaculture industries. If natural subsidence is enhanced by sea-level rise, these industries may be severely impacted. There are also salinity issues associated with the interface between the coastal salt water and the brackish and fresh water marshes.

e. Chemical

While the chemical industry is generally not significantly impacted by climate, it relies on the oil and gas industries for much of its raw materials, and is also subject to the policy actions of local governments which often act to limit emissions. Environmental activism is also playing a more pronounced role, as the activist groups grow and become more vocal about their environmental concerns. Vocal public opposition to the proposed Shintech PVC plastics plant in Louisiana is one of the examples.

f. Port transfer and shipping

This industry depends upon port access that in some cases may be affected by river flow rates, sedimentation, and the need for dredging. Ship traffic can also be significantly impacted by severe storms.

2.8 Potential Futures

2.8.1 Climate Change and Sea Level Raise

Rising global temperatures are expected to raise sea level, and change precipitation and other local climate conditions. Changing regional climate could alter forests, crop yields, and water supplies. It could also threaten human health, and harm birds, fish, and many types of ecosystems.

There are five major physical impacts of sea-level rise: (1) erosion; (2) inundation; (3) salinization; (4) increased flooding and storm damage; and (5) rising water tables (Nicholls et al., 1994). Sea-level rise does not act in isolation and these impacts can be offset or reinforced by other factors such as sediment availability, or changing freshwater runoff. It is also important to recognize that the coastal zone will evolve due to processes other than sea-level rise. Therefore, when examining potential impacts of sea-level rise for planning purposes, it is important to consider all coastal processes (Stive et al., 1990).

Rising sea level is gradually inundating wetlands and lowlands; eroding beaches; exacerbating coastal flooding; threatening coastal structures; raising water tables; and increasing the salinity of rivers, bays, and aquifers (Barth and Titus, 1984). The areas most vulnerable to rising seas are found along the Gulf of Mexico and the Atlantic Ocean south of Cape Cod. Although there also are large low areas around San Francisco Bay and the Fraser delta (British Columbia), most of the Pacific coast is less vulnerable than the Atlantic and Gulf coasts.

Coastal marshes and swamps generally are found between the highest tide of the year and mean sea level. Coastal wetlands provide important habitat and nourishment for a large number of birds and fish found in coastal areas. Wetlands generally have been able to keep pace with the historic rate of sea-level rise (Kaye and Barghoorn, 1964). If sea level rises more rapidly than wetlands can accrete, however, there will be a substantial net loss of wetlands (Titus, 1986; Park et al., 1989).

Coastal development is likely to increase the vulnerability of wetlands to rising sea-level. In many areas, development will prevent the wetland creation that otherwise would result from the gradual inundation of areas that are barely above today's high-water level (Titus, 1986, 1988). In Louisiana, flood control levees, navigation infrastructure, and other human activities have disabled the natural processes by which the Mississippi delta otherwise could keep pace with rising relative sea level; as a result, Louisiana currently is losing about 90 km^2 (35 mi^2) of wetlands per year (Gagliano et al., 1981; Penland et al., 1997).

Louisiana is expected to experience the greatest wetland loss from rising sea level, although most of these losses are predicted to occur even with the current rate of relative sea-level rise. A 50-cm rise in sea level would cause a net loss of 17 – 43% of the wetlands, even if no additional bulkheads or dikes are erected to prevent new wetland creation. The table presents estimated losses in U.S. wetlands by region.

The dry land within 1m above high tide includes forests, farms, low parts of some port cities, communities that sank after they were built and that now are protected with levees, parts of deltas, and the bay sides of barrier islands. Major port cities with low areas include Miami, and New Orleans. New Orleans' average elevation is about 2m below sea level.

The most economically important vulnerable areas are recreational resorts on the coastal barriers-generally long and narrow islands of spits (peninsulas) with ocean on one side and a bay on the other-of the gulf coasts. Typically, the ocean front block is 2-5m above high tide; the bay sides often are 0.5m above high water. Rising sea level tends to cause narrow islands to migrate landward through the overwash process (Leatherman, 1979).

Changing climate generally is increasing the vulnerability of Gulf Coast areas to flooding both because higher sea level raises the flood level from a storm of a given severity and because rainstorms are becoming more severe in many areas. It also is possible that hurricanes could become more intense, thus producing greater storm surges. The IPCC (1996) concluded, however, that the science currently is inadequate to state whether or not this is likely to occur. Many Gulf Coastal areas currently are protected with levees and seawalls. Because these structures have been designed for current sea level, however, higher storm surges might overtop seawalls, and erosion could undermine them from below (National Research Council, 1987). In areas that are drained artificially, such as New Orleans, the increased need for pumping could exceed current pumping capacity (Titus et al., 1987).

Higher sea level and more intense precipitation could combine synergistically to increase flood levels by more than the rise in sea level alone in much of coastal Louisiana and Florida. The direct effect of higher sea level also could be exacerbated throughout the coastal zone if hurricanes or northeasters become more severe-a possibility that has been suggested but not established (IPCC, 1996).

Rising sea level also enables saltwater to penetrate farther inland and upstream in rivers, bays, wetlands, and aquifers. Saltwater intrusion would harm some aquatic plants and animals and threaten human uses of water. Increased drought severity, where it occurs, would further elevate salinity. Higher salinity can impair both surface and groundwater supplies. If saltwater were able to reach farther upstream in the future, the existing intakes would draw salty water during droughts. Louisiana's coastal wetlands are disappearing at the rate of 25 square miles per year — equal to 16,000 acres annually. In this century, the state of Louisiana lost between 600,000 and 900,000 acres of valuable coastal vegetative wetlands. Estimates reveal that another 600,000 acres will be lost between now and the year 2040. A commitment to establish cost-effective coastal restoration projects is essential if Louisiana's costal wetlands are to be saved.

The aquifers that are most vulnerable to rising sea level are those that are recharged in areas that currently are fresh but could become salty in the future. The South Florida Water Management District already spends millions of dollars each year to prevent the aquifer from becoming salty (Miller et al.,

Table 4 Regional and national wetland losses in the U.S. for the trend and 1-m global sea-level rise scenarios (% loss of current area).

Current Wetland Area			1-m Shore Protection Policy		
Region	**(mi^2)**	**Trend**	**Total**[a]	**Developed**[a]	**None**[a]
Northeast	600	7	16	10	1[d]
Mid-Atlantic	746	-5	70	46	38
South Atlantic	3,814	-2	64	44	40
South/Gulf					
Coast of Florida	1,869	-8	44	8d	7[d]
Louisiana[b]	4,835	52	85	85	85
Florida Panhandle, Alabama, Mississippi, And Texas	1,218	22	85	77	75
West Coast[c]	64	-111	56	-688	-809
United States	13,145	17	66	49	50
Confidence Intervals					
95% Low	-	9	50	29	26
95% High	-	25	82	69	66

a The "total" scenario implies that all shorelines are protected with structures; hence, as existing wetlands are inundated, no new wetlands are formed. "Developed" implies that only areas that are currently developed will be protected; "no protection" assumes that no structures will be built to hold back the sea.

b Evaluation of management options currently contemplated for Louisiana (e.g., restoring natural deltaic processes) was outside the scope of this study.

c This anomalous result is from small sample size. The impact on nationwide results is small.

d Results are not statistically significant; sampling error exceeds estimate of wetlands lost.

Source: Titus et al., 1991, and USEPA website at
http://www.epa.gov/globalwarming/publications/reference/ipcc/chp8/america13.html

1992). A second class of vulnerable aquifers consists of those in barrier islands and other low areas with water tables close to the surface, which could lose their freshwater lens entirely (IPCC, 1990).

Finally, rising sea level tends to make some agricultural lands too saline for cultivation. In areas where shorefront lands are cultivated, the seaward boundary for cultivation often is the point where saltwater penetrates inland far enough to prevent crops from growing. As sea level rises, this boundary penetrates inland-often rendering farmland too salty for cultivation long before inundation converts the land to coastal marsh (Toll, 1997).

Table 5 Loss of dry land from sea-level rise (95% confidence interval, mi²).

	Rise in Sea Level (cm)			
	Baseline	50	100	200
If no shores are protected	NR	3,300-7,300	5,100-10,300	9,200-15,400
If developed areas are protected	1,500-4,700	2, 200-6,100	4,100-9,200	6,400-13,500

(NR=not reported) Source: Titus *et al*., 1991.

2.8.2 Climate Change and Its Potential Impacts to Five Gulf Coastal States (USEPA, 1999)

Alabama

Coasts

Alabama has a 600-mile tidally influenced shoreline along the Gulf of Mexico. The shoreline consists of a low-lying coastal plain, narrow barrier islands, forested swamps, and low terraces. Along much of the Florida Panhandle and Alabama Gulf Coast, sea level already is rising by approximately 9 inches per century, and it is likely to rise another 20 inches by 2100.

Water resources

In a warmer climate, runoff is likely to be reduced primarily because of higher temperatures, increased evaporations, and changes in precipitation. Reduced runoff and the resulting lower groundwater levels, especially in the summer, could affect the availability of water to satisfy Alabama's growing and competing needs for municipal, industrial, irrigation, and recreational uses of water. Large groundwater withdrawals in the coastal zones of Baldwin and Mobile counties, which include the Mobile Bay and Gulf Shores regions, have resulted in increased salinity in wells because when freshwater is drawn down saltwater can then intrude into the aquifers. An increase in sinkhole formation has also been associated with large groundwater withdrawals. Showed warmer and drier conditions occur, particularly if accompanied by rising sea levels, they could compound the problems of high demand for water and low availability. Lower water levels and higher temperatures could also impact water quality by concentrating pollutants.

Forests

In Alabama, longleaf and slash pine forests could expand northward and replace some of the loblolly and shortleaf pine forests. Wetter conditions would favor expansion of southern pine forests, as well as oak and hickory forests and the gum and cypress forests found along the Gulf Coast. In contrast, under drier conditions, 40 – 70% of forests in the east –central part of the state could be replaced by grasslands and pasture. Warmer and drier conditions could increase the frequency and intensity of fires, which could result in increased losses to important commercial timber areas. Even warmer and wetter conditions could stress forests by increasing the winter survival of insect pests.

Ecosystem

Alabama is located at the intersection of several geographic areas, and it's ancient and complex geological terrain is home to a variety of ecosystems, ranging from the Appalachians in the north to the coastal plain in the south. Although it ranks 29th of all the states in area, it is the nation's fourth in terms of plant and animal species richness. With 235,000 miles of waterways spanning three major river basins (the Mobile, Tennessee, and Apalachicola), it's aquatic biodiversity is particularly notable. Freshwater fauna in the rivers and Streams include 52% of North American's known freshwater turtles (of these, 22%

are endemic to the state), 38% (41% endemic) of freshwater fishes, 60% (34% endemic) of freshwater mussels, and 43% (77% endemic) of all gill-breathing snails. The Cahaba River, Alabama's longest free-flowing river, is home to 131 species of fish, the greatest diversity for any river of its size on the continent. Habitat for warm water fish could be reduced by hotter temperatures. Alabama's coastline may be small in comparison to other Gulf Coast States, but over 500 species of marine mollusks have been found in the coastal sands and waters of Alabama. Climate Changes could exacerbate threats to coastal and freshwater ecosystems. For example, warmer air temperatures could lead to reduced stream flow and warmer water temperatures, which would significantly impair reproduction of fish and other animals and favor the spread of exotic species that exhibit a high tolerance for extremes environmental conditions. The low-lying Mississippi Delta is particularly vulnerable to the effects of sea level rise – inundation of coastal lands, intrusion of saltwater into coastal freshwater ecosystems, and increases in erosion rates and storm damage resulting from increase storm frequency. If rainfall increases, runoff along the Gulf Coast and the rate of estuarine flushing are expected to increase, leading to reduced yields in shrimp and other species favoring high salinities. Higher runoff rates and outflow into the Gulf of Mexico could increase nutrient loads and alter water temperatures, exacerbating the already serious eutrophication and hypoxia.

Florida

Coasts

Along much of the Florida coast, the sea level already is rising 7-9 inches per century. Because of local factors such as land subsidence and groundwater depletion, sea level rise will vary by location. The sea level in this area is likely to rise 18-20 inches by 2100. As sea level rises, coastal areas in Florida, particularly wetlands and lowlands along the Gulf and Atlantic coasts, could be inundated. Adverse impacts in these areas could include loss of land and structures, loss of wildlife habitat, accelerated coastal erosion, exacerbated flooding and increased vulnerability to storm damage, and increased salinity of rivers, bays, and aquifers, which would threaten supplies of fresh water.

Water resources

A critical factor in Florida's development, especially in southern Florida, has been water. Competing demands for water – for residences, agriculture, and the Everglades and other natural areas – are placing stresses on south Florida's water resources. Although south Florida receives an annual average of 60 inches of rain, annual evaporation sometimes can exceed this amount. Rainfall variability from year to year is also high, resulting in periodic droughts and floods. Higher temperatures increase evaporation, which could reduce water supplies, particularly in the summer. Saltwater intrusion from sea level rise also could threaten aquifers used for urban water supplies. These changes could further stress south Florida's water resources.

Forests

The mixed conifer/hardwood forests found in the northern and panhandle sections of Florida are likely to retreat northward. These forests eventually could give way to wet tropical forests such as tropical evergreen broadleaf forests and dry tropical savanna. These changes would be accompanied by a reduction in forest density. The dry tropical savanna of the Florida peninsula could become more of a seasonal tropical forest with a corresponding increase in forest density. The potential dieback of forests along the Gulf coast could adversely affect forest-based recreation and commercial timber.

Ecosystems

Southern Florida has natural national treasures in the Big Cypress Swamp, the Everglades, and the Keys. These three ecosystems are interlined and have a common history. The Big Cypress Swamp is part of the broad, shallow river moving fresh water south into the Everglades. The keys mark the last outposts of the Everglades lands. Once hummocks of higher vegetation set in a prehistoric swamp, they have maintained themselves against the rising sea. Mangroves on their perimeters collect silt and organic material, building a barricade secure against all but the most severe hurricane winds and tides. In the Everglades and Big Cypress Swamps, there is a strong contrast between the seasons. From early spring well into autumn, they have ample rainfall, averaging 50 inches per year. Winter is a time of drought and fire, and saltwater penetrates farther inland.

Already stressed by water diversions, non-native species of plants and animals, and the natural phenomena of drought, flood, and storms, these ecosystems will be stressed further by climate change. A 20-inch sea level rise would cause large losses of mangroves in southwest Florida. Increase salinity, resulting from rising saltwater into the Everglades from Florida Bay, also would damage freshwater ecosystems containing sawgrass and slough. Communities of wet prairie also would decline with the rise in sea level. Climatic conditions in central Florida may become suitable for subtropical species such a Gumbo-limbo, now confined to subtropical hummocks in the southern part of the peninsula and the Keys. Theoretically, under projected climate change, such species could be found as far north as Gainesville and Jacksonville, but agricultural and urban development will likely preclude such a progression.

Louisiana

Coasts

At Grand Isle, Louisiana, relative sea level is rising by 41 inches per century mostly due to land subsidence, and is likely to rise another 55 inches by 2100. Louisiana currently is losing coastal wetlands at a more rapid rate (approximately 25 square miles a year) than any other coastal state or region in the United States. Louisiana's low-lying delta coastal wetlands are a unique case — these wetlands receive large deposits of sediment from the outflow of the Mississippi River. These deposits provide wetlands with a natural defense against the effects of sea-level rise.

However, because the land surface is subsiding faster than sedimentation is occurring, Louisiana wetlands could be flooded extensively even by relatively changes in sea level. A 1 – 3 foot increase in sea level over the next century is projected to submerge at least 70% of Louisiana's remaining salt marshes. Even freshwater marshes located far inland may convert to brackish or salt marsh.

Water resources

Most of Louisiana drains to the lower Mississippi and Red rivers, both of which have headwaters thousands of miles from their mouths. Stream flow in these rivers is affected mostly by conditions outside Louisiana's borders. Because much of the runoff of the Red and Mississippi rivers comes from areas where there is little snowfall, stream flow is affected by changes in precipitation and temperature. Summer flows of these rivers could be reduced by the increased evaporation that would occur in a warmer climate. The part of Louisiana that is not in the Red or Mississippi river basins is drained by smaller rivers and streams that flow directly to the Gulf of Mexico.

Forests

With changes in climate, the extent and density of forested areas in Louisiana could change little or decline by 5 – 15%. Hotter, drier weather could increase wildfires, particularly in the important timber producing regions in the northern part of the state. In some areas, the types of trees dominating Louisiana forests are likely to change. Longleaf and slash pine densities could increase, as would the extent of cypress and gum dominated forests in southeastern Louisiana. Loblolly and shortleaf pines would continue to thrive over much of the state; however, drier conditions could result in increased areas of grassland and savanna in the western part of the state.

Ecosystem

Louisiana's Mississippi river delta contains the largest wetlands in the nation. These coastal wetlands support 30% of national commercial fish and shellfish harvests. They are also the winter home of 20 – 25% of the ducks that frequent ponds in North America. These wetlands are among the most commercially and ecologically productive in the United States. The coastal marshes in Louisiana generate over $2 billion worth of commercial species such as oysters, crabs, fish and shrimp each year. They also are an invaluable buffer against storm surges.

Louisiana is already losing many of its wetlands because levees and other structures along the Mississippi River prevent soil deposition. Sea level rise most likely will accelerate wetland loss. Reducing important habitats for migratory birds, crayfish, sport fish, and other species. Some warm water fish species such as black crappie could lose all of their habitat in Louisiana as a result of the effects of climate change. In addition, spotted sea trout, oyster larvae, pinfish, and flounder would lose much, if not all, of their habitat.

Mississippi

Coast

Mississippi coast has a 360-mile tidally influenced shoreline along the Gulf of Mexico. The shoreline consists of a low-lying coastal plain, narrow barrier islands, and low terraces. At Pass Christian, sea level already is rising by 5 inches per century, and it is likely to rise another 15 inches by 2100. Possible responses to sea level rise include building walls to hold back the sea, allowing the sea to advance and adapting to it, and raising the land and structures (e.g., by replenishing beach sand, elevating Houses and infrastructure). Each of these responses will be costly, either in out-of-pocket costs or in land and structures.

Water resources

Declining groundwater levels are a matter of concern throughout the state. Increased rice irrigation and fish farming in the northwestern Delta region have reduced groundwater levels in the Mississippi alluvial aquifer. Increased municipal and industrial withdrawals in the metropolitan Jackson area, along the Gulf Coast, and in northeastern Mississippi also have lowered groundwater levels. Additionally, in the southern half of the state, saline water has begun to intrude into freshwater aquifers because of declining groundwater levels along the coast as well as from saline waste water injection into oil-field production zones. Warmer and drier conditions, particularly if accompanied by sea-level rise, could compound these types of problems due to higher water demand and lower flows.

Warmer temperatures could lead to reduce stream flow and warmer water temperatures, which would significantly impair reproduction of fish and other animals and favor the spread of exotic species that exhibit a high tolerance for extreme environmental conditions.

Forests

About 55% of the land area of Mississippi is covered with forests, including bottomland hardwoods, pine woods, and oak-hickory forests. In Mississippi, longleaf and slash pine forests could expand northward and replace loblolly and shortleaf pine forests if the climate changes as predicted. Wetter conditions would favor expansion of southern pine forests as well as oak and hickory forests and the gum and cypress forests found along the Gulf Coast. In contrast, under drier conditions, 50-75% of forests in the east-central part of the state could be replaced by grasslands and pasture.

Ecosystem

Most of Mississippi is made up of habitats associated with either the coastal plain or the Mississippi Delta. The coastline is separated from the Gulf of Mexico by a shallow sound and is paralleled by a series of barrier islands. The Mississippi flatlands in the alluvial plain attract hundreds of thousands of migrating snow geese, Canada geese, and ducks in the winter. Wetlands play a major role in basin hydrology and serve as wildlife habitats.

The low-lying Mississippi Delta is particularly vulnerable to the effects of sea level rise—inundation of coastal lands, intrusion of saltwater into coastal freshwater ecosystems, increase in erosion rates and storm damage with increasing wave force and storm frequency. If runoff along the Gulf Coast increases, estuarine flushing rates would increase, leading to reduced yields in shrimp and other species favoring high salinities. Increasing runoff rates and outflow into the Gulf of Mexico could increase nutrient loads and alter water temperatures, exacerbating already serious eutronphication and low oxygen levels. Loss of coastal wetlands and marshes with rapid sea level rise would reduce estuarine health because many estuarine species depend on wetlands as nursery areas and source of organic matter.

Texas

Coasts

The Texas coastline is over 1,400 miles long. The coastline is composed of wind tidal flats, sandy marshes, salt marshes, and beaches. About 75% of the ducks and geese found in the United States move through the Texas coastal wetlands. The salt marshes provide a home for oysters and clams, and serve as nursery grounds for young shrimp, crab, and fish. These marshes protect the shorelines from erosion and also act as a purification system by filtering out many pollutants added to the waters by human activities. At Galveston, sea level already is rising by 25 inches per century, and it is likely to rise another 38 inches by 2100. Brown shrimp catch in the U.S. Gulf Coast could fall 25% with only a 10-inch rise in sea level.

Water resources

Several major river basins lie in part, or entirely, within Texas. Most of the state is drained by several south-flowing rivers, including the Neches, Trinity, Brazos, Colorado, San Antonio, and Nueces. Western Texas drains into the Rio Grande or its major tributary, the Pecos River. Unless increased temperatures are coupled with a strong increase in rainfall, water could become more scarce. A warmer and dryer climate would lead to greater evaporation, as much as a 35% decrease in streamflow, and less water for recharging groundwater aquifers. Increased rainfall could mitigate these effects, but also could contribute to localized flooding. Additionally, climate change could give rise to more frequent and intense rainfall, resulting in flash flooding.

Forests

With changes in climate, the extent and density of forested areas in east Texas could change little or decline by 50-70%. Hotter, drier weather could increase wildfires and the susceptibility of pine forests to pine bark beetles and other pests, which would reduce forests and expand grasslands and arid shrublands. With increased rainfall, however, these effects could be less severe. In some areas, the types of trees dominating Texas forests would change; for example, longleaf and slash pine densities could increase in the deciduous forests of east Texas.

Ecosystems

The coasts wetlands, which support important fisheries and provide vital wildlife habitat, are also vulnerable to climate change. For example, Brazoria National Wildlife Refuge, a 43,388 acre coastal estuarine and coastal prairie habitat on the Gulf Coast, provides winter habitat for 30,000 – 40,000 ducks and 40,000 snow geese. The refuge also contains about 4,000 acres of native coastal systems, and sea level rise would accelerate loss of wetlands and estuaries, eliminating breeding and foraging habitat for commercial, game, and threatened and endangered species.

The vast area within Texas includes a great diversity of ecosystems, from forests to grasslands to semiarid shrublands to extensive coastal and inland wetlands. In land-based Texas, climate change could weaken and stress trees, making them more susceptible to pine bark beetle outbreaks. Semi-arid grasslands and shrublands are very sensitive to changes in rainfall season and in the amount of rainfall, and could be affected adversely by warmer, drier conditions.

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Chapter 3

Socioeconomic Environment of the Region

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3.1 Introduction

The Gulf Coastal Plain includes portions of six states (Texas, Louisiana, Mississippi, Georgia, Alabama, and Florida) and borders the Gulf of Mexico from Florida to Southern Texas. Numerous rivers - including the Alabama, Mississippi, Rio Grande, and Trinity– cross the plain and flow into the Gulf. The Mississippi which originates in the Interior Plains to the north, is the most important of these rivers. Barges carrying cargoes from many parts of the country travel along the river. Soil deposited along the banks of the Mississippi and other rivers in the Gulf Coastal Plain creates fertile farmland. The Plain also has belts of hilly forests and grazing land, and large deposits of petroleum and natural gas lie beneath it and in the offshore Gulf waters. The Gulf Coastal Plain has many sandy beaches, swamps, bays and offshore islands (World Book, 1994)

The purpose of this research is to provide a socio-demographic profile of the Gulf Coastal Plain. The profile presented includes the following (1) land area, agriculture, forest, oil , gas and related industries, (2) demographic and social characteristics; (3) major economic indicators; and (4) productivity measures.

3.2 Land Area, Agriculture, Forests, Oil and Gas and Related Industries

As of 1999 (Table 1), the total area for the States of Alabama, Florida, Louisiana, Mississippi and Texas was 477, 379 square miles which included a land area of 457,081 square miles, a water area of 15,544 square miles and 4,753 coastal square miles. Louisiana has the greatest number of coastal square miles (1,931) followed by Florida (1,308), Mississippi (591), Alabama (519), and Texas (404). Florida has the largest number of square miles of inland water area (4,683), followed by Texas (4,959), Louisiana (4,153), Alabama (968) and Mississippi (781). The land mass of the targeted area (Table 2) consists of 302.7 million acres. Texas with the largest land area of 170.8 million acres, reported 155.5 million acres as rural land and 28.3 million acres of this acreage as crop land. The States of Alabama, Florida, Louisiana, and Mississippi have less than six percent of rural land as cropland. Table 3 summarizes the number of farms, average farm size and total cropland. As can be seen, Texas with the unusually large land mass has a greater number and size of farms. The average farm size in Texas, 676 acres, was 39 percent greater than the national average while the average farm size was only 291 acres in the States of Alabama, Louisiana, Mississippi and Florida. The U.S. average farm size of 487 acres was 68 percent greater than the average for these four states.

Table 1 Land and Water Area.

State	Total Area	Land Area	Water Area		
			Total	Inland Sq. Mi.	Coastal Sq. Mi.
Alabama	52,237	50,750	1,487	968	519
Florida	59,928	53,937	5,991	4,683	1,308
Louisiana	49,651	43,566	6,084	4,153	1,931
Mississippi	48,286	46,914	1,372	781	591
Texas	267,277	261,914	5,363	4,959	404
Total	477,379	457,081	20,297	15,544	4,753

Source: Statistical Abstract of the United States, 1999.

Table 2 Land Cover/Use by State (non-federal - 1992) in millions of acres.

State	Total Surface area 1	Total	Developed 2	Rural Land	
				Total	Crop Land
Alabama	33.1	31.2	2.0	29.1	3.1
Florida	37.7	30.4	4.6	25.8	3.0
Louisiana	30.6	26.4	1.8	24.8	6.0
Mississippi	30.5	28.0	1.3	26.7	5.7
Texas	170.8	163.7	8.2	155.5	28.3
Total	302.7	279.7	17.9	261.9	46.1

Source: Statistical Abstract of the United States, 1999.

1- Includes Water land not shown separately
2- Includes urban and built up areas in units of 10 acres or grater. And rural transportation.

Table 3 Number of Farms, Size of Farm and Farm Acreage.

State	Number of Farms	Average Size of Farm	Total Cropland
United States	1,911,859	487	431,144
Alabama	43,384	210	4,198
Florida	34,799	300	3,640
Louisiana	23,823	331	5,331
Mississippi	31,318	323	5,947
Texas	194,301	676	37,662
Average (Alabama, Florida, Louisiana, Mississippi, Texas)	65,525	548	11,356

Source: 1999 County and City Extra

Table 4 Farm Income - Farm Marketing, 1997 and Principal Commodities, by State.

State	Total	Crops	Livestock and Products	State rank for total farm marketings and four principal commodities in order of marketing receipts
United States	208,665	112,097	96,568	Cattle, dairy products, corns, soybeans
Alabama	3,227	796	2,431	26 - Broilers, cattle, cotton, chicken, eggs
Florida	6,243	4,978	1,265	9 - Greenhouse, oranges, tomatoes, sugar
Louisiana	2,140	1,481	659	32 - Cotton, sugar, rice, soybeans
Mississippi	3,476	1,470	2,006	23 - Broilers, cotton, soybeans, aquaculture
Texas	13,461	5,277	8,184	2 - Cattle, cotton, greenhouse, dairy products

Source: Statistical Abstract of the United States, 1999.

In millions of dollars, cattle includes calves and greenhouse includes nursery.

Table 4 summarizes productivity for crops and livestock for each state in the region. During 1997, Alabama reported total farm related incomes of $3.2 billion which included $797 million in crop sales and $2.4 billion dollars in livestock and other product sales. Louisiana reported the lowest crop and livestock sales of only $2.1 billion. As expected, Texas ($13.4 billion) and Florida ($6.2 billion) reported greatest farm income. Table 4 also provides state rankings for total farm marketing and the four principal commodities in order of farm receipts. Texas ranked second in the nation in the sale of farm commodities. The four leading commodities sold included cattle, cotton, greenhouse including nursery products and dairy products. Florida ranked 9th in the sale of farm commodities. Major commodities sold included greenhouse, oranges, tomatoes, and sugar. The States of Mississippi (23rd) , Alabama (26th), and Louisiana (32nd) national rankings ranged from 23rd to 32nd. Major commodities sold in these states included cattle, cotton, soybeans, and broilers.

Table 5 presents data on the national forest system land for 1997; the gross area within unit boundaries which comprises all publicly and privately owned land within authorized boundaries of the national forests; and national grasslands, land utilization projects, and research and experimental areas. Also reported is land in the national forest system. Presently, there are 191 million acres in the national forest land system, of which 1.2 million acres are in Mississippi, 1.1 million acres are in Florida, 665 thousand acres are in Alabama, 755 thousand acres are in Texas and 604 thousand acres are in Louisiana.

Also presented are data on crude petroleum and

Table 5 National Forest System Land, 1997.

State	1 Gross area within unit boundaries	2 National Forest System Land	Other lands within unit boundaries
United States	231,664	191,913	40,051
Alabama	1,290	665	625
Florida	1,418	1,147	271
Louisiana	1,025	604	421
Mississippi	2,312	1,158	1,154
Texas	1,994	755	1,239

Source: Statistical Abstract of the United States, 1999.
In thousands of acres
1 - Comprises all publicly and privately owned land within authorized boundaries of national forests, purchase units, national grasslands, land utilization projects, research and experimental areas, and other areas
2 - Federally owned land within the gross area within unit boundaries

natural gas production in the region for year 1997. The value and quantity of crude petroleum production are given in Table 6. Texas (537 million barrels) leads the region in the production of crude petroleum, followed by Louisiana (134 million barrels), Mississippi (21 million barrels), Alabama (15 million barrels) and Florida (6 million barrels). The value of the crude petroleum in the State of Texas ($10 billion) was almost 25 percent of the value of all petroleum production in the United States ($40.6 billion). Texas (6.454 billion cubic feet) also leads the region in natural gas production and was followed by Louisiana (5,230 billion cubic feet), and Alabama (553 billion cubic feet). Again, Texas, generating $15.9 billion dollars from the marketing of natural gas in 1997, produced almost one third of all U.S. revenues from natural gas productivity. Louisiana ($12.4 billion) had significant revenues from the sale of natural gas. Together, the States of Texas and Louisiana generated 59 percent of all natural gas produced in the United States and 63 percent of all revenues generated from the sale of natural gas during 1997.

The States of Texas and Louisiana have significant oil and natural gas reserves (Table 7). Texas alone had 5,687 billion barrels of proved crude oil reserves and 37,761 billion cubic feet of natural gas reserves which represented more than 20 percent of the total U.S. oil and gas reserves. Louisiana has a little less than 5 percent of the national oil and gas reserves.

Table 6 Crude Petroleum and Natural Gas - Productions and Value, by State, 1997.

State	Crude Petroleum		Natural Gas Marketed Production - 1	
	Quantity (mil. Bbl)	Value (mil dol.)	Quantity (bil. Cu ft)	Value (mil dol.)
United States	2.355	40,574	19,865	46,131
Alabama	15	276	553	1,557
Florida	6	na	6	na
Louisiana	134	2,578	5,230	12,352
Mississippi	21	356	107	186
Texas	537	10,013	6,454	15,976

Source: Statistical Abstract of the United States, 1999.
1- Excludes non-hydrocarbon gases

We also examined the toxic release by states from 1988 to 1996 (Table 8). These data summarize the release of core chemicals for the years 1988, 1994, 1995, and 1996. During 1988, Texas and Louisiana had the greatest amount of release of toxic chemicals, 318,632 and 250,845 pounds respectively. When compared to 1996 data, these states also had the greatest decrease in release of core toxic chemicals. Louisiana reduced toxic chemical release by 48.26 percent and Texas by 41.16 percent. Another major environmental concern for the region is hazardous waste sites on the national priority list located in each of the targeted states. Table 9 provides a ranking of each state in terms of the number of hazardous waste sites on the national priority list for 1998. As can be seen, Mississippi ranked 47th with three sites; Alabama ranked 32nd with 12 sites; Louisiana ranked 27th with 15 sites; Texas ranked 11th with 32 sites; and Florida ranked 6th with 53 sites on the national priority list.

Finally, serious crime known to police was assessed as a major environmental concern (See Table 10). Crime rates are reported per 100,000 persons in the population. The crimes in the State of Louisiana (6,741) and Texas (5,707) were higher than the national crime rate (5,079) while the crime rate in Alabama (4,857) was lower.

Table 7 Crude Oil, Natural Gas, and Natural Gas Liquids - Reserves by States, 1997.

State	Crude Oil		Natural gas (bil cu ft)	Natural gas liquids (mil bbl)
	Proved (bil bbl)	Indicated (bil bbl)		
United States	22,546	3,207	167,223	7,973
Alabama	47	—	4,968	93
Florida	91	—	96	17
Louisiana	714	313	9,673	437
Mississippi	183	—	582	6
Texas	5,687	479	37.761	2,687

Source: Statistical Abstract of the United States, 1999.
Proved reserves are estimated quantities of the mineral, which geological and engineering data demonstrate with reasonable certainty to be recoverable in future years from known reservoirs under existing economic and operating conditions. Indicated reserves of crude oil are quantities other than Proved reserved, which may become economically recoverable from existing productive reservoirs through the application of improved recovery techniques using current technology. Based on a sample of operators of oil and gas wells.

Table 8 Toxic Release by States: 1988 to 1996 (in thousands of pounds).

State and outlying area	Core Chemicals				
	1988	1994	1995	1996	% Change 1988- 96
Alabama	109,690	96,649	100,495	89,469	18.42
Florida	61,527	71,434	52,111	46,914	23.75
Louisiana	250,845	114,824	122,288	129,789	48.26
Mississippi	59,600	42,834	39,671	39,321	34.03
Texas	318,632	199,765	205,724	187,485	41.16

Source: Statistical Abstract of the United States, 1999.

Table 9 Hazardous Waste Sites on the National Priority List: 1998.

	Total Sites	Rank	Federal	Non-Federal
Alabama	12	32	3	9
Florida	53	6	6	47
Louisiana	15	27	1	14
Mississippi	3	47	–	3
Texas	32	11	4	28
Total	115		14	101

Source: Statistical Abstract of the United States, 1999.

Table 10 Serious Crime Known to Police 1996.

	Rate	Violent	Property
United States	5,079	634	4,445
Alabama	4,8567	569	4,287
Florida	na	na	na
Louisiana	6,741	912	5,829
Mississippi	na	na	na
Texas	5,706	644	5,062

Source: 1999 County and City Extra
Per 100,000 estimated by FBI.

3.3 Social and Demographic Profile

3.3.1 Population Distribution

This section of the profile summarizes available social and demographic data for the States of Alabama, Florida, Louisiana, Mississippi and Texas. In some instances, where applicable, comparisons were made between the targeted states and the U.S. population. The area had a 1998 population of 46.2 million (Table 11). Texas and Florida had the largest population with 19.8 million and 14.9 million persons, respectively. States of Louisiana, Alabama and Mississippi had much smaller populations ranging from 2.7 million to 4.6 million persons. The population density in the region was greater than the U.S. population density. This is particularly noted in Florida with 104.8 persons per square kilometer compared to the U.S. average of 29.2 persons per square kilometer. Mississippi was the only state in the targeted region with a population density lower than the U.S. average of 22.5 persons per square kilometer. The U.S. population grew by 9.8 percent between 1980 and 1990, 5.6 percent between 1990 and 1995, and another 2.9 percent between 1995 and 1998. Population growth in Texas and Florida grew at a faster pace than the U.S. population for this same period. As can be seen in Table 12, Florida grew by 32.7 percent between 1980 and 1990, by 9.6 percent between 1990 and 1995, and by 5.2 percent between 1995-1998. During the period 1980 to 1998, the U.S. population increased by 19.32 percent, compared to population increases of 11.77 percent in Alabama, 53.05 percent in Florida, 3.8 percent in Louisiana, 6.71 percent in Mississippi and 38.88 percent in Texas. Average population growth for the period more than doubled U.S. population growth in the States of Florida and Texas while population growth in Mississippi and Louisiana languished at less than seven percent.

As population density rises to high levels, familiar problems of urban living can be expected to occur, such as high crime rates. Expected to interact with these problems are crises in the physical environment, such as air and water pollution, acid rain, and growing outputs of hazardous waste (Anderson and Taylor, 2000). However, these data present conflicting views. For example, while the population density of Texas was increasing, release of core toxic chemicals has been reduced by approximately 40 percent. This trend also holds in the State of Florida where the population increased by 53 percent between 1980 and 1998 while the release of hazardous chemicals was reduced by 15 percent between 1988 and 1996.

Table 13 summarizes population distribution by race. There appears to be significant variation in the racial distribution of the population in the region. The U.S. had a 1997 white population of 270 million (82.7 percent) and a black population of 34 million (12.7). Included in these populations were 30 million (11.0 percent) Hispanics. Other races comprised approximately five percent of the U.S. population. The Hispanic population is counted in the black and white population as well as presented as a stand alone category (Tables 13 and 14). The Gulf Coastal Plain States presented a somewhat different population distribution. For example, in the State of Alabama, 73 percent of the 1998 population was white, 25.9 percent was black, and only .9 percent was Hispanic. Mississippi and Louisiana also had similar patterns of population distribution. In Mississippi, 62.6 percent of the population was white, 36.4 percent was black, and only .8 percent was Hispanic. In Louisiana 66.2 percent of the population was white, 36.4 percent was black, and 2.6 percent was Hispanic. As expected, Texas and Florida had larger Hispanic populations. In Texas, 29.4 percent of the population was Hispanic and in Florida 14.4 percent of the population was Hispanic. In summary, a large percentage of blacks was found in the States of Mississippi, Louisiana, and Alabama and a large percentage of Hispanics was found in the States of Florida and Texas. Additionally, the percentage of blacks and Hispanics in Gulf Coastal Plain States is more than twice as great as these populations were in other parts of the country.

Table 11 Population in thousands.

State	Number (1998)	Per Square Kilometer (1997)
United States	270,299	29.2
Alabama	4,352	32.9
Florida	14,916	104.8
Louisiana	4,369	38.6
Mississippi	2,752	22.5
Texas	19,760	28.7

Source: Statistical Abstract of the United States, 1999.

Table 12 Resident Population in thousands.

States	1980	1990	1995	1998	Percent Change				Popu Dens
					1980 - 1990	1990 - 1995	1995 - 1998	1980 - 1998	1998
United States	226,546	248,765	262,765	270,299	9.8	5.6	2.9	19.32	76.4
Alabama	3,894	4,040	4,270	4,352	3.8	5.7	1.9	11.77	85.8
Florida	9,746	12,938	14,180	14,916	32.7	9.6	5.2	53.05	276.2
Louisiana	4,206	4,222	4,328	4,369	0.4	2.5	0.9	3.8	100.3
Mississippi	2,521	2,575	2,690	2,752	2.2	4.5	2.3	6.71	58.7
Texas	14,229	16,986	18,694	19,760	19.4	10.1	5.7	38.88	75.4

Source: Statistical Abstract of the United States

Table 13 Population by Race (1998).

Area	Total	White		Black	American Indian, Eskimo Aleut	Asian, Pacific Islander	Hispanic Origin 1
		Hispanic	Non Hispanic				
Alabama	4,352	36	3,141	1,132	15	28	43
Florida	14,916	2,080	10,239	2,268	58	271	2,243
Louisiana	4,369	100	2,787	1,407	19	55	117
Mississippi	2,752	18	1,701	1,003	10	19	23
Texas	19,760	5,640	1,038	2,430	96	556	5,863

1 - Persons of Hispanic Origin may be of any race
Source: Statistical Abstract of the United States, 1999.

Table 14 Population by Race (1997).

State	White	Black	American Indian, Eskimo Aleut	Asian, Pacific Islander	Hispanic
United States	82.7	12.7	0.9	3.7	11.0
Alabama	73.1	25.9	0.4	0.6	0.9
Florida	82.5	15.4	0.4	1.7	14.4
Louisiana	66.2	32.1	0.4	1.2	2.6
Mississippi	62.6	36.4	0.4	0.7	0.8
Texas	84.6	12.2	0.5	2.7	29.4

Hispanic persons may be any race
Source: 1999 County and City Extra

3.3.1 Age, Sex Distribution and Educational Attainment

Tables 15 and 16 summarize the population distribution in the region by age. Florida has a larger percentage of persons 65 years of age and older. Generally, when reviewing population distribution by age, little discernable difference can be found between the United States population and the population in the Gulf Coastal Plain States. However, the dependency ratio may be a little more meaningful. The dependency ratio is the distribution of persons in the dependent population. Here, we are using ages less than 18 and ages greater than 65 years of age to compare with persons ages 18 to 64. This crude dependency ratio for the United States was .6281. For every 1,000 persons ages 18 to 64 there were approximately 628 persons less than age 18 and age 65 and older. The dependency ratio was .5485 in Alabama, .6218 in Florida, .6339 in Louisiana, .6585 in Mississippi and .7816 in Texas. Surprisingly, Texas had the highest dependency ratio. Proportionately, the States of Alabama, Florida, and Louisiana had a proportionately higher working age population than Mississippi and Texas. We also looked at the percentage of the population in each state 65 years of age and older. As of 1998, 12.7 percent of the U.S. population was 65 years of age and older compared to 13.1 percent in Alabama, 18.3 percent in Florida, 11.5 percent in Louisiana, 12.2 percent in Mississippi, and 10.1 percent in Texas. Persons less than age 17 would provide some indication of the future viability of the labor force. In 1997, persons less than 18 years of age comprised 26.0 percent of the U.S. population compared to 24.6 percent in Alabama, 23.7 percent in Florida, 27.4 percent in Louisiana, 27.6 percent in Mississippi, and 28.7 percent in Texas.

Age distributions has important implications for the region. Currently, the U.S. population has an increasing proportion of older people. With the shrinking size of families, the proportion of elderly people is growing faster than the number of younger potential caretakers. With regard to age, the following generalizations can be made: (1) racial minorities and ethnic groups are an increasing proportion of the older population; (2) the proportion of the population classified as the oldest old (those over eighty-five) will also continue to grow (Treas, Judith. 1997); (3) women will continue to outnumber men in old age, especially among the oldest old (Treas, 1997); and (4) since the educational status of the elderly is increasing rapidly, the historical gap in educational attainment between the old and the young will likely disappear by the middle of the twenty-first century (Uhlenbert, 1992).

Table 15 Population by age in thousands as of July 1998.

Age Distribution	United States	Alabama	Florida	Louisiana	Mississippi	Texas
Total	270,299	4,352	14,916	4,369	2,752	19,760
Under 5 years	18,966	295	953	313	202	1,615
5 to 17 years	50,906	789	2,587	878	555	4,014
18-24 years	25,470	436	1,206	475	300	2,049
25-34 years	38,774	620	1,926	589	381	2,829
35-44 years	44,520	687	2,318	683	415	3,242
45-54 years	34,585	561	1,816	551	330	2,451
55-64 years	22,676	395	1,377	376	234	1,560
65-74 years	18,395	313	1,448	280	184	1,113
75 to 84 years	11,952	191	976	168	112	661
85 years and over	4,054	64	310	56	40	227
% 65 years and over	12.7	13.1	18.3	11.5	12.2	10.1

Source: Statistical Abstract of the United States, 1999

Table 16 Population(Percent) by age - 1997.

Age Distribution	United States	Alabama	Florida	Louisiana	Mississippi	Texas
Under 5 years	7.2	6.8	6.5	7.2	7.4	8.3
5 to 17 years	18.8	18.0	17.2	20.2	20.2	20.4
18-24 years	9.3	10.1	8.1	10.7	10.9	10.3
25-34 years	14.8	14.6	13.4	14.0	14.1	14.4
35-44 years	16.4	15.8	15.4	15.8	15.1	16.4
45-54 years	12.6	12.6	12.0	12.4	11.8	12.1
55-64 years	8.2	8.2	9.0	8.4	8.3	7.6
65-74 years	6.9	6.9	10.0	6.4	6.7	5.7
75 years and older	5.8	5.8	8.5	5.0	5.5	4.4

Source: 1999 County and City Extra

The population for the Gulf Coastal Plain States was also characterized by sex (Table 17). In all states reviewed, the proportion of women exceeded the proportion of men. The sex ratio for the United States in 1996 was 96. The sex ratio in the Gulf Coastal Plain States was lower than the U.S. average for all states except Texas. Texas had a 1996 sex ratio of 98. There were 98 men for every 100 women in Texas, 93 men for every 100 women in Alabama, 95 men for every 100 women in Louisiana, and 92 men for every 100 women in Mississippi.

Educational attainment, dropout rate, and college complete rates were used to measure educational attainment. Educational attainment is a good measure of skill level and future levels of potential productivity of a region. Often times these factors are associated with location and type of industry in an area. These values are used to provide some indication of the literacy level of the general population of the region. The dropout rate is calculated for persons 16 years of age and older. A dropout is a person who is not in regular school and who has not completed the 12th grade or received a general equivalency degree. The high school completion and college graduate rates were calculated for persons age 25 years old and over. In all states, the 1990 dropout rate was higher than the U.S. average (U.S. - 11.2, Alabama - 12.6, Florida - 14.3, Louisiana - 12.5, Mis-

Table 17 Population by Sex (1996).

State	Total (1996)	Male		Female		Sex Ratio
		Number	Percent	Number	Percent	
United States	267,636,091	131,141,684	49.0	136,494,406	51.0	96
Alabama	4,319,154	2,077,103	48.1	2,242,051	51.9	93
Florida	14,653,945	7,121,971	48.6	7,531,974	51.4	95
Louisiana	4,351,769	2,097,553	48.2	2,254,216	51.8	93
Mississippi	2,730,501	1,310,640	48.0	1,419,861	52.0	92
Texas	19,439,337	9,603,032	49.4	9,836,305	50.6	98

Source: 1999 County and City Extra

sissippi - 11.8, and Texas - 12.9). Similarly, the high school completion rates were lower in the Gulf Coastal Plain States than for the U.S. as a whole. The college completion rates were also lower for populations in the target area. While the national college completion rate was 23.9 percent for persons 25 years of age and older, the completion rates were 19.3 percent in Alabama, 21.7 percent in Florida, 18.1 percent in Louisiana, 20.9 percent in Mississippi, and 22.4 percent in Texas.

Table 18 Educational Attainment, Dropout rate, College Completion.

State	Dropout Rate (1990)	Educational Attainment	
		High School Graduated	B.S. Degree or more
U.S.	11.2	82.1	23.9
Alabama	12.6	77.6	19.3
Florida	14.3	81.4	21.7
Louisiana	12.5	75.7	18.1
Mississippi	11.8	77.5	20.9
Texas	12.9	78.5	22.4

Source: 1999 County and City Extra

3.3.2 Labor Force Participation

Data are presented on labor force participation in Tables 19, 20, and 21. When examining the employment ratio, the data suggested greater than 60 percent of the U.S. population was employed in the civilian labor force. However, in the States of Louisiana, Mississippi and Florida, less than 60 percent of the population was employed in the civilian labor force. On the other hand, labor force participation was greater than 65 percent in the State of Texas. The unemployment rate is another indicator of labor force participation. These data suggest that the 1997 unemployment rate was higher in the Gulf Coastal Plain States than for the U.S. as a whole. Louisiana had the highest unemployment rate with 6.1 percent of the civilian labor force being unemployed. Florida had the lowest unemployment rate, 4.8. When viewing unemployment rates by sex (Table 19), male unemployment rates for these states does not appear to vary greatly from the U.S. unemployment rate of 4.9. However, the unemployment rates for females was higher in all states except Florida where the female unemployment rate was 4.8 compared to the national rate of 5.0. Again, female unemployment rates in Louisiana and Mississippi were higher than the U.S. average. In these states, the female unemployment rate was 6.9 while the female unemployment rates in Texas was 5.6 and 5.9 in Alabama.

Table 20 summarizes the number of employees in non-farm establishments in 1998. The data suggests that a large proportion of the civilian labor force were employed in manufacturing in Alabama and Mississippi while larger proportions of the population were employed in services in the Louisiana and Florida.

Two sectors of civilian unemployment were reviewed (Table 21); professional, managerial and technical; and precision, production, craft, and repair. The Gulf Coastal Plain States were less likely to have persons employed in professional, managerial and technical fields and also less likely to have persons employed in the precision, production, craft and repair occupations. Almost 50 percent of the U.S. population was employed in these professional and skilled occupations compared to little over 40 percent of the population in the target area.

3.3.3 Personal Income and Poverty Indicators

Personal income is the current income received by persons from all sources minus their personal contributions for social insurance. Classified as persons are individuals (including owners of unincorporated firms), nonprofit institutions that primarily serve individuals, private trust funds, and private non-insured welfare funds. Personal income includes transfers from government and business such as social security benefits, public assistance, etc., but excludes transfers among persons. Disposable personal income is personal tax and non-tax payments. It is the income available to persons for spending or savings. So as to provide a more complete depiction of income in the Gulf Coastal Plain States, four income scenarios are presented, per capita income, disposable per capita income, median household income, and median income for family of four. Average per capita income in 1998 was $26,412 in the United States, $21,442 in Alabama, $25,852 in Florida, $18,958 in Mississippi, and $24,957 in Texas. In the State of Mississippi, the per capita income was almost 40 percent lower than the U.S. average; the median household income was 30 percent lower than the U.S. median household income; and the median income of a family of four was 33 percent lower than the U.S. median income for a family of four. Persons residing in Louisiana and Alabama also had much lower per capita, disposable and median household incomes than the national average. In these states, income was at least 20 percent lower than the U.S. average while the per capita income in Florida was only 2.1 percent lower than the U.S. per capita income. These trends hold true for the median household income and the median income for a family of four in Texas and Florida.

Earnings from selected industries were also examined. As seen in Table 23, almost 70 percent of earning in the State of Florida came from the service related industries including retail trade, finance, insurance, and real estate. A larger than average proportion of earnings came from goods-related industries in Alabama, Mississippi, Texas, and Louisiana.

Table 19 Characteristics of the Civilian Labor Force: 1997.

Area	Employed Population Ratio	Unemployment Rate		
		Total	Male	Female
United States	63.8	4.9	4.9	5.0
Alabama	61.8	5.1	4.4	5.9
Florida	59.3	4.8	4.7	4.8
Louisiana	58.3	6.1	5.4	6.9
Mississippi	58.4	5.7	4.7	6.9
Texas	65.2	5.4	5.2	5.6

Source: Statistical Abstract of the United States, 1999.

Poverty rates are an indicator of economic well-being. The United States had a 1997 poverty rate of 13.3 percent for all persons and 19.9 percent for children under age 18 (Table 24). All states in the region had poverty levels higher than the national average. There were also larger percentages of children under

Table 20 Employees in Non-farm Establishment 1998 in thousands.

Sector	U.S.	Alabama	Florida	Louisiana	Mississippi	Texas
Total	125,832	1,804	6,667	1,897	1,132	8,939
Construction	5,965 (4.75)	102 (5.66)	351 (5.27)	128 (6.75)	55 (4.86)	496 (5.55)
Manufacturing	18,716 (14.88)	379 (21.01)	496 (7.44)	192 (19.13)	245 (21.65)	1,107 (12.39)
Transportation and Public Utilities	6,549 (5.21)	92 (5.10)	336 (5.04)	114 (6.01)	54 (4.78)	542 (6.07)
Wholesale and Retail Trade	29,300 (23.29)	439 (24.34)	1,684 (25.26)	442 (23.30)	244 (19.75)	2,107 (23.58)
Finance, Insurance and Real Estate	7,341 (5.84)	87 (4.83)	430 (6.45)	87 (4.59)	42 (3.72)	495 (5.54)
Services	37,525 (29.83)	449 (24.89)	2,415 (36.23)	510 (26.89)	262 (23.15)	2,515 (28.14)
Government	19,862 (15.79)	347 (19.24)	957 (14.36)	367 (19.35)	223 (19.70)	1,510 (16.9)

Source: Statistical Abstract of the United States, 1999.
* National totals differ from the sum of the state figures because of differing benchmarks among States and differing industrial and geographic stratification.

Table 21 Civilian Employment.

State	Professional Managerial, Technical	Precision Prod, Craft and Repair	Total
United States	38.4	11.0	49.4
Alabama	30.4	11.3	41.3
Florida	31.2	11.5	42.7
Louisiana	31.6	9.7	40.3
Mississippi	28.4	13.7	42.1
Texas	31.2	12.2	43.4

Source: Statistical Abstract of the United States, 1999.

age 18 living in poverty in the target region. In Alabama, 25.6 percent of children live at or below the poverty level which is almost 30 percent higher than the U.S. poverty rate for children. These trends also exist in Louisiana and Texas, where 23.6 percent of children live in poverty. When assessing data summarizing percentage of persons and children lacking health insurance in the region as another indicator of economic well-being, we found 16.1 percent of persons and 15 percent of children in the U.S. lacked some form of health insurance in 1997. This problem was perhaps worse in the State of Texas where 23.6 percent of the population and 24.5 percent of children lack health insurance. Lack of health insurance can possibly be explained by the large first generation Hispanic population in Texas. Mississippi, Louisiana, and Florida also had large proportions of children without insurance. Again, larger minority populations, greater proportions of children and families living below the poverty level, and lower family and per capita incomes exist and could be related to lower levels of health insurance among these populations.

3.3.4 Health Indicators

This section will summarize the general health status of residents of the region. It will include a discussion of birth and fertility rates, death and infant death rates by race, and death rate by leading cause. Birth rate and fertility rates for 1997 are presented in Table 25. The crude birth rate of a population is the number of babies born each year for every 1000 member of the population. The U.S. birth rate was 14.5. As expected, with a larger proportion of older persons in the population, Florida had a lower birth rate of 13.5 while Texas (17.2), Mississippi (15.2), and Louisiana (15.2) had higher birth rates. In general, minority groups tend to have somewhat higher birthrates than White non-minority groups and lower socio-economic groups tends to have higher birthrates than those higher on the socio-economic scale. This region had larger black and Hispanic populations coupled with lower socio-economic indicators for the population in general. The total fertility rate is defined as the number of births that 1,000 women would have in their lifetime, if at each year of age, they experienced the birth rates occurring in that specified year. Fertility rates were estimated for women age 15-44 years. The U.S. average fertility rate was 65.0. Fertility rate in the region ranged from a low of 62.1 in Alabama to a high of 75.3 for Texas. The U.S. teenage pregnancy rate for

Table 22 Per capita, disposable and median income.

State	Per Capita Income	Disposable Per Capita Income	Median Household Income	Median Income of Family of Four
	1998	1998	1997	1996
United States	26,412	22,353	37,005	51,518
Alabama	21,442	18,818	31,939	44,879
Florida	25,852	22,064	32,455	44,829
Louisiana	21,346	18,771	33,260	41,851
Mississippi	18,958	17,067	28,499	38,748
Texas	24,957	21,928	35,075	46,757

Source: Statistical Abstract of the United States, 1999

1997 was 12.8. Teen pregnancy rates were much higher in the target area. Alabama had a rate of 17.6; Florida had a rate of 13.4; Louisiana had a rate of 18.6; Mississippi had a rate of 20.7; and Texas had a rate of 16.1. In Mississippi, the teenage pregnancy rate was more than 60 percent greater than the national average. The region also reported somewhat higher than average births to unmarried women rate. For all states, the birth rate to unmarried women was greater than the national average. While the national average was 32.4 percent, Mississippi had a births to unmarried women rate of 45.5 which was 40 percent higher than the U.S. average. Similarly, Louisiana had an unmarried women birth rate of 43.9, more than 35 percent greater than the U.S. average rate.

The average lifetime expectancy for a person born in the United States (Table 26) in between 1989 and 1991 was 75.37 years. The average life expectancy in Alabama (73.64), Louisiana (73.05) and Mississippi (73.03) was lower than the national average. However, in the States of Florida (75.84) and Texas (75.14), the life expectancy was higher than the national average. Life expectancy also varied with regard to race. The average life expectancy for

Table 23 Earnings as of1997, and percent by selected industries.

State	Farm	Goods-related including manufacturing	Service Related including retail trade, finance, insurance and real estate	Government
United States	0.9	24.3	59.9	14.8
Alabama	1.7	28.9	51.5	18.0
Florida	0.8	15.1	68.8	14.8
Louisiana	0.8	26.5	55.8	16.9
Mississippi	2.1	28.7	50.2	19.0
Texas	0.8	26.7	58.6	13.8

Source: Statistical Abstract of the United States, 1999.

Table 24 Poverty and Health Insurance.

State	% below poverty		Average % lacking health insurance		Home Ownership Rate
	Persons	Children < 18	Persons	Children < 18	
	1997	1997	1997	1997	1998
United States	13.3	19.9	16.1	15.0	66.3
Alabama	15.7	25.6	15.5	14.4	72.9
Florida	14.3	20.9	19.6	20.3	66.9
Louisiana	16.3	23.6	14.9	21.3	66.6
Mississippi	16.7	22.3	20.1	18.4	75.1
Texas	16.7	23.6	24.5	24.9	62.5

Source: 1999 County and City Extra

Table 25 Birth rate and fertility rates (1997).

State	Birth Rate	Fertility Rate	Births to teenage mothers % of total	Births to unmarried women % of total
United States	14.5	65.0	12.8	32.4
Alabama	14.1	62.1	17.6	33.9
Florida	13.1	64.9	13.4	36.0
Louisiana	15.2	65.7	18.6	43.9
Mississippi	15.2	66.3	20.7	45.5
Texas	17.2	75.3	16.1	30.7

Source: Statistical Abstract of the United States, 1999.
Birth rate per 1,000 estimated population.
Fertility rate per 1,000 women age 15-44 years estimated.

Table 26 Average Lifetime in Years by Race (1989-91).

State	Total	White	Black
United States	75.37	76.13	69.13
Alabama	73.64	75.01	69.23
Florida	75.84	76.82	68.77
Louisiana	73.05	74.87	68.62
Mississippi	73.03	74.78	69.41
Texas	75.14	75.75	69.79

Source: Statistical Abstract of the United States, 1999.

whites was 76.13 years and 69.13 years for blacks. Blacks in Alabama (69.23), Mississippi (69.41) and Texas (69.79) had higher life expectancy than the national average (69.13). In summary, this region, with its larger minority population was expected to have lower life expectancy because blacks and Hispanics have shorter life expectancies than whites.

In reviewing data on death and infant mortality rates (Table 27), it is interesting to note that Mississippi (10.1) and Florida (10.6) had death rates much higher than the U.S. average death rate (8.6). Texas was the only state with a lower death rate (7.3). The crude death rate can be an important measure of the overall standard of living of a population. In general, the higher the standard of living enjoyed by a group within the country, the lower the death rate (Anderson and Taylor, 2000). The death rate also reflects factors such as the quality of medicine and health-care. Poor medical care, which goes along with a low standard of living will correlate with a high death rate (Anderson and Taylor, 2000).

The infant death rate represents deaths to infants under one year old and excludes fetal deaths. The infant death rate in Alabama (10.5), Mississippi (11.0), and Louisiana (9.0) was higher than the U.S. average (7.3). The black and white infant mortality rates were higher than the national average in the States of Alabama, Louisiana, and Mississippi.

Infant mortality rates are important to compare across racial-ethnic groups since they are a good indicator of the overall quality of life as well as the chances of survival for members of that racial group.

Inadequate health care and health facilities may cause higher infant mortality rates, and consequently the greater infant mortality among minorities and those in lower socio-economic strata in the United States suggest the lack of adequate health care and adequate access to health facilities is one cause of the high infant mortality rates. Other causes include presence of toxic waste, malnutrition of the mother, inadequate food, and outright starvation.

Table 27 Death and Infant Mortality Rate.

State	Death Rate	Infant Mortality Rate by Race (1996)		
		Total	White	Black
United States	8.6	7.3	6.1	14.7
Alabama	9.9	10.5	8.2	15.5
Florida	10.6	7.5	5.8	13.3
Louisiana	9.2	9.0	6.5	12.8
Mississippi	10.1	11.0	8.0	14.6
Texas	7.3	6.3	5.7	11.7

Source: Statistical Abstract of the United States, 1999.
Death rate per 1,000 population, Infant mortality rate per 1,000 live birth.

Table 28 is a compilation of data on death rates by leading cause. The leading cause of death for all states in the region was heart disease, cancer, cerebro-vascular diseases, and chronic obstructive pulmonary diseases.

3.3.5 General Indicators

Table 29 presents a summary, profile of social, economic, and demographic characteristics of the States of Alabama, Louisiana, Florida, Mississippi, and Texas which can be compared to similar U.S. indicators. Deviation from U.S. indicators can be seen in the population distribution by race, birth rate, teen pregnancy rate, births to unmarried women, female headed households, percentage of families below poverty, percentage of children below poverty, medi-

Table 28 Death Rates, by Leading Cause (1996).

Cause	U.S.	Alabama	Florida	Louisiana	Mississippi	Texas
Heart Disease	276.4	315.9	345.4	270.4	351.2	221.8
Cancer	203.4	222.4	261.8	214.1	212.0	167.3
Cerebro-vascular diseases	60.3	66.9	68.6	59.2	62.9	51.5
Accidents and Adverse effects	35.8	51.4	37.5	41.7	55.6	38.0
Motor Vehicle Accidents	16.5	27.5	19.5	20.9	31.9	20.7
Chronic Obstructive pulmonary diseases	40.0	40.7	53.5	33.1	37.1	33.3
Diabetes Mellitus	23.3	26.6	26.4	37.3	19.8	24.0
HIV	na	8.3	21.4	13.8	8.5	10.8
Suicide	11.6	12.0	15.0	12.2	11.4	11.6
Homicide	7.9	12.4	8.3	18.3	13.8	8.3
Total	872.5	1002.3	1065.6	909.9	982.4	731.7

Source: Statistical Abstract of the United States, 1999.
Deaths per 100,000 resident population.

an family and per capita income, and high school completion rate.

Viewing the summary profile of the socio economic and demographic characterization of the region found large minority populations, greater percentage female population, higher birth rate, higher teen pregnancy rate, higher death and infant death rate, larger household size, greater proportion of female headed households, greater percentage of persons and children in poverty, lower per capita and median family income, lower physician rate, and higher crime rates.

Table 29 Social, economic, and demographic profile of the U.S., Alabama, Florida, Mississippi, and Texas.

Cause	U.S.	Alabama	Florida	Louisiana	Mississippi	Texas
Population	270,298,524	4,351,999	14,915,980	4,358,967	2,752,092	19,759,614
% Hispanic[1]	11.0	0.9	14.4	2.6	0.8	29.4
% African American	12.7	25.9	15.4	32.1	36.4	12.2
% Female	51.0	51.9	51.4	51.8	52.0	50.6
Birth rate[2]	14.7	14.1	13.1	15.0	15.1	17.3
Teen Pregnancy Rate (1997)	12.8	17.6	13.4	18.6	20.7	16.1
Birth Unmarried Women (1997)	32.4	33.9	36.0	43.9	45.5	30.7
Infant death rate[3]	7.3	10.5	7.5	9.0	11.0	6.3
Death rate	8.7	10.0	10.6	9.1	7.3	9.8
# Persons per household	2.63	2.58	2.46	2.74	2.75	2.73
% Owner occupied housing	65.4	71.0	67.1	64.9	73.0	61.8
% Female households	11.6	13.4	10.7	15.6	15.9	11.8
% Families below poverty	10.0	14.3	9.0	19.4	20.2	14.1
% persons below poverty	13.3	15.7	14.3	16.3	16.7	16.7
% children <18 below poverty	19.7	25.6	20.9	23.6	22.3	23.6
Median Family Income	37,005	31,939	32,455	33,260	28,499	35,073
Med family income of family of 4	51,518	44,879	44,829	41,851	38,748	46,757
Per capita income ($/year)	14,420	11,486	14,698	10,635	9,648	12,904
Unemployment rate[4]	4.9	5.1	4.8	6.1	5.7	5.4
% High School graduates	82.1	77.6	81.4	75.7	77.5	78.5
Physician rate[5]	224	169	213	200	129	176
Hospital bed rate[6]	455	565	459	556	630	441
Crime rate[7]	5,079	4,857	na	6,741	na	5,070

Source: Country & City Data Book 2000. [1] Persons of Hispanic or Latino Origin may be of any race, [2] per 1,000 resident population as of July 1, 1997, [3] Infant death per 1,000 live births, [4] Civilian Unemployed as a percent of the total civilian labor force, [5] Active, nonfederal physicians per 100,000 resident population estimated as of July 1, 1999, [6] Per 100,000 resident population estimated as of July 1, 1999, [7] per 100,000 residents.

Productivity

This section of the report provides a summary of some indicators of productivity for the region. Included are measures of gross state product by industry, manufacturers summaries, average hourly wage, business starts and failures, private employer firms, employment, and estimated receipts, summary of retail trade, residential and non-residential construction contracts, and performance sector research and development expenditures by states. Gross products by state data are presented for construction, manufacturing, transportation, public utilities, wholesale trade, retail trade, finance, insurance and real estate, services and government. As can be seen in Table 30, the gross state products in the region were higher in the agricultural products sector. Gross state products in Louisiana, Mississippi, and Alabama were lower than the national average in nearly all sectors except farm related products. However, in Alabama gross state products were higher than the national average in the government sector. Gross state products in Texas and Florida were higher than the national average in the industry sectors.

We also examined change in productivity between 1990 and 1996. In the United States, gross national products increased by 34.8 percent between 1990 and 1996. We compared the rate of increase in gross national products for the country as a whole to the rate of change in gross state products for Gulf Coastal Plain States. Rate of growth as measured by gross state products increased by 39.5 percent in Alabama, 41.3 percent in Florida, 32.9 percent in Louisiana, 31.4 percent in Mississippi and 41.9 percent in Texas. Between 1990 and 1996, productivity rate increases were greater in Alabama and Texas than the national average. We also looked at more recent changes in the rate of change in gross national products. Percent change in gross state products between 1995 and 1996 indicate that productivity in the region was increasing at rates higher than the national average in all states in the region. These trend data indicate that perhaps the Gulf Coastal Plain region was beginning to grow at rate higher than other parts of the nation as measured by gross state products.

Hourly wages (Table 32) also can be an indicator of the health of the economy for the region. The national average wage for employees in the manufacturing sector in 1998 was $34,561. Income was generally lower than the national average in all states in the region. Per employee income was 32 percent lower than the national average in Mississippi ($23,666), 19 percent lower in Alabama ($27,679), 12 percent lower in Florida ($30,554), a little over one percent lower in Texas ($34,131), and less than one percent lower in Louisiana ($34,439). Average production rate per employee was higher in the State of Louisiana and lower in the other states in the region.

Productivity in private employer firms (Table 34) and retail establishments (Table 35 was also examined. In 1996, there were 80,000 private employer firms in Alabama, 341,600 in Florida, 81,000 in Louisiana, 48,300 in Mississippi, and 359,400 in Texas. These companies provided employment to 16,260,700 persons in 1996. Estimated receipts for all states in the region were $2.5 trillion dollars. There were 260,500 retail trade establishments in the five state region in 1996. Almost half, 104,100 were located in the State of Texas and another 91,300 could be found in Florida. Less than 25 percent of the retail trade establishments in the region were located in the States of Alabama (25,700 establishments), Louisiana (23,600 establishments), and Mississippi (15,800 establishments). Upon closer scrutiny of retail sales by type of stores, nationally, we found that retail receipts increased by 1.8 percent between 1996 and 1997. Comparatively, these sales increased by 2.1 percent in Alabama, 1.9 percent in Florida, 2.2 percent in Louisiana, 1.6 percent in Mississippi, and 1.0 percent in Texas. Next, we looked at the region compared nationally to average household retails sales during 1997. The average household in the United States spent $25,437 on retail sales in 1997 compared to $23,122 in Alabama, $28,015 in Florida, $24,866 in Louisiana, 19,888 in Mississippi, and $25,302 in Texas. Since Alabama, Mississippi and Louisiana had similar population sizes and distributions of population by race, we compared retail sales receipt by sector in these three states in the region. Total retail receipts in 1997 in Alabama were $38.1 billion, in Louisiana were $39.1 billion, and in Mississippi were $19.6 billion.

Business starts and failures were used as indicators of long term growth and productivity. Florida had 13,029 new business start-up and 2,047 business failures in 1998. Texas had fewer business start-ups, 10,936 but more business failures, 6,785. Alabama with a relative high rate of growth as indicated by increases in gross state products had a large number of business start ups (2,645) compared to its relative strength in the region. On the other hand, Louisiana which has a population about the same size as Alabama had fewer business start-ups (1,849).

Finally, we examined expenditures by state for research and development. It is thought that dollar allocation to research and development would stimulate development of industry start-up and hence spur the economy. Proportionately, industrial expenditures for research and development in Alabama was higher than in other states in the region. This factor may very well be associated with increases in state national products and business start-up in the state.

Table 30 Gross State Product by Industry (1996)*.

Industry	U.S.	Alabama	Florida	Louisiana	Mississippi	Texas	U.S. Aver.
Farms, Forestry Fisheries[1]	11.7	1.8	5.8	1.3	1.5	6.4	.23
Construction	264.3	3.6	14.7	4.4	1.9	20.8	5.3
Manufacturing	1,323.7	21.0	28.8	21.9	12.8	90.8	26.4
Transportation, Public Utilities	611.7	8.8	30.4	10.2	5.7	55.4	12.2
Wholesale Trade	493.3	6.0	25.2	6.2	3.0	38.4	9.9
Retail Trade	648.5	9.5	39.2	9.2	5.5	46.6	13.0
Finance, Insurance Real Estate	1,255.9	10.6	67.8	13.4	5.4	66.6	25.1
Services[2]	1,342.9	13.9	73.4	16.5	7.8	86.7	28.6
Government [3]	839.6	14.0	40.1	11.8	7.6	57.9	16.8
Total[1]	6,923.1	90.7	326.1	109.6	51.7	502.0	138.5

* in billion dollars
1 - includes mining not shown separately.
2 - includes agricultural services.
3 - includes federal civilian and military and state and local governments.

Table 31 Gross State Product in 1996 in billion of dollars.

Area	1990	1993	1994	1995	1996	Percent Change 1990 – 1996	Percent Change 1995 – 1996
United States	5,659.8	6,440.0	6,868.0	7,228.3	7,631.8	34.8	5.3
Alabama	71.1	83.0	89.3	95.0	99.2	39.5	4.44
Florida	255.2	300.7	321.7	339.0	360.5	41.3	6.4
Louisiana	91.1	94.7	103.9	112.9	121.1	32.9	7.3
Mississippi	38.7	46.6	50.8	53.6	56.4	31.4	5.2
Texas	388.9	453.0	484.1	511.2	551.8	41.9	8.0

Source: Statistical Abstract of the United States, 1999.

Table 32 Manufacturers Summary and Average Hourly Wages (1998).

Area	Number (1,000)	Total Payroll (million dollars)	Per Employees (dollars)	Average Hourly Wage Production Employee
United States	18,667	645,140	34,561	13.49
Alabama	383	10,587	27,679	12.11
Florida	486	14,853	30,554	11.43
Louisiana	175	6,037	34,439	14.64
Mississippi	239	5,654	23,666	10.72
Texas	1,055	36,008	34,131	12.15

Source: Statistical Abstract of the United States, 1999.

Table 33 Business Starts and Business Failures (1998).

Area	Business Starts	Business Failures
United States	155,141	71,857
Alabama	2,645	546
Florida	13,029	2,047
Louisiana	1,849	377
Mississippi	1,347	177
Texas	10,936	6,785

Source: Statistical Abstract of the United States, 1999.

Table 34 Private employer Firms, Employment and Estimated Receipts (1996).

	Employer Firms (1,000)	Employment (1,000)	Estimated Receipts (billion dollars)
United States	5,478.0	102,187.3	16,665
Alabama	80.4	1,568.8	222
Florida	341.6	5,357.9	714
Louisiana	81.0	1,498.1	241
Mississippi	48.3	883.3	116
Texas	359.4	6,952.6	1,163

Source: Statistical Abstract of the United States, 1999.

Table 35 Retail Trade, Summary of Establishment 1996.

Area	Total Establishments	Paid Employees	Annual Payroll
United States	1,597.3	21,487	317,660
Alabama	25.7	337	4,181
Florida	91.3	1,276	18,727
Louisiana	23.6	334	4,230
Mississippi	15.8	187	2,315
Texas	104.1	1,525	22,339

Source: Statistical Abstract of the United States, 1999.

Table 36 Retail Sales by Type of Store (1997).

Sector	U.S.	Alabama	Florida	Louisiana	Mississippi	Texas
Total all stores 1996 - 1	2,465,147	36,729	158,978	37,956	19,021	170,864
Total all stores 1997 - 1	2,546,287	38,063	166,211	39,122	19,635	176,772
%Change 1996-97	1.8	2.1	1.9	2.2	1.6	1.0
Average Household Sales 1997	25,437	23,122	28,015	24,866	19,888	25,302
Food Stores 428,842	6,600	26,312	7,289	3,918	30,153	
General Merchandise	322,463	5,964	19,552	5,971	3,367	24,528
Automotive Dealers	631,625	9,833	45,848	9,993	4,746	49,451
Eating and Drinking Places	245,314	3,138	16,474	3,747	1,517	17,095
Gasoline Service Stations	156,291	2,742	7,972	2,703	1,342	10,939
Building Materials and Garden Supplies	144,681	2,357	8,722	2,088	1,239	8,034
Apparel and Accessory Stores	112,577	1,615	7,689	1,543	627	7,684
Furniture and Home Furnishings	141,851	1,617	10,212	1,566	729	8,623

Source: Statistical Abstract of the United States, 1999.
1 - includes other types stores shown separately.

Table 37 Construction Contracts Value (1998).

Area	Total	Residential	Non Residential
United States	375,263	173,008	134,038
Alabama	5,976	2,241	2,243
Florida	28,200	15,192	9,411
Louisiana	4,371	1,544	1,685
Mississippi	3,391	1,101	1,245
Texas	32,415	15,168	11,988

Source: Statistical Abstract of the United States, 1999.

Table 38 New Privately Owned Housing Units Started , 1999 (in thousand of units).

Area	Total Units (1996)	Total Units (1999)	Percent Change 1996 – 1999	Single Family Units 1999
United States	1,469	1,631	11.03	1,386
Alabama	23.6	23.1	(-2.12)	18.1
Florida	129.1	152.6	18.2	111.0
Louisiana	19.3	14.3	25.8	12.3
Mississippi	13.1	14.5	10.7	11.0
Texas	125.0	155.3	24.2	107.9

Source: Statistical Abstract of the United States, 1999.

Table 39 Performance Sector of R& D Expenditures by States, 1995 (in million of dollars).

State	Industry	Universities and Colleges
United States	183,013	22,101
Alabama	1,681	335
Florida	5,223	559
Louisiana	423	315
Mississippi	315	113
Texas	8,385	1,472

Source: Statistical Abstract of the United States, 1999.

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Chapter 4

Regional Socioeconomic Trends Projection

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4.1 Population Projections

This chapter examines various indicators of future growth and development in the Gulf Coastal Plains Region as indicated by projections from 2000 to 2045. The first section will review population projections for the States of Alabama, Florida, Louisiana, Mississippi, and Texas and will compare these projections to expected average rates of growth for the United States (See Table 1).

Alabama is projected to have a year 2000 population of 4.3 million persons. By 2025, the state is projected to have a population of 5.2 million which is expected to have grown to 5.9 million by 2045. Alabama is the country's 22nd most populous state. By 2010, the population of Alabama is expected to increase by 285,000. Over the next twenty five years, the population is expected to increase by 828,000 persons. According to a U.S. Census report, 1.6 percent of the nation's population resides in Alabama. This percentage is not expected to have changed by 2025. Alabama is expected to gain approximately 71,000 persons through international migration between 1995 and 2000. The state ranks it 34th in the number of international migrants. It is ranked 9th among states in projected population gained through net internal migration between 1995 and 2025. During this period, Alabama is projected to have 1.8 million births and 1.6 million deaths. The State will rank 24th largest in births, 19th largest in deaths, and 17th largest in natural increase (birth minus deaths).

Florida, one of the fastest growing states in the nation, has a projected 2000 population of 15.6 million persons. By 2005, the population is expected to increase by 1.65 million. By the end of the first decade of the 21st century, Florida is expected to have a population of 18.2 million. The population increase is expected to continue through out the next twenty-five years. By 2025, the population is projected to be 21.9 million, an increase of 6.2 million persons. Among the 50 states and the District of Columbia, the state will rank 3rd in net population gain. Florida has the 9th highest rate of change at 46.2 percent. In 2000, 5.5 percent of the Nation's population resided in Florida (ranked 4th) and 6.2 percent is projected to resided in Florida by 2025 (ranked 3rd). Florida is projected to gain 1.9 million people through international migration between 1995 and 2025, making the state the 3rd largest in net international migration gains. Florida is also expected to have 6.2 million births and 5.8 million deaths between 1995 and 2025. It ranks 4th in the projected number of births, 2nd in the projected number of deaths, and 3rd in natural increase (birth minus deaths).

Louisiana is expected to have a 2000 population of 4.5 million. By 2010, the population is expected to have increased to 4.7 million. The population is projected to grow to 5.2 million by 2025 and 5.8 million by 2045. Its population net gain ranks at 23rd. The rate of population change of 18.2 is projected to rank as the 31st largest. In 2000, 1.6 percent of the nation's population lived in Louisiana (ranked 23rd) and by 2025, 1.5 percent of the country's population is projected to reside in the State (ranked 24th). Louisiana is expected to gain 90 thousand people through international migration between 1995 and 2025 (ranked

31st). Louisiana is expected to rank 26th in the number of persons gained through net internal migration between 1995 and 2025, representing a gain o f 45 thousand persons. The state is projected to have 2.1 million births and 1.5 million deaths, making it 21st largest in births and deaths and 23rd in natural increase.

Mississippi, the 31st most populous state with projected 2000 population of 2.75 million persons, is expected to increase to 2.82 million by 2005; to 2.9 million by 2010; to 3.2 million by 2025; and to 3.5 million by 2045. By 2025, Mississippi is projected to be the 30th most populous state. Only one percent of the nation's population resided in Mississippi in 2000 (ranked 31st). By 2025 approximately 0.9 percent of the country's population is expected to reside in Mississippi (ranked 30th). The state is expected to gain 27,000 persons through net international migration between 1995 and 2025 (ranked 42nd). The population in Mississippi is expected to increase by 140,000 through net internal migration between 1995 and 2025 (ranked 21st). The state is projected to have 1.2 million births and 975,000 deaths (ranked 31st) and is expected to rank 37th largest in terms of natural increase.

The Nation's second most populous state, Texas, has a projected 2000 population of 19.7 million. By 2010, the population of Texas is projected to be 21.7 million, 24.5 million by 2025 and 27.6 million by 2045. In 2000, 7.3 percent of the nation's population is expected to reside in Texas (ranked 2nd). By 2010, the population of the state is expected to increase by 2 million. By 2025, 8.1 percent of the population is expected to reside in Texas. The state is projected to gain 1 million people through international migration between 1995 and 2025 (ranked 6th). Texas is also expected to rank 2nd in the number of persons gained through net internal migration between 1995 and 2025, gaining 1.7 million people. Texas is projected to have 11.4 million births and 5.7 million deaths ranking 2nd largest in number of births, 3rd largest in number of deaths, and 2nd largest in natural increase.

Over the next three decades, Texas and Florida will experience large net population changes (births minus deaths plus net migration). Ranking only behind California in the largest projected net increase in population, Texas is expected to gain more than 8.5 million persons and Florida is expected to gain 6.5 million. Together, they will account for 20 percent of the net population change in the United States from 1995 to 2025. These most populous states in the South will continue to grow fairly rapidly. During 1994, Texas replaced New York as the second most populous states and is expected to remain in that position throughout the projection period. Florida is projected to replace New York as the third most populous state by 2020. When comparing the rate of growth of states in the region, Florida ranked 9th, Texas ranked 10th, Alabama ranked 25th, Louisiana ranked 31st and Mississippi ranked 35th (Campbell, 1997).

In summary, Florida and Texas will each gain one million or more persons over the 30-year period from 1995 to 2025 through net interstate migration with Florida gaining nearly 4 million persons. Florida will have the highest annual net internal migration rate from 1995 to 2025 with a rate of 8 persons per 1000. Florida also ranks 3rd in states with the largest projected net increase in immigrants between 1995 and 2025. During this period, a projected 1.8 million international immigrants will come into Florida and a projected one million international immigrants will migrate to Texas while Mississippi is expected to be among states with the lowest rates of international migration (less than 0.4 persons per 1,000 population).

Population by Age

Table 3 summarizes population projections by age for the states of Alabama, Florida, Louisiana, Mississippi and Texas for the years 2005, 2015 and 2045. In the state of Alabama, it is expected that youth 17 years of age and younger will comprise 24 percent of the population by 2005 and 22 percent of the population by year 2025. The 65 years of age and older age group is expected to grow at a faster rate than all other age groups. The percentage of the population classified as elderly is projected to increase from 13 percent in 2005 to 20 percent in 2025. In 2005, it is projected that 613,000 persons residing in Alabama will be age 65 years or older. By 2015, this figure is projected to have increased to 785,000 and increased to 1.1 million by 2025. Alabama, like other states, is expected to experience a decline in the proportion of youth in it's population. Proportionately, the elderly population in Alabama is growing faster than in other parts of the country. The state is projected to have the 24th highest proportion of elderly in 1995 and the 20th highest proportion of elderly in 2025. The dependency ratio (the number of youth under age 20 and elderly 65 years and older for every 100 working age persons 20 – 64 years of age) is expected to rise from 70.4 in 1995 to 81.3 in 2025.

Table 1 Population Projections to 2045 for the United States and Regions (Thousands, Resident Population).

Projections for July 1								July 1, 1995 to July 1, 2025			
Area	2000	2005	2010	2015	2025	2045	Net Change	Components of Change			
								Births	Deaths	Net Migration	
										Inter-state Migration	Immigra-tion
US	276,241	288,286	300,431	313,116	338,338	381,779	72,294	126,986	84,633	—	24,666
Ala	4,383	4,516	4,668	4,841	5,211	5,899	971	1,759	1,563	577	71
Fla	15,642	16,900	18,127	19,383	21,860	25,498	6,544	6,169	5,829	3,879	1,856
La	4,478	4,611	4,749	4,901	5,221	5,751	790	2,054	1,501	45	90
Miss	2,750	2,819	2,897	2,967	3,180	3,524	445	1,179	975	140	27
Tex	19,724	26,734	21,703	22,673	24,514	27,635	8,459	11,403	5,676	1,730	1,008

Table 2 Population Change.

July 1, 2000 to July 1, 2005					
Area	Net Change		Components of Change		
		Births	Deaths	Net Migration	
				Interstate Migration	Immigration
United States	11,347	19,645	13,240	—	4,112
Alabama	181	287	240	103	12
Florida	1,046	950	891	612	299
Louisiana	111	333	229	(21)	15
Mississippi	93	200	151	30	4
Texas	1,368	1,703	837	318	187

We also examined the population by age distributions for the State of Florida. The population over 18 years of age is expected to increase from 11.7 million or 77 percent in 2000 and to 16.7 million or 80.8 percent by 2025. The number of persons under 18 years of age is excepted to decrease from 21 percent in 2005 to 19 percent in 2025. By 2025, Florida is expected to rank 50th in proportion of youth. On the other hand, the elderly population is expected to increase from 17 percent in 2005 to 26 percent by 2025. Similarly, the dependency ratio is also expected to increase from 80.6 in 1995 to 91.2 in 2025.

Louisiana's elderly population is expected to increase from 555,000 persons (12 percent) in 2005 to 945,000 (18 percent) in 2025. The state is also expected to experience a decline in proportion of youth under the age of 18. By 2005 it is projected that this age group will comprise approximately 26 percent of the population. However, by 2025, youth under the age of 18 will comprise only 24 percent of this population. The dependency ratio is expected to rise from 75.7 in 1995 to 86.3 in 2025.

The youthful population (age 17 and under) in Mississippi is expected to decrease from 769,000 (26 percent) in 2005 to 736,000 (23 percent) by 2025. Like other states in the region, the proportion of older persons is expected to increase. It is expected that 363,000 (12 percent) will be age 65 or older by 2005. The number of elderly is expected to have increased to 615,000 (19 percent) by 2025. The dependency ratio is expected to rise from 77.9 in 1995 to 84.1 in 2025.

The state of Texas is expected to have 6 million (27 percent change) persons under the age of 18 by 2005. The proportionate change is expected to remain relatively stable over the next 20 years. In 2025, the population aged 17 years and under is expected to have increased to 7.4 million (27 percent change). The elderly population is expected to increase from 2.3 million (10 percent) in 2005 to 4.4 million (16 percent) in 2025. Texas' dependency rate is projected to increase from 72.5 to 1995 to 85.4 in 2025.

In summary, the states in the region show similar patterns of population growth by age. States in the region show a projected decline in the number of youth under the age of 18 as a proportion of their populations. As the baby boom generation (those born between 1946 and 1964) reaches retirement age, the growth of the elderly population (65 years and over) is expected to accelerate rapidly. The size of the elderly population is projected to increase over the next 25 years. Correspondingly, the dependency ratio is also expected to increase for states in the region.

4.2 Race and Ethnic Groups

This section of the report provides population projections by race and Hispanic origin. Alabama is projected to have a 2000 white population of 3.3 million and a black population of 1.1 million. By 2005, these populations are expected to have increased to 3.4 million whites and 1.2 million Blacks. Alabama is projected to have 3.2 million non-Hispanic whites. By 2005, non-Hispanic whites are expected to increase to 3.4 million and by 2025, to have increased to 3.7 million. Non-Hispanic Whites comprised 72.8 percent of the population of Alabama in 1995 and is expected to decrease to 71.3 percent by 2025. The non-Hispanic African American population comprised 25.5 percent of the population of Alabama in 1995 but is expected to be 26 percent of the population by 2025. Persons of Hispanic origin of any race is projected to increase from 0.7 percent in 1995 to 1.2 percent in 2025. The non-Hispanic African American population is expected to grow by a rate of 25.4 percent between 1995 and 2025. Over this same thirty year period, the non-Hispanic white population is projected to grow by 20.4 percent, the non-Hispanic American Indian, Eskimo, and Aleut population is expected to grow by 40.4 percent, the non-Hispanic Asian and Pacific Islander population to grow by 103.4 percent and the Hispanic population to grow by 99.8.

Florida has a 2000 projected white population of 12.6 million and 2.3 million African Americans. Included in these populations were 2.4 million Hispanics. The projected 2000 non-Hispanic white population for the State of Florida is 10.4 million. In 1995, 70.7 percent of the population of Florida was non-Hispanic whites. By 2025, it is expected that only 58.9 percent of the population of Florida will be non-Hispanic whites. It is also expected that the non-Hispanic African American population will have increased from 13.9 percent in 1995 to 14.8 percent in 2025. The population of persons of Hispanic origin of any race is expected to increase from13.8 percent in 1995 to 23.9 percent by 2025.

Louisiana has a projected 2000 population to 2.9 million whites and 1.4 million whites. Included in these populations were 119,000 Hispanics. Louisiana is projected to have 2.8 million non-Hispanic whites. In 1995, 64.5 percent of the population was non-His-

Table 3 Population Projections by Age (numbers in thousands as of July 1).

Age	Alabama			Florida			Louisiana			Mississippi			Texas		
	2005	2015	2025	2005	2015	2025	2005	2015	2025	2005	2015	2025	2005	2015	2025
0-4	285	296	300	922	1,032	1,086	320	338	346	196	193	190	1,629	1,886	2,073
5-17	834	811	838	2,641	2,641	2,894	884	887	936	573	544	546	4,347	4,641	5,277
18-24	444	474	452	1,407	1,536	1,524	487	501	498	287	294	278	2,348	2,639	2,746
25-64	2,455	2,590	2,565	8,398	9,463	9,753	2,289	2,409	2,408	1,489	1,548	1,513	10,866	12,025	12,723
65 & up	613	785	1,069	2,911	3,825	5,453	555	705	945	363	456	615	2,297	3,089	4,364
Total	4,631	4,956	5,224	16,279	18,497	20,710	4,535	4,840	5,133	2,908	3,035	3,142	21,487	24,280	27,183

Source: Paul R. Campbell. Series A Projections. See Population Paper #47, "Population Projections by States by Age, Sex, Race and Hispanic Origin: 1995 to 2025".

Table 4 Population Projections by Age and Sex (numbers in thousands as of July 1).

Age	Alabama (Female)			Florida (Female)			Louisiana (Female)			Mississippi (Female)			Texas (Female)		
	2005	2015	2025	2005	2015	2025	2005	2015	2025	2005	2015	2025	2005	2015	2025
0-4	139	144	146	451	503	530	156	165	169	96	94	93	796	920	1,011
5-17	407	395	408	1,288	1,288	1,409	433	432	456	280	265	265	2,122	2,264	2,572
18-24	218	234	222	695	758	751	241	249	247	144	145	135	1,160	1,303	1,356
25-64	1,272	1,341	1,327	4,311	4,869	5,026	1,193	1,255	1,254	776	808	790	5,514	6,138	6,517
65 & up	366	452	600	1,667	2,133	2,954	328	406	532	217	266	351	1,327	1,734	2,393
Total Female	2,402	2,566	2,703	8,412	9,551	10,670	2,351	2,507	2,658	1,513	1,578	1,634	10,919	12,359	13,849
Total Male	2,229	2390	2,521	7,867	8,946	10,040	2,184	2,333	2,475	1,395	1,457	1,508	10,568	11,921	13,334
Total–All	4,631	4,956	5,224	16,279	18,497	20,710	4,535	4,840	5,133	2,908	3,035	3,142	21,487	24,280	27,183
Sex Ratio	93	93	93	93	93	94	92	93	93	92	92	92	96	96	96

Source: Paul R. Campbell. Series A Projections. See Population Paper #47, "Population Projections by States by Age, Sex, Race and Hispanic Origin: 1995 to 2025".

Table 5 Population Projections by Race and Sex (numbers in thousands as of July 1).

Age	Alabama			Florida			Louisiana			Mississippi			Texas		
	2005	2015	2025	2005	2015	2025	2005	2015	2025	2005	2015	2025	2005	2015	2025
Total	4,516	4,841	5,211	16,900	19,383	21,860	4,611	4,901	5,221	2,819	2,967	3,180	26,734	22,673	24,514
White Total	3,391	3,614	3,780	13,332	14,938	16,541	2,923	3,041	3,145	1,826	1,891	1,939	17,916	19,962	22,089
White Female	1,739	1,849	1,933	6,863	7,673	8,465	1,495	1,552	1,604	935	968	992	9,069	10,113	11,195
Black Total	1,183	1,273	1,364	2,573	3,071	3,556	1,521	1,685	1,849	1,049	1,107	1,162	2,797	3,325	3,871
Black Female	634	681	729	1,349	1,617	1,877	809	896	983	651	591	621	1,450	1,729	2,017
American Eskimo, Indian, Aleut Total	18	20	23	58	70	84	20	22	25	8	8	8	107	134	159
American Indian, Eskimo, Aleut Female	9	10	12	29	35	42	10	11	13	4	4	4	53	68	81
Asian and Pacific Islander Total	40	48	57	316	417	526	72	92	115	23	27	32	667	860	1,065
Asian and Pacific Islander Female	21	25	30	170	225	284	37	48	60	13	14	17	347	450	558
Hispanic Total	42	51	63	2,845	3,828	4,944	138	179	227	24	30	39	6,624	8,294	10,230
Hispanic Female	21	25	31	1,459	1,971	2,545	70	91	117	12	15	19	3,332	4,195	5,190
Non-Hispanic White – Total	3,355	3,569	3,724	10,764	11,540	12,196	2,803	2,882	2,942	1,804	1,863	1,904	11,587	12,122	12,501
Non-Hispanic White – Female	1,721	1,827	1,905	5,546	5,924	6,229	1,434	1,471	1,500	924	954	975	5,883	6,146	6,329

Source: Paul R. Campbell. Series A Projections. See Population Paper #47, "Population Projections by States by Age, Sex, Race and Hispanic Origin: 1995 to 2025".

panic whites. By 2025, it is expected that only 57.3 percent of Louisiana's population will be non-Hispanic whites while the non-Hispanic African American population is expected to grow from 31.6 percent of the population in 1995 to 35.7 percent by 2025. The percentage of persons of Hispanic origin of any race is expected to grow form 2.4 percent of the population in the state to 4.4 percent of the population by 2025.

Mississippi has a projected 2000 population of 1.8 million whites and one million African Americans. By 2000 there are expected to be only 21,000 persons of Hispanic origin residing in Mississippi. Non-Hispanic whites who comprised 62.6 percent of the population of Mississippi in 1995 are expected to have decreased to 60.6 percent of the population by 2025. The non-Hispanic African American population in the State is expected to increase from 35.8 percent in 1995 to 36.9 percent by 2025 and the number of persons of Hispanic origin of any race is expected to increase from 0.7 percent in 1995 to 1.3 percent by 2025.

Texas has the largest Hispanic population in the nation. The 2000 projected population for the state included 16.9 million whites and 2.5 million African Americans. Included in these figures were 5.9 million persons of Hispanic origin. Non-Hispanic whites comprised 58.2 percent of the population of Texas in 1995. By 2025, they will comprise only 46 percent of the population. During this thirty year period, the non-Hispanic African American population in Texas will increase from 11.7 percent in 1995 to 12.8 percent by 2025. The number of persons of Hispanic origin of any race is expected to increase from 27.6 percent in 1995 to 37.6 percent by the 2025.

4.3 Education

School enrollment and projected number of high school graduates are indicators of potential skill level of future work force for the region. We have assessed grades k-12 school enrollment projections, percent change in k-12 school enrollment and projected graduates for the states in the Gulf Coastal Plain Region and compared these projections to national averages. The State of Alabama is projected to have 771,000 students enrolled in the public school system in 2000, 795,000 enrolled by 2005 and 789,000 enrolled by 2008. As can be seen, enrollment in public school is expected to begin decreasing by 2008. These projections are in keeping with figures on the decreasing proportion of young people not only in the State of Alabama but all across the nation. Between 1996-2002, public school enrollment in the State of Alabama increased by 5.1 percent. However, between 2002 and 2008, enrollment is projected to increase only .6 percent. Between 2002 and 2008, the projected number of high school graduates will have increased by 20.2 percent.

Public school projection figures for the state of Florida suggest that enrollment appears to have increased marginally (6.9 percent) from 2.25 million students to 2.39 million (6.9 percent) from 1996 to 2002. Between 2002 and 2006, school enrollment is expected to decrease to 2.36 million (-1.6 percent). The projected number of high school graduates for the State of Florida is higher than the national average. Between 1996 and 2002, the projected number of high school graduates is expected to increase by 14.3 percent. Between 2002 and 2008, the percent age of high school graduates is expected to have increased by another 45.2 percent.

There were 803,000 students enrolled in public schools in Louisiana in 1996. Public school enrollment remained constant in the state for the year 1997. However, by 1998, public school enrollment had decreased to 800,000, to 793,000 by 2000 and 787,000 by 2002. Public school enrollment is expected to decrease by 2.1 percent between 1996 and 2002 and by 1.6 percent between 2002 and 2008. Louisiana is also projected to have a decrease in the projected number of high school graduates from 1996 to 2002 (1.6 percent) and another decrease in the number of graduates from 2002 to 2008 (0.5 percent).

School enrollment and high school graduates are also summarized for the State of Mississippi. By 2008, the enrollment in public schools in Mississippi is expected to be 523,000, down from a high of 530,000 in 2005. Between 1996 and 2002, school enrollment is expected to increase by 3.2 percent. However, enrollment is expected to decrease by 1.2 percent between 2002 and 2008.

School enrollment and high school graduation rates are expected increase in Texas at a rate greater than the national average. Enrollment in public school is expected to increase by 8.9 percent between 1996 and 20002 and by 4.4 percent between 2002 and 2008. Similarly, high graduation rates are also expected to increase. Between 1996 and 2002, the high school graduation rate is expected to have increased by 5.4 percent and by 22.9 percent between 2002 and 2008.

Table 7 School Enrollment Projections for Grades K-12 (in thousands).

Area	1996	2000	2002	2005	2008	Percent Change in grades k-12 enrollment in public schools 1996-2002	Percent Change in grades k-12 enrollment in public schools 2002-2008	Precent Change in Projected Number of Graduates 1995-2002	Precent Change in Projected Number of Graduates 2002-08
U.S.	45,630	47,439	47,924	48,335	48,201	5.0	0.6	7.2	20.2
Alabama	750	771	782	795	789	5.1	0.6	7.1	20.2
Florida	2,246	2,391	2,401	2,387	2,364	6.9	-1.6	14.3	45.2
Louisiana	803	793	787	784	781	-2.1	-0.7	-1.6	-0.5
Mississippi	507	518	524	530	523	3.2	-0.1	-2.2	-1.2
Texas	3,818	4,117	4,159	4,273	4,343	8.9	4.4	5.4	22.9

Source: U.S. Department of Education. National Center for Education Statistics, Common Core Of Data Survey, 1997.

Income

This section of the report will examine income as a component of economic well-being of the residents in the region. Income in the states in the region is expected to grow at a higher average rate than for the United States. Personal income is expected to grow in by 106 percent in Alabama, 142 percent in Florida, 96 percent in Louisiana, 100 percent in Mississippi and 110 percent in Texas, compared to a percent change of 104 percent for the entire United States. A more meaningful picture of income projections for the region is seen when assessing per capita income. Table 10 summarizes data on personal income projections through the year 2045. As can be seen the personal income projections for all states in the region are lower than the national average for the year 2000. The per capital income for the United States in 2000 is projected to be $17,718 compared to $14,745 for Alabama, $17,690 for Florida, $14,247 for Louisiana, $12,747 for Mississippi and $16,422 for Texas. By 2010, the per capita income for the United States is expected to have increased to $19,696 compared to per capita incomes of $16,593 in the State of Alabama, $19,708 in the State of Florida, $15,972 in the State of Louisiana, $14,360 in the State of Mississippi and $18,362 in the State of Texas. However, by 2025, per capita income in the State of Florida ($22,031) is expected to be modestly higher than the national per capita income ($22,003). By 2045, per capita income in the states of Alabama, Florida, Louisiana, Mississippi and Texas is projected to be $22,659, $26,279, $21,854, $19,905, and $24,712, respectively.

We have also examined the personal income and earning projections for each of the states in the region. Table 11 provides a summary of these indicators for the State of Alabama. As noted, Alabama has a projected 2000 population of 4.4 million persons including 1.1 million youth 17 years of age and younger, 2.7 million persons 18-64 years of age, and 583,000 persons 65 years of age older. Relative per capita income is a good indicator of how personal income of residents in the State of Alabama compared to residents in other parts of the country. In 2000, the per capita income for Alabama is projected to be $14,745 which is only 83 percent (.83) of the per capita income of the United States. However, by 2015, the relative per capita income for the state is expected to have increased to .86 and to .87 by 2045. We have also examined sources of personal income for the state of Alabama. The majority of income and earnings are generated from non-farm sources. Major sources of non-farm earnings for the state by rank order are services ($11.2 billion), manufacturing ($10.2 billion), government and government enterprises ($8.5 billion) and retail trade ($4.3 billion). By 2025, a larger proportion of the population will work in the service sector as indicated by changes in earning from this sector. In 2000, 24 percent of non-farming earnings were generated in the service sector. However, by 2025, it is expected that 29 percent of non-farming earning will be generated from the service sector.

Table 12 summarizes data on populations, personal income and earning projections for the State of Florida. As of July 1, 2000, Florida with a projected population of 15.6 million, had a expected per capita income of $17,690. We compared the per capita income for residents in Florida to the per capita income of persons residing in the United States. The relative per capita income for the State of Florida is 1.00 which means that the per capita income for the state is on par with the per capita income for the rest of the nation. Nearly all personal income and earnings are generated from non-farm sources. The major sources of income by rank order for residents in 2000 are services ($59.7 billion), government and government enterprises ($27.9 billion), retail trade ($19.2 billion), finance, insurance and real estate ($14.5 billion), and manufacturing ($14.3 billion). Over the next twenty-five years, some changes are expected in major sources of earning. By 2025, the major source of earned income by rank order are projected to be services ($108.2 billion), government and government services ($39.6 billion), retail trade ($26.9 billion), finance, insurance and real estate ($25.1 billion) and manufacturing ($17.6 billion.). Similar to Alabama, the proportion of earnings from the service sector is also expected to increase significantly. In 2000, 16 percent of all non-farm earnings were garnered from the service sector. By 2025, it is expected that 40 percent of all non-farm earnings will be generated from the service sector.

Personal income and earning projections were also assessed for the State of Louisiana (See Table 13). Louisiana had a projected 2000 population of 4.5 million and per capita income of $14,247. The relative per capita income for the state is .80 for 2000. The relative per capita income is expected to increase to .81 by 2010, to .83 by 2025 and to .84 by 2045. Most of the total personal income and total income is expected to be generated in the non-farm

Table 8 Personal Income Projections to 2045.

Area	2000	2005	2010	2015	2025	2045	Percent Change
US	4,894,480.0	5,405,904.0	5,917,220.5	6,424,299.0	7,444,510.3	9,986,217.8	104
Alabama	64,629.5	70,965.4	77,459.1	84,146.7	98,220.1	133,660.4	106
Florida	276,699.7	316,841.8	357,244.6	397,954.5	481,409.6	670,046.4	142
Louisiana	63,796.3	69,780.3	75,848.3	82,057.8	95,061.9	125,669.9	96
Mississippi	35,049.8	38,269.4	41,6059.2	45,063.3	52,459.7	70,144.0	100
Texas	323,907.7	361,361.0	398,501.7	434,993.4	507,148.1	682,904.4	110

Source: Paul R. Campbell. Series A Projections. See Population Paper #47, "Population Projections by States by Age, Sex, Race and Hispanic Origin: 1995 to 2025".

Table 9 Total Earnings Projections to 2045 for the Region and the United States.

Area	2000	2005	2010	2015	2025	2045
US	3,532,680.0	3,878,404.0	4,207,520.5	4,505,929.0	5,039,010.3	6,538,617.8
Alabama	46,341.9	50,551.2	54,661.8	58,458.7	65,487.9	86,079.0
Florida	170,136.9	193,380.7	215,661.8	234,940.0	269,036.7	356,194.7
Louisiana	44,861.2	48,729.8	52,408.6	55,746.9	61,763.1	78,549.1
Mississippi	24,072.8	26,139.2	28,136.6	29,242.7	33,215.3	42,724.5
Texas	245,711.0	272,134.2	297,376.1	320,467.8	361,841.0	471,924.5

Source: Paul R. Campbell. Series A Projections. See Population Paper #47, "Population Projections by States by Age, Sex, Race and Hispanic Origin: 1995 to 2025".

Table 10 Per Capita Personal Income Projections to 2045.

Area	2000	2005	2010	2015	2025	2045
US	17,718	18,752	19,696	20,517	22,003	26,157
Alabama	14,745	15,706	16,593	17,384	18,849	22,659
Florida	17,690	18,749	19,708	20,531	22,023	26,279
Louisiana	14,247	15,134	15,972	16,742	18,206	21,854
Mississippi	12,747	13,575	14,360	15,089	16,497	19,905
Texas	16,422	17,429	18,362	19,186	20,688	24,712

Source: Paul R. Campbell. Series A Projections. See Population Paper #47, "Population Projections by States by Age, Sex, Race and Hispanic Origin: 1995 to 2025".

sector. During 2000, non-farm earnings are largely generated from services ($12.8 billion), government and government enterprises ($8.0 billion), manufacturing ($6.2 billion), and retail trade (4.2 billion). By 2025, major sources of non-farm earning are projected to be services (20.7 billion), government and government enterprises (0.6 billion), manufacturing ($7.6 billion), and retail trade ($5.3 billion).

Table 14 summarizes personal income and earning projections for Mississippi. The 2000 per capita income for persons residing in Mississippi is projected to be $12,747 which is a relative income of .72. By 2025, it is projected that the per capita income for persons residing in the state will be $16,497 which is a relative income of .75. Thus a person residing in the Mississippi can expect to earn about 75 cents for every $1.00 in earning from persons living in other parts of the country. Major sources of income by rank order for 2000 are manufacturing ($5.8 billion dollars), services ($5.4 billion), and government and government enterprises ($4.6 billion). By 2025, major sources of personal income will include services ($8.9 billion), manufacturing ($7.3 billion), and government and government enterprises ($5.8 billion).

Texas has a projected 2000 population of 19.7 million (See Table 15). The per capita income is projected to be $16,422 in 2000, $19,186 by 2015, $20,688 by 2025 and $24,712 by 2045. The relative per capita income is expected to increase only slightly from .93 in 2000 to .94 by 2025. Major sources of income are services ($69.9 billion), government and government services ($37.7 billion), manufacturing ($34.6 billion), retail trade ($23.3 billion), and transportation and public utilities ($20.6 billion). By 2025, major sources of earnings are projected to include services ($121.7 billion), government and government services ($52 billion), manufacturing ($43.6 billion), retail trade ($31.2 billion), and transportation and public utilities ($29.1 billion).

Employment Projections

This section of the report provides a summary of total employment projections and employment by place of work for the States of Alabama, Florida, Louisiana, Mississippi, and Texas (See Tables 16, 17, 18, 19, 20, and 21). A projected 2.3 million persons were employed in Alabama in 2000 compared to 8.4 million in Florida, 2.3 million in Louisiana, 1.4 million in Mississippi, and 11.2 million in Texas. Employment projections show an increase by 10.2 million (6 percent change) between 2000 and 2005 in the United States. Employment for states in the region is also expected to increase by 2005. Over the five year period, we can expect the number of employed persons in Alabama to increase by 124,000 persons (5 percent change), in Florida to increase by 820,000 persons (9 percent change), in Louisiana to increase by 21,000 persons (5 percent change), in Mississippi to increase by 66,000 persons (4 percent change), and in Texas to increase by 792,000 persons (7 percent change). With a growing population, we can expect to see this pattern continue over the next 25 years. By 2025, it is projected that the number of employed persons will have increased by 30.7 million (19 percent change) for the entire United States. We expect similar increases in the number of employed persons in the region. By 2025, the number of employed persons is expected to have increased to 2.7 million persons (16 percent change) in Alabama, to 11 million (30 percent change) in Florida, to 2.6 million (15 percent change) in Louisiana, to 1.6 million (13 percent change), and to 13.7 million (21 percent change) in Texas. As can be seen, the rate of employment growth is higher than the national average for the States of Florida and Texas and lower than the national rate of growth in Alabama, Louisiana, and Mississippi. Although the number of employed persons in the region continues to grow, the rate of growth is expected to slow substantially by 2010 as more baby boomers reach retirement age.

We also provide a more detailed assessment of employment trends for the region. Employment by place of work projections are provided for all states in the region. We thought it would be interesting to see which of the major employment sectors is expected to have the greatest increases in employment projection. As noted earlier, most persons are employed in the services, manufacturing, government enterprises and retail trade sectors in Alabama. Over the next decade, we expect to see decreased employment in the farming sector and mining sectors in Alabama. By 2010, we expect to see growth of 19 percent in the service sectors, 10 percent in the retail trade, 9 percent in construction, 2 percent in manufacturing, 10 percent in the transportation and public utilities, 9 percent in the wholesale trade, 9 percent in the finance, insurance and real estate, and 4 percent in the government and government enterprise. Over the next twenty-five years, we expect to see similar change. Between 2010 and 2025, sectors having the greatest increase in the number of employed persons are the services sectors which will have an

Table 11 Populations, Personal Income and Earnings Projections to 2045 for Alabama.

Area	2000	2005	2010	2015	2025	2045
Total Population as of July 1	4,383	4,516	4,668	4,841	5,211	5,899
17 years and under	1,109	1,110	1,104	1,116	1,189	1,313
18-64 years	2,691	2,799	2,908	2,977	3,014	3,329
65 years and over	583	607	656	747	1,008	1,256
Per capita income (1987 dollars)	14,745	15,706	16,593	17,384	18,849	22,659
Relative Per Capita Income (U.S. – 1.00)	.83	.84	.84	.85	.86	.87
Total Personal Income	64,629.5	70,935.4	77,459.1	84,146.7	98,220.1	133,660.4
Farm Income	992.3	1,021.8	1,0414.7	1,057.0	1,072.0	1,219.9
Non Farm Income	63,637.2	69,913.7	76,414.5	83,089.7	97,148.0	132,440.5
Total Earnings	46,341.9	50,551.2	54,661.8	58,458.7	65,487.9	86,079.0
Farm Earnings	992.3	1,021.8	1,044.7	1,057.0	1,072.0	1,219.9
Non Farm Earnings	45,349.7	49,529.4	53,617.2	57,401.8	64,415.8	84,859.1
Agricultural services forestry, fishing, & other	333.6	395.0	453.6	506.0	598.3	827.3
Mining	431.1	446.7	463.2	482.6	513.4	605.1
Construction	2,331.9	2,497.4	2,661.7	2,803.2	3,061.8	3,924.3
Manufacturing	10,181.3	10,822.7	11,439.8	12,004.0	13,049.3	16,543.1
Transportation and public utilities	3,072.3	3,330.4	3,583.5	3,811.2	4,225.7	5,479.3
Whole trade	2,584.5	2,800.1	3,000.7	3,175.8	3,498.4	4,539.3
Retail trade	4,294.8	4,575.1	4,865.2	5,115.5	5,579.1	7,141.6
Finance, Insurance and real estate	2,365.3	2,665.6	2,964.4	3,249.2	3,783.0	5,215.1
Services	11,231.7	12,978.9	14,670.8	16,264.5	19,195.8	26,713.3
Gov’t and gov’t enterprises	8,523.3	9,017.5	9,514.4	9,989.8	10,911.0	13,870.8

Source: Paul R. Campbell. Series A Projections. See Population Paper #47, “Population Projections by States by Age, Sex, Race and Hispanic Origin: 1995 to 2025”.

Table 12 Populations, Personal Income and Earning Projections to 2045 for Florida.

Area	2000	2005	2010	2015	2025	2045
Total Pop as of July 1	15,642	16,900	18,127	19,383	21,860	25,498
17 years & Under	3,648	3,852	3,987	4,148	4,583	5,190
18 – 64 years	9,115	9,936	10,682	11,207	11,672	13,094
65 years & over	2,879	3,111	3,459	4,028	5,605	7,213
Per capita income (1987 dollars)	17,690	18,749	19,708	20,531	22,023	26,279
Relative Per Capita Income (U.S. - 1.00)	1.00	1.00	1.00	1.00	1.00	1.00
Total Personal Income	276,699.7	316,841.8	357,244.6	397,954.5	481,409.5	670,046.4
Farm Income	2,343.9	2,451.5	2,530.1	2,573.1	2,617.5	2,961.5
Non Farm Income	274,355.8	314,390.3	354,714.5	393,381.3	478,792.1	667,084.9
Total Earnings	170,136.9	193,380.7	215,310.9	234,940.0	269,036.7	356,194.7
Farm Earnings	2,343.9	2,451.5	2,530.1	2,573.1	2,617.5	2,961.5
Non Farm Earnings	167,793.0	190,929.2	212,780.8	232,366.9	266,419.2	353,233.3
Agricultural services, forestry, fishing, & other	1,964.1	2,320.8	2,661.3	2,964.8	3,496.2	4,816.6
Mining	244.2	249.7	256.5	262.8	274.4	322.7
Construction	9,593.7	10,644.1	11,637.0	12,475.9	13,902.0	17,966.4
Manufacturing	14,314.7	15,073.4	15,793.2	16,439.3	17,649.2	21,998.3
Transportation & Public Utilities	10,617.4	11,718.7	12,741.9	13,623.8	15,118.1	19,330.6
Wholesale Trade	10,709.5	12,057.6	13,269.3	14,294.7	16,026.6	20,821.8
Retail Trade	19,207.8	21,122.8	22,954.1	24,457.9	26,945.0	34,154.0
Finance, Insurance & Real Estate	14,465.2	16,868.4	19,183.8	21,328.5	25,136.3	34,430.4
Services	59,659.8	70,888.9	81,531.6	91,280.6	108,289.7	148,314.4
Gov't & Gov't enterprises	27,916.6	29,984.9	32,752.2	35,238.9	39,581.8	51,078.1

Source: Paul R. Campbell. Series A Projections. See Population Paper #47, "Population Projections by States by Age, Sex, Race and Hispanic Origin: 1995 to 2025".

Table 13 Populations, Personal Income and Earnings Projections to 2045 for Louisiana.

Area	2000	2005	2010	2015	2025	2045
Total Pop as of July 1	4,478.0	4,611.0	4,749.0	4,901.0	5,221.0	5,751.0
17 years and Under	1,277.0	1,281.0	1,275.0	1,287.0	1,366.0	1,471.0
18 - 64 years	2,688.0	2,798.0	2,903.0	2,966.0	2,983.0	3,205.0
65 years and over	513.0	531.0	571.0	648.0	873.0	1,075.0
Per capita income (1987 dollars)	14,247.0	15,134.0	15,972.0	16,742.0	18,206.0	21,854.0
Relative Per Capita Income (U.S.-1.00)	0.8	00.81	.81	.82	.83	.84
Total Personal Income	63,796.3	69,780.3	75,848.3	82,057.8	95,061.9	125,686.9
Farm Income	403.2	420.3	434.4	443.6	456.4	528.1
Non Farm Income	63,393.1	69,360.0	75,413.9	81,614.2	94,605.5	125,158.9
Total Earnings	44,861.2	48,729.8	52,408.6	55,746.9	61,763.1	78,549.1
Farm Earnings	403.2	420.3	434.0	443.6	456.4	528.1
Non Farm Earnings	44,458.0	48,309.5	51,974.2	55,303.3	61,306.7	78,021.0
Agricultural services, forestry, fishing, & other	277.9	324.9	369.0	407.9	474.9	643.7
Mining	1,784.9	1,753.9	1,733.3	1,724.2	1,727.4	1,820.9
Construction	2,902.2	3,126.0	3,338.6	3,516.7	3,826.2	4,772.1
Manufacturing	6,205.2	6,492.9	6,773.8	7,035.5	7,534.6	9,355.7
Transportation & Public Utilities	3,382.8	3,552.0	3,719.5	3,868.9	4,144.3	5,105.8
Wholesale Trade	2,493.9	2,696.8	2,878.9	3,033.8	3,308.6	4,154.3
Retail Trade	4,155.8	4,409.1	4,665.1	4,878.1	5,255.2	6,487.4
Finance, Insurance & Real Estate	2,405.0	2,704.7	2,994.7	3,266.6	3,763.3	5,022.8
Services	12,818.7	14,653.0	16,366.7	17,937.8	20,716.0	27,448.4
Gov and Gov enterprises	8,031.7	8,596.6	9,134.6	9,633.6	10.556.2	13,210.0

Source: Paul R. Campbell. Series A Projections. See Population Paper #47, "Population Projections by States by Age, Sex, Race and Hispanic Origin: 1995 to 2025".

increase of 58,000 employed persons (8 percent increase) and retail trade which will have an increase of 27,000 employed persons (6 percent increase). Only modest gains in the number of employed persons are expected in the other employment sectors.

We found similar employment projections for the State of Florida (See Table 17). By 2000, it is expected that 8.4 million persons will be employed in the State of Florida. Over the next decade the number of employed persons is expected to increase by 1.5 million (17.9 percent increase). Between 2010 and 2025 the number of employed persons will have increased to 11.0 million, an increase of 1.1 million persons (10.1 percent increase). By 2045, the number of employed persons is expected to have increased 12.4 million persons. The largest employment sectors for 2000 are services with 3.0 million employed persons, retail trade with 1.6 million employed persons, and government and government services with 1.1 million employed persons. Over the next 45 years, these sectors will continue to provide the largest number of jobs for residents in the State. In fact, all employment sectors expect to see continue growth over the next four decades.

The employment outlook for the State of Louisiana was also examined (See Table 19). During 2000, 2.3 million persons are expected to be employed in non-farm work and 398,000 persons are expected to be employed in farm work. Like other states in the region, the number of farm workers is expected to decline to 370,000 workers by 2010, to 319,000 workers by 2025, and to 296,000 by 2045. On the other hand, the number of non-farm workers is expected to see an increase to 2.5 million by 2010, to 2.6 million by 2025, and to 2.8 million by 2045. The largest employment sectors in Louisiana are services with 681,000 employees, government and government enterprises with 413,900 employees, and retail trade with 385,000 employees. By 2010, the service sector is expected to see the greatest increase in the number of employed persons with an increase to 800,600 persons. The second fastest growing employment sector is expected to be retail trade with an increase to 420,100 employed persons. These trends are expected to continue over the next four decades.

Table 20 summarizes employment projections for the State of Mississippi. Mississippi is projected to have 1.4 million persons employed in 2000. It is projected that there will be 1.5 million persons employed in the state by 2010, 1.6 million persons employed by 2025 and 1.7 million persons employed by 2045. Employment in farm work is expected to decrease from 521,000 persons in 2000 to 483,000 in 2010. Over the next twenty-five year, further declines in the number of persons employed in farm work is expected. By 2025, the number of persons employed in farm work is expected to have decreased to 416,000. Mississippi only expects to experience modest growth in the number of non-farm workers over the next decade. Non-farm workers are expected to increase from 1.4 million workers in 2000 to 1.51 million workers in 2010. Only modest gains in the number of employed persons are expected over the next twenty-five years. By 2025, it is projected that there will be only 1.55 million workers in the non-farm sector. The largest employing sectors by rank order in the State are expected to be services, manufacturing, government and government services, and retail trade. The sectors expected to have the greatest growth in the number of employed persons over the next twenty years are services and retail trade.

The employment outlook for Texas is presented in Table 21. During 2000, 11.2 million persons are expected to be employed in the State of Texas. Over the next twenty-five years, the number of employed persons is expected to have increased to 13.7 million. The number of person employed in farm work is expected to decrease from 250,3000 in 2000 to 243,900 by 2010 and to 219,800 by 2025. The number of non-farm workers is expected to increase from 11.0 millions persons in 2000 to 13.4 million persons by 2025. The largest employment sectors are services, retail trade, and government and government related services. The service sector is expected to see the greatest growth in number of jobs by 2025. Over this period, employment sectors with the largest number of persons employed is expected to be services, retail trade and government and government services.

We have also examined the average annual projected rate of change in employment for the United States and made comparisons to the states in the region (See Table 22). Employment projections are expected to increase at an annual rate of 1.05 percent in the United States between 2000 and 2010. The States of Florida and Texas can expect a higher rate of increase in persons employed between 2000 and 2010. Florida can expect a 2.2 percent annual rate of growth of persons employed and Texas can expect an annual rate of growth in employment of 1.29. The States of Alabama (.98 percent annual

Table 14 Populations, Personal Income and Earnings Projections to 2045 for Mississippi.

Area	2000	2005	2010	2015	2025	2045
Total Pop as of July 1	2,750.0	2,819.0	2,897.0	2,987.0	3,180.0	3,524.0
17 years and Under	771.0	770.0	763.0	768.0	812.0	878.0
18 - 64 years	1,633.0	1,693.0	1,752.0	1,786.0	1,790.0	1,932.0
65 years and over	345.0	356.0	382.0	433.0	578.0	714.0
Per capita income (1987 dollars)	12,747	13,575	14,360	15,089	16,497	19,905
Relative Per Capita Income (U.S. - 1.00)	.72	.72	.73	.74	.75	.76
Total Personal Income	35,049.8	38,269.4	41,605.2	45,063.3	52,459.7	70,144.0
Farm Income	476.4	495.8	512.1	523.1	539.4	628.2
Non Farm Income	34,573.4	37,773.7	41,093.1	44,540.2	51,920.3	69,515.8
Total Earnings	24,072.8	26,139.2	28,136.6	29,942.2	33,215.3	42,724.5
Farm Earnings	476.4	495.8	512.1	523.1	539.4	628.2
Non Farm Earnings	23,596.4	25,643.4	27,624.5	29,419.6	32,675.9	42,096.3
Agricultural services, forestry, fishing, and other	202.6	239.7	275.2	307.0	363.5	504.8
Mining	139.8	137.9	136.8	136.5	137.2	146.1
Construction	1,238.9	1,342.4	1,443.6	1,526.9	1,674.7	2,129.1
Manufacturing	5,779.9	6,119.7	6,449.2	6,750.2	7,310.0	9,206.3
Transportation & Public Utilities	1,507.3	1,622.7	1,735.5	1,835.2	2,013.0	2,563.3
Wholesale trade	1,163.6	1,247.8	1,324.1	1,388.0	1,502.3	1,886.5
Retail Trade	2,436.5	2,580.9	2,730.1	2,854.2	3,076.3	3,837.1
Finance, Insurance & Real Estate	1,171.9	1,325.6	1,477.4	1,620.5	1885.0	2,573.1
Services	5,380.7	6,190.0	6,960.9	7,671.2	8,935.6	12,064.7
Gov and Gov enterprises	4,575.2	4,836.9	5,092.6	5,330.0	5,778.1	7,185.3

Source: Paul R. Campbell. Series A Projections. See Population Paper #47, "Population Projections by States by Age, Sex, Race and Hispanic Origin: 1995 to 2025".

Table 15 Populations, Personal Income and Earnings Projections to 2045 for Texas.

Area	2000	2005	2010	2015	2025	2045
Total Population as of July 1	19,724	20,734	21,703	22,673	24,514	27,635
17 years and Under	5,645	5,785	5,851	5,988	6,478	7,161
18 - 64 years	12,065	12,824	13,534	14,020	14,388	16,860
65 years and over	2,015	2,125	2,318	2,664	3,647	4,594
Per capita income (1987 dollars)	16,422	17,429	18,362	19,186	20,688	24,712
Relative Per Capita Income (U.S. - 1.00)	.93	.93	.93	.94	.94	.94
Total Personal Income	323,907.7	361,361.0	398,501.7	434,993.7	507,148.1	682,904.4
Farm Income	3,266.2	3,450.3	3,603.5	3,711.1	386.6	4,544.7
Non Farm Income	320,641.5	357,910.7	394,898.2	431,282.6	503,280.6	676,359.8
Total Earnings	245,711.0	272.134.2	297,376.1	320,467.8	361,841.0	471,924.5
Farm Earnings	3,266.2	3,450.2	3,603.5	3,717.1	3,867.6	4,544.7
Non Farm Earnings	242,444.8	268,683.9	293,772.5	316,756.6	357,973.5	467,379.9
Agricultural services, forestry, fishing, and other	1,672.2	1,988.7	2,293.5	2,568.1	3,054.6	4,259.3
Mining	8,848.1	8,864.5	8,897.9	8,961.5	9,157.2	9,833.1
Construction	13,112.4	14,273.3	15,388.8	16,346.6	18,029.9	23,016.7
Manufacturing	34,612.4	36,550.0	38,443.8	40,217.4	43,576.4	55,028.6
Transportation and Public Utilities	20,605.4	22,553.4	24,418.0	26,095.4	29,089.6	37,578.3
Whole trade	16,388.0	17,875.3	19,213.5	20,257.5	22,361.0	28,399.6
Retail Trade	23,275.0	25,120.9	26,944.4	28,490.4	31,188.9	39,271.4
Finance, Insurance and Real Estate	16,389.2	18,868.4	21,291.3	23,584.5	27,769.0	38,081.9
Services	69,872.5	81,685.7	92,907.0	103,305.8	121,728.0	165,441.8
Gov't & Gov't enterprises	37,669.5	40,900.0	43,973.8	46,829.4	52,018.9	66,369.2

Source: Paul R. Campbell. Series A Projections. See Population Paper #47, "Population Projections by States by Age, Sex, Race and Hispanic Origin: 1995 to 2025".

change), Louisiana (.95 percent annual change), and Mississippi (.85 percent annual change) are projected to have annual growth in the number of employed persons lower than the national average.

4.5 Productivity

Indicators of productivity are examined in Tables 23 to 28. Measures of productivity include gross state production (GSP) projections to 2045, and GSP by place of work to 2045. Table 23 provides a summary of GSP projections for the United States and states in the Gulf Coastal Plain Region. GSP projections for the State of Alabama are projected to increase by $15.6 billion from $79.6 billion to $95.2 billion from 2000 to 2010. GSP is expected to increase to $116 billion by 2025 and $155 billion by 2045. GSP in Florida is expected to grow at a faster rate than other states in the Gulf Coastal Plain Region. By 2010, GSP is expected to increase from $288 billion in 2000 to $364 billion. By 2025, GSP for the state is expected to have reached an all time high of $456 billion and to have more than doubled to $609 billion by 2045. Louisiana also expects increases in GSP over the next four decades. GSP is expected to increase from $93 billion in 2000 to $107 billion by 2010. It is expected that GSP will have increased to $126 billion by 2025 and to $160 billion by 2045. Mississippi has the lowest GSP in the region with revenues of only $45 billion in 2000. However, GSP is expected to have increased to $54 billion by 2010, to $65 billion by 2025, and to $85 billion by 2045. Texas is expected to have the highest GSP in the Gulf Coastal Plain Region in 2000 with revenues of $434 billion. GSP is expected to have increased to $525 billion by 2010, to $643 billion by 2025 and to $848 billion by 2045. Over the next four decades, Florida is expected to have the fastest growing economy followed by Texas. Texas is expected to continue its thriving economy with a growth rate greater than other states in the region. Although the GSP in Louisiana is the third largest in the regions, the GSP in the state of Alabama is growing at a faster rate than that of Louisiana. For this region, the economy of Alabama when viewed in terms of GSP appears to be the third fastest growing state in the region. In summary, productivity appears to be growing faster than the national average in the States of Florida and Texas and lower than the national average in the States of Louisiana and Mississippi.

Table 16 Total Employment Projections to 2045.

Area	2000	2005	2010	2015	2025	2045
United States	157,656.0	167,817.0	176,164.0	182,191.0	188,329.0	208,789.0
Alabama	2,343.7	2,467.9	2,573.5	2,650.8	2,734.6	3,058.8
Florida	8,413.1	9,233.7	9,917.1	10,425.7	10,999.0	12,402.7
Louisiana	2,293.4	2,414.1	2,511.4	2,579.0	2,640.3	2,868.8
Mississippi	1,407.5	1,473.1	1,526.6	1,562.3	1,591.2	1,732.8
Texas	11,200.3	11,992.3	12,648.7	13,135.5	13,662.8	15,168.3

Source: Paul R. Campbell. Series A Projections. See Population Paper #47, "Population Projections by States by Age, Sex, Race and Hispanic Origin: 1995 to 2025".

Table 17 Employment by Place of Work Projections for Alabama.

Area	2000	2005	2010	2015	2025	2045
Total Employment	2,343.7	2,467.9	2,573.5	2,650.8	2,734.6	3,058.8
Farm	59.3	58.1	56.5	54.3	49.7	46.9
Non-Farm	2,228.4	2,409.8	2,517.1	2,596.5	2,684.9	3,011.9
Agricultural Services	25.2	28.6	31.5	33.8	36.5	42.5
Mining	10.6	10.1	9.7	9.4	8.7	8.1
Construction	126.1	132.2	137.5	140.9	144.1	160.6
Manufacturing	414.9	421.7	426.6	428.4	424.3	451.5
Transportation and Public Utilities	108.7	114.9	120.0	123.6	127.3	141.8
Wholesale Trade	103.1	108.3	112.4	115.0	117.4	130.5
Retail Trade	385.8	406.0	424.7	437.6	451.8	509.7
Finance, Insurance and Real Estate	119.6	125.8	131.2	135.3	140.0	157.3
Services	589.3	650.4	703.1	746.2	804.0	943.5
Gov't and Gov't Enterprises	401.0	411.7	420.3	426.4	430.8	466.5

Source: Paul R. Campbell. Series A Projections. See Population Paper #47, "Population Projections by States by Age, Sex, Race and Hispanic Origin: 1995 to 2025".

Table 18 Employment by Place of Work Projections for Florida.

Area	2000	2005	2010	2015	2025	2045
Total Employment	8,413.1	9,233.7	9,917.1,	10,425.7	10,999.0	12,402.7
Farm	117.0	118.0	117.3	114.8	107.3	103.0
Non-Farm	8,296.2	9,115.6	9,799.8	10,310.9	10,891.7	12,299.7
Agricultural Services	161.3	181.0	197.2	209.0	222.6	254.2
Mining	11.2	11.0	10.9	10.6	10.1	10.0
Construction	480.6	522.3	557.5	581.9	607.6	683.4
Manufacturing	525.8	533.6	538.5	539.3	531.6	560.8
Transportation and Public Utilities	386.8	417.8	442.4	459.5	475.9	525.9
Wholesale Trade	391.8	427.0	454.4	472.8	490.7	546.8
Retail Trade	1,564.3	1,703.9	1,824.7	1,908.4	1,995.4	2,235.8
Finance, Insurance and Real Estate	659.1	709.9	750.7	780.8	811.8	900.6
Services	2,984.6	3,396.4	3,745.2	4,022.2	4,371.0	5,070.2
Gov't and Gov't Enterprises	1,130.6	1,212.6	1,278.3	1,326.3	1,374.9	1,512.1

Source: Paul R. Campbell. Series A Projections. See Population Paper #47, "Population Projections by States by Age, Sex, Race and Hispanic Origin: 1995 to 2025".

Table 19 Employment by Place of Work Projections for Louisiana.

Area	2000	2005	2010	2015	2025	2045
Total Employment	2,293.4	2,414.1	2,511.4	2,579.0	2,640.3	2,868.8
Farm	39.8	38.5	37.0	35.3	31.9	29.6
Non-Farm	2,253.6	2,375.6	2,474.3	2,543.7	2,608.4	2,839.2
Agricultural Services	26.2	29.2	31.7	33.4	35.3	39.8
Mining	51.5	49.0	46.8	44.8	41.4	36.9
Construction	141.5	148.0	153.3	156.4	158.3	170.7
Manufacturing	198.7	200.7	202.0	202.2	199.5	210.9
Transportation and Public Utilities	126.6	130.4	133.2	134.8	135.1	144.1
Wholesale Trade	102.8	107.6	111.0	112.9	113.8	122.2
Retail Trade	385.0	403.7	420.1	430.4	439.0	477.7
Finance, Insurance and Real Estate	126.4	133.1	138.5	142.5	146.5	160.2
Services	681.1	746.7	800.6	842.5	892.6	1,003.3
Gov't and Gov't Enterprises	413.9	427.3	437.2	443.7	446.9	473.2

Source: Paul R. Campbell. Series A Projections. See Population Paper #47, "Population Projections by States by Age, Sex, Race and Hispanic Origin: 1995 to 2025".

Table 20 Employment by Place of Work Projections for Mississippi.

Area	2000	2005	2010	2015	2025	2045
Total Employment	1,407.5	1,473.1	1,526.6	1,562.3	1,591.2	1,732.8
Farm	52.1	50.3	48.3	46.1	41.6	38.7
Non-Farm	1,355.4	1,422.8	1,478.3	1,516.2	1,549.6	1,694.1
Agricultural Services	16.0	18.0	19.7	20.9	22.4	25.8
Mining	8.1	7.7	7.4	7.1	6.6	6.0
Construction	68.7	72.3	75.3	77.1	78.7	86.3
Manufacturing	277.0	282.7	287.0	288.9	287.3	306.1
Transportation and Public Utilities	60.9	64.2	66.9	68.7	70.2	77.3
Wholesale Trade	50.9	53.0	54.5	55.3	55.4	59.7
Retail Trade	227.4	237.9	247.5	253.5	258.4	283.4
Finance, Insurance and Real Estate	64.6	67.7	70.2	71.9	73.6	80.5
Services	326.3	358.1	384.5	404.9	429.3	486.5
Govt and Govt Enterprises	255.4	261.1	265.4	267.8	267.7	282.5

Source: Paul R. Campbell. Series A Projections. See Population Paper #47, "Population Projections by States by Age, Sex, Race and Hispanic Origin: 1995 to 2025".

Table 21 Employment by Place of Work Projections for Texas (Thousands of Jobs).

Area	2000	2005	2010	2015	2025	2045
Total Employment	11,200.3	11,992.3	12,648.7	13,135.5	13,662.8	15,168.3
Farm	250.3	248.2	243.9	236.9	219.8	210.4
Non-Farm	10,950.0	11,744.1	12,404.8	12,898.6	13,443.0	14,958.0
Agricultural Services	142.9	162.4	179.0	191.6	207.3	241.9
Mining	245.2	234.4	224.6	216.0	200.7	180.1
Construction	617.6	658.2	692.2	715.5	738.9	820.3
Manufacturing	1,075.3	1,092.2	1,104.5	1,110.2	1,103.1	1,178.3
Transportation and Public Utilities	566.5	604.5	635.4	657.8	681.1	755.9
Wholesale Trade	560.8	594.6	619.8	635.7	648.1	707.5
Retail Trade	1,902.2	2,027.8	2,138.9	2,215.9	2,295.3	2,550.5
Finance, Insurance and Real Estate	789.9	843.7	887.6	921.1	957.5	1,061.9
Services	3,358.9	3,753.8	4,085.6	4,350.5	4,683.5	5,373.9
Gov't and Gov't Enterprises	1,690.8	1,722.6	1,837.2	1,884.4	1,927.4	2,087.7

Source: Paul R. Campbell. Series A Projections. See Population Paper #47, "Population Projections by States by Age, Sex, Race and Hispanic Origin: 1995 to 2025".

Table 22 Total Average Annual Rate of Change for Employment Projections to 2045.

Area	2000 to 2010	2010 to 2025	2025 to 2045
United States	1.05	.46	.43
Alabama	.98	.42	.59
Florida	2.2	.72	.67
Louisiana	.95	.34	.43
Mississippi	.85	.28	.44
Texas	1.29	.53	.55

Source: Paul R. Campbell. Series A Projections. See Population Paper #47, "Population Projections by States by Age, Sex, Race and Hispanic Origin: 1995 to 2025".

Table 23 Total Gross State Product Projections to 2045 (Millions of 1987 dollars).

Area	2000	2005	2010	2015	2025	2045
United States	6,025,600	6,635,000	7,219,400	7,754,500	8,723,700	11,455,400
Alabama	79,573.4	87,431.2	95,159.0	102,378.1	115,832.9	154,532.2
Florida	288,404.7	327,280.1	364,173.1	397,421.1	455,945.0	608,551.0
Louisiana	92,506.8	99,750.5	106,819.1	113,374.7	125,550.2	160,314.6
Mississippi	45,701.8	50,072.0	54,320.1	58,202.4	65,301.3	85,487.7
Texas	433,554.3	480,169.0	525,221.6	566,947.7	643,071.8	847,967.7

Source: Paul R. Campbell. Series A Projections. See Population Paper #47, "Population Projections by States by Age, Sex, Race and Hispanic Origin: 1995 to 2025".

Table 24 Gross State Products by Place of Work Projections for Alabama.

Area	2000	2005	2010	2015	2025	2045
Total Gross State Product	79,573.4	87,431.2	95,159.0	102,378.1	115,832.9	154,532.2
Farm	1,677.3	1,839.1	1,977.5	2,083.3	2,243.3	2,735.6
Non Farm	77,896.1	85,592.1	93,181.5	100,294.8	113,589.6	151,796.6
Agricultural Services	570.7	690.5	808.4	917.5	1,116.0	1,603.7
Mining	1,549.0	1,692.3	1,802.4	1,916.4	2,070.9	2,374.0
Construction	2,562.8	2,675.0	2,792.4	2,891.3	3,079.1	3,839.6
Manufacturing	19,242.7	21,248.7	23,201.6	25,032.7	28,439.6	38,156.6
Transportation and Public Utilities	9,129.2	10,222.3	11,283.0	12,262.4	14,069.8	19.062.6
Wholesale trade	5,190.8	5,803.9	6,385.9	6,912.4	7,889.2	10,712.6
Retail Trade	7,996.3	8,740.3	9,516.7	10,222.6	11,559.0	15,571.3
Finance Insurance, and real estate	10,331.6	11,387.6	12,455.5	13,485.9	15,453.2	21,021.7
Services	11,486.0	12,920.8	14,314.0	15,617.6	18,020.6	24,522.5
Govt and govt enterprises	9,836.9	10,210.5	10,621.6	11,036.1	11,892.1	14,931.9

Source: Paul R. Campbell. Series A Projections. See Population Paper #47, "Population Projections by States by Age, Sex, Race and Hispanic Origin: 1995 to 2025".

Table 25 Gross State Products by Place of Work Projections for Florida.

Area	2000	2005	2010	2015	2025	2045
Total Gross State Product	288,404.7	327,280.1	364,173.1	397,421.1	455,945.0	608,551.0
Farm	5,214.7	5,793.5	6,275.1	6,633.2	7,143.2	8,629.3
Non Farm	283,190.0	321,486.6	357,898.0	390,787.9	448,801.8	599,921.7
Agricultural Services	3,419.3	4,131.3	4,833.1	5,480.9	6,655.7	9,543.7
Mining	745.8	794.1	846.2	892.6	979.7	1,231.3
Construction	12,773.9	13,806.3	14,777.5	15,570.7	16,907.3	21,245.3
Manufacturing	26,291.8	29,042.2	31,611.3	33,935.8	38,141.9	50,274.3
Transportation and Public Utilities	32,419.9	37,293.1	41,911.5	46,074.9	53,409.6	72,206.7
Wholesale trade	57,756.6	66,075.5	74,101.7	81,187.2	93,619.8	126,308.4
Retail Trade	35,479.4	40,115.5	44,686.5	48,690.9	55,964.4	74,403.2
Finance Insurance, and real estate	55,298.1	63,073.7	70,505.1	77,397.2	89,715.8	121,159.9
Services	63,315.5	73,216.4	82,538.7	91,012.3	105,763.3	142,152.8
Govt and govt enterprises	31,169.2	34,054.0	36,772.9	39,236.3	43,608.8	55,799.3

Source: Paul R. Campbell. Series A Projections. See Population Paper #47, "Population Projections by States by Age, Sex, Race and Hispanic Origin: 1995 to 2025".

Table 26 Gross State Products by Place of Work Projections for Louisiana.

Area	2000	2005	2010	2015	2025	2045
Total Gross State Product	92,506.8	99,750.5	106,819.1	113,374.7	125,550.2	160,314.6
Farm	895.3	980.9	1,054.2	1,110.3	1,195.9	1,461.3
Non Farm	91,611.5	98,769.6	105,764.9	112,264.4	124,354.3	158,853.3
Agricultural Services	476.7	570.7	661.8	744.7	892.5	1,255.4
Mining	1,147.8	11,008.5	10,955.4	10,973.8	11,165.4	11,989.6
Construction	3,858.0	4,051.3	4,238.7	4,390.6	4,658.9	5,655.7
Manufacturing	16,407.4	17,725.1	19,008.0	20,220.3	22,507.8	29,493.5
Transportation and Public Utilities	10,875.2	11,870.8	12,827.3	13,700.0	15,289.1	19,846.1
Wholesale trade	5,488.1	6,129.1	6,722.0	7,249.4	8,200.1	10,791.8
Retail Trade	8,450.8	9,224.3	10,011.6	10,713.2	12,000.4	15,654.0
Finance Insurance, and real estate	13,045.2	14,365.6	15,652.6	16,870.7	19,137.9	25,230.4
Services	13,118.4	14,616.8	16,021.3	17,297.1	19,554.6	25,371.0
Govt and govt enterprises	8,743.9	9,207.3	9,666.3	10,104.6	10,947.5	13,565.8

Source: Paul R. Campbell. Series A Projections. See Population Paper #47, "Population Projections by States by Age, Sex, Race and Hispanic Origin: 1995 to 2025".

Table 27 Gross State Products by Place of Work Projections for Mississippi.

Area	2000	2005	2010	2015	2025	2045
Total Gross State Product	45,701.8	50,072.0	54,320.1	58,202.4	65,301.3	85,487.7
Farm	1,088.6	1,195.0	1,287.9	1,361.0	1,475.2	1,817.7
Non Farm	44,613.2	48,876.9	53,032.2	56,841.3	63,826.1	83,670.0
Agricultural Services	354.5	427.5	498.4	564.3	684.2	981.2
Mining	692.3	692.6	697.6	705.1	728.4	800.5
Construction	1,559.1	1,643.5	1,727.5	1,796.7	1,920.5	2,374.1
Manufacturing	11,636.6	12,872.0	14,063.8	15,167.0	17,193.8	22,902.7
Transportation and Public Utilities	6,370.7	7,073.3	7,746.4	8,358.7	9,467.5	12,548.0
Wholesale trade	2,523.5	2,800.6	3,058.6	3,285.5	3,695.0	4,872.2
Retail Trade	4,885.3	5,320.9	5,770.2	6,168.9	6,902.7	9,070.2
Finance Insurance, and real estate	5,969.3	6,557.4	7,137.3	7,684.5	8,700.8	11,518.7
Services	5,550.2	6,214.7	6,844.5	7,415.1	8,422.7	11,068.9
Govt and govt enterprises	5,071.7	5,274.9	5,488.4	5,695.5	6,110.4	7,533.5

Source: Paul R. Campbell. Series A Projections. See Population Paper #47, "Population Projections by States by Age, Sex, Race and Hispanic Origin: 1995 to 2025".

Table 28 Gross State Products by Place of Work Projections for Texas.

Area	2000	2005	2010	2015	2025	2045
Total Gross State Product	433,554.3	480,169.0	525,221.6	566,947.7	643,071.8	847,967.6
Farm	5,973.9	6,689.4	7,319.7	7,824.2	8,614.0	10,781.5
Non Farm	427,580.5	473,479.6	517,901.9	559,123.5	634,457.8	837,186.1
Agricultural Services	2,884.9	3,512.2	4,134.8	4,715.4	5,779.9	8,392.6
Mining	25,410.1	25,370.6	25,473.4	25,715.3	26,453.0	28,744.3
Construction	15,763.9	16,760.6	17,721.3	18,531.7	19,968.6	24,861.2
Manufacturing	69,341.9	76,336.5	83,047.0	89,342.2	101,046.8	134,783.6
Transportation and Public Utilities	56,145.2	63,545.3	70,731.9	77,430.9	89,719.0	121,834.4
Wholesale trade	32,727.8	36,947.2	40,870.9	44,380.3	50,667.3	67,601.6
Retail Trade	44,688.7	49,464.5	54,290.9	58,622.1	66,481.6	88,215.5
Finance Insurance, and real estate	65,747.7	73,854.0	81,750.8	89,235.0	102,996.9	138,640.4
Services	73,002.1	83,050.5	92,498.4	101,182.5	116,546.3	154,992.6
Govt and govt enterprises	41,868.1	44,638.3	47,382.7	49,968.1	54,798.4	69,120.0

Source: Paul R. Campbell. Series A Projections. See Population Paper #47, "Population Projections by States by Age, Sex, Race and Hispanic Origin: 1995 to 2025".

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Chapter 5

Gulf Coast Regional Climate

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5.1 General Climate of the Gulf Coastal States

Alabama

Alabama has a mild climate. January temperature averages about 52°F in the southern part of the state, and about 46°F in the north. July temperatures average about 80°F throughout the state. Alabama's annual precipitation averages from about 65 inches on the coast to 53 inches in the north. Snow falls in the north, but is rare on the coast.

Florida

Most of Florida has a warm, humid climate similar to that of the other southern states. Florida's southern tip has a tropical wet and dry climate like that of Central America and large parts of Africa and South America. Nearly all of Florida's precipitation occurs in the form of rain. Florida has an average yearly precipitation of 54 inches. An average of 32 inches falls in the rainy season, which lasts from May to October.

Louisiana

Most of Louisiana has a hot, humid, subtropical climate. It is one of the wettest states, with a yearly average of 57 inches of precipitation. Southern Louisiana has an average January temperature of 55°F, and a July average of 82°F. Hurricanes sometimes strike the coastal areas of Louisiana, causing loss of life and damage to property.

Mississippi

Mississippi has a warm, moist climate with long summers and short winters. In July, Mississippi temperatures average about 81°F. Winds from the Gulf of Mexico and frequent thundershowers cool much of the state during the summer. January temperatures average 46°F in Mississippi. Mississippi's precipitation ranges from about 50 inches a year in the northwestern part of the state to about 65 inches in the southeast. Hurricanes sometimes sweep northward from the Gulf in late summer and fall.

Texas

The climate of Texas ranges from subtropical in the lower Rio Grande Valley to moderately temperate in the northwest. Along the Gulf of Mexico the coast has a warm, damp climate. There, winds from the Gulf reduce the heat of summer and the cold of winter. Rainfall in Texas decreases from east to west. East Texas averages 46 inches of precipitation a year. Part of west Texas averages only 12 inches a year.

5.2 Observed Regional Climate Trends

The Gulf Coast regional temperature over the 20th century, according to data from the United States Historical Climatology Network data set (Easterling et al., 1996) increased from the turn of this century until the 1950s, when a significant cooling took place. Since that time a general warming trend has been established again. The largest warming during the last century in the Southeast of the US has occurred along the Gulf Coast region. Much of the warming since the 1950s has occurred in winter (Fig 1).

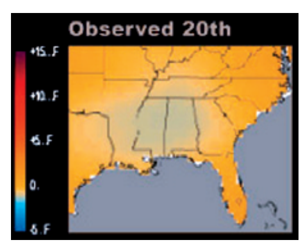

Figure 1. Observed 20th century temperature trend in the Southeast and the Gulf Coast region of the US. The largest warming during the last century has occurred along the coastal region. From NAST, 2002.

Over that same time period, the annual precipitation has increased some 20-30% and the past ten years appear to be getting wetter (Fig 2). Dating back to 1895, the wetness during the 1990s were clearly noted (Fig. 3). Data for 1997 from the National Climate Data Center indicated record wetness in many parts of the Gulf Coast region, enhanced by the strong El Nino event (Fig 4).

The El Nino event which has been creating anomalous weather in many parts of the globe contributed to 1997 being the warmest year of the century taking into account land and sea surface temperatures. El Nino has also contributed to the excess moisture along the Gulf Coast region. The Gulf Coast region precipitation departured for 1997 from 1961–90 normals is consistent with El Nino projection.

Many of the regional climate change findings over the past five to ten years can be summarized as followings (Crowe and Quayle, in Ning et al. 2000):

- Temperatures are increasing.
- Regional temperature changes are several times larger than the global average:

  Daily minimum temperatures are increasing at twice the rate of maximum temperatures and several times the rate of global temperature increase.

  Increase for minimum is 1.5° F since 1950 (0.7° F for maximum).
- There is evidence for an enhanced hydrologic cycle:

  Decrease in daily temperature range

  More atmospheric water vapor

  More precipitation

  More intense precipitation events

  Stronger extratropical storms
- There is no evidence for changes in hurricane frequency or intensity.

A most serious consequence of climate change during the past Century to the Gulf Coast environments is sea-level rise in response to melting of some polar ice and thermal expansion of warmer oceans (Muller and Grymes in Ning et al. 2000). The historical data suggested sea-level rise of about 12 cm (5 inches) over the last 100 years, and a much greater rise during the next 100 years. It must be stressed that for the Gulf Coast region these are very conservative estimates of local sea level rise, as continued deltaic and coastal subsidence is likely to significantly enhance the apparent sea-level rise above global projections.

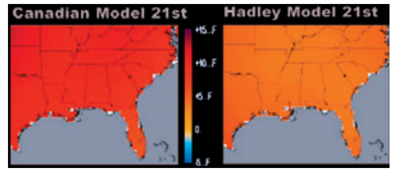

Figure 2. Observed precipitation changes during the last century are a patchwork of moderate increases and decreases. From NAST, 2002

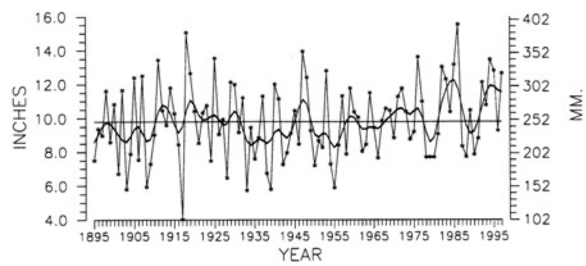

Figure 3. A time series of Oct-Dec average precipitation of the Gulf Coast region dating back to 1895. Note wetness during the 1990's. (From Crow and Quayle, 2000).

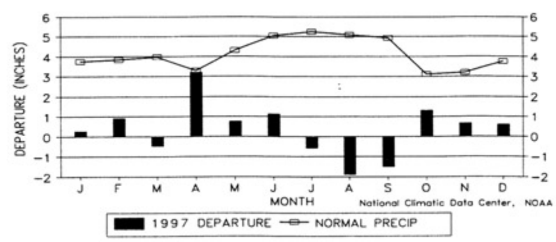

Figure 4. Gulf Coast region precipitation. Precipitation departures for 1997 from 1961–90 normals. The last three months wetness is consistent with El Nino projections. (From Crow and Quayle, 2000).

Sea-level rise has already had significant impacts on coastal areas and these impacts are very likely to increase (NAST, 2000). Between 1985 and 1995, southeastern states lost more than 32,000 acres of coastal salt marsh due to a combination of human development activities, sea-level rise, natural subsidence, and erosion. About 35 square miles of coastal land were lost each year in Louisiana alone from 1978 to 1990. Flood and erosion damage stemming from sea-level rise coupled with storm surges are very likely to increase in coastal communities.

Along with the change and variability in temperature and precipitation, the Gulf Coast region has also experienced change and variability in extreme weather events. For the past 10–20 years, this region

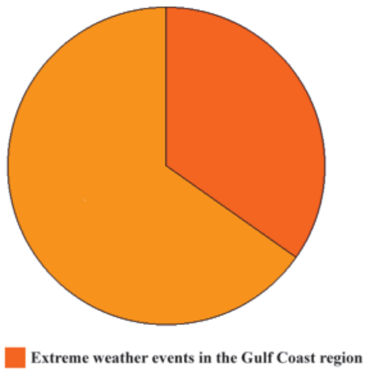

Figure 5a

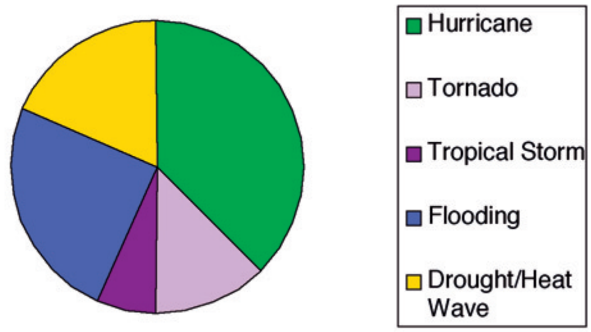

Figure 5b

Figure 5. Extreme weather events and disasters in the Gulf Coast region for the past 20 years. **5a,** among all extreme weather events in US, 34% of them happened in the gulf Coast Region. **5b,** types and frequencies of the extreme weather events in the Gulf Coast region. Based on the data from US Census Bureau, Statistic Abstracts 2001.

has experienced high frequency of weather related extreme events and disasters. The data of 1980–2000 (US Census Bureau, Statistical Abstracts 2001) indicated that of total 46 weather related extreme events and disasters occurred in US, 16 of them (34%) occurred in the Gulf Coast region, with 6 hurricanes, 4 flooding, 3 drought/heat wave, 2 tornado, and 1 tropical storm (Fig. 5 a and b).

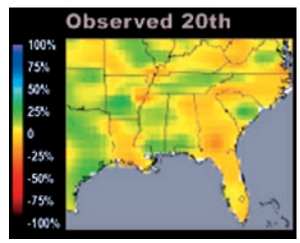

Figure 6. Scenario of the future temperature in the region. Model scenarios project relatively uniform increases in annually averaged temperatures. However, the Canadian model projects increases that are twice as large as the Hadley model. From NAST, 2000.

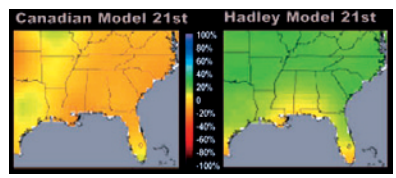

Figure 7. Scenario of the future precipitation in the region. The Canadian model scenario for the 21st century indicates near neutral trends or modest increases, while the Hadley model projects increases of near 25% for the region. From NAST, 2000.

5.3 Future Climate Scenarios

Climate has changed many times in the past, but the current rate of change seems to be large and there are enough similarities between observed changes and expected changes due to increased greenhouse gas. Based on climate perspectives studies and computer models of climate, it now seems probable that changes in regional weather patterns will accompany global warming (Karl et al., 1997). Longer and more intense heat could likely result in public health threats and increased heat-related mortality, as well as infrastructure stress like to electrical power outages and structural damage.

Climate change will also affect the patterns of precipitation, with some areas getting more and others less, changing global patterns and occurrences of droughts and floods. Similarly, increased variability and extremes in precipitation can exacerbate existing problems in water quality and sewage treatment and in erosion and urban storm-water routing, among others (Karl et al., 1997). Such possibilities underscore the need to understand the consequences of humankind's effect on climate.

Climate model projections exhibit a wide range of plausible scenarios for both temperature and precipitation over the next century. Both of the principal climate models used in the National Assessment project warming in the Gulf Coast by the 2090s, but at different rates (NAST, 2002). The Canadian model scenario shows the Southeast including the Gulf Coast region experiencing a high degree of warming, which translates into lower soil moisture as higher temperatures increase evaporation. The Hadley model scenario simulates less warming and a significant increase in precipitation (about 20%). Some climate models suggest that rainfall associated with El Niño and the intensity of droughts during La Niña phases will be intensified as atmospheric CO_2 increases (Fig. 6 and 7).

As the regional population and technology increase, the global average temperature is likely to

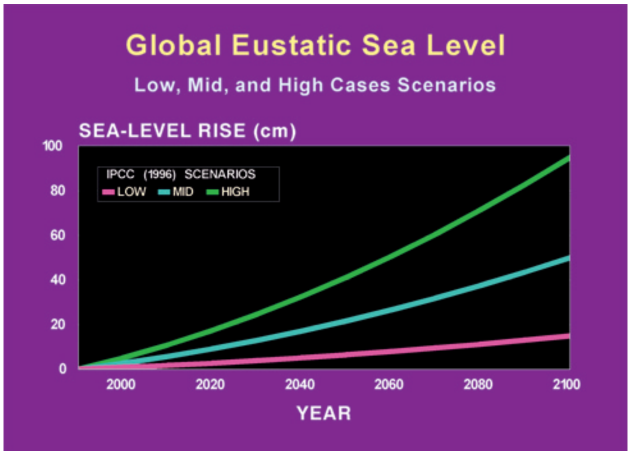

Figure 8. Eustatic sea-level rise projections for scenarios of low, moderate, and high cases based in IPCC 1996. From Doyle, 2002, in Ning et al. 2003.

rise an additional 1.0° to 3.5°C by the year 2100. The resulting sea level rise (Fig 8) could be devastating for coastal areas. Sea level rise is more dramatic than the global average along the Gulf Coast. The Hadley model predicted an average sea-level rise of 8.4 inches over next 100 years in the Gulf Coast region while the Canadian model predicted 15.6 to 19.2 inches. Coastal ecosystems and the services they provide to human society are likely to be negatively affected by sea level rise (NAST, 2000). Projected impacts are likely to include the loss of barrier islands and wetlands that protect coastal communities and ecosystems from storm surges, reduced fisheries productivity as coastal marshes and submerged grass beds are displaced or eliminated, and saltwater intrusion into surface and ground water supplies. The extent of the ecological impacts of sea-level rise is largely dependent upon the rate of rise and the development that has occurred along the shoreline. Other threats to these ecosystems come from changes in rainfall in coastal watersheds which are likely to alter fresh water inflows into estuaries, altering salinity patterns that determine the type and distribution of coastal plant and animal communities. There are few practical options for protecting natural ecosystems as a whole from increasing temperature, changes in precipitation, or rapidly rising sea level.

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Part II

Coastal Ecosystems and Climate Change

Chapter 6

Coastal Ecosystems of the Gulf of Mexico and Climate Change

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6.1 Current Status and Stresses

6.2 Climate Variability and Change

6.3 Response/Coping/Adaptation Options Information and Research Needs in the Future

Summary

Coastal ecosystems in the Gulf of Mexico (GOM) are an important national and regional resource because of their many significant ecological functions. They support diverse life forms, including commercially-valuable fisheries species, provide recreational opportunities, storm protection, and are a home for millions of humans. The stressors on coastal resources have continued to increase over the last century under the intertwined pressures of population growth and intensified resource use. Now climate change (temperature, precipitation, discharge, sea-level rise, etc.) is an anticipated additional stressor in this century, and with sometimes clear, but often unclear, consequences.

This section provides a brief overview of some of the important ecological aspects of the Gulf of Mexico coastal ecosystems and major (but not all) changes. Subsequent sections discuss four key ecological behaviors that the anticipated future climate changes will likely impact: estuarine salinity, salt marsh sustainability, commercial fisheries (especially shrimp), and low oxygen zones. Each of these is representative of a key aspect of the health of the GOM coastal ecosystems.

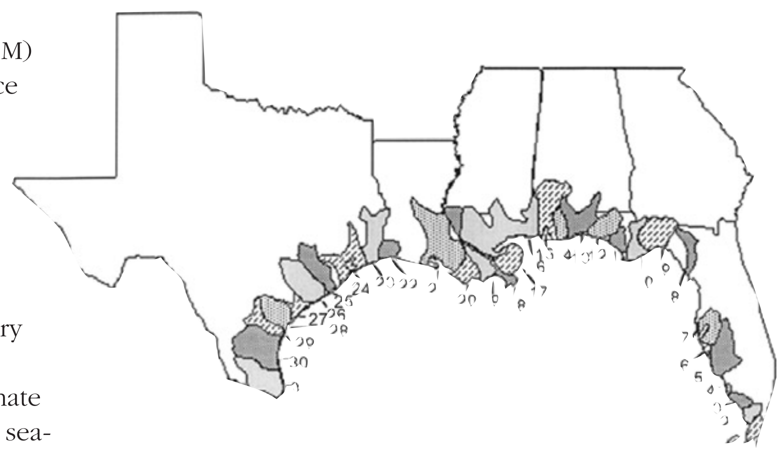

Figure 1. The major coastal watersheds in the Gulf of Mexico.

1 Florida Bay
2 South Ten Thousand Islands
3 North Ten Thousand Islands
4 Rookery Bay
5 Charlotte Harbor
6 Sarasota Bay
7 Tampa Bay
8 Suwanee River
9 Apalachee Bay
10 Apalachicola Bay
11 St. Andrew Bay
12 Choctawhatchee Bay
13 Pensacola Bay
14 Perdido Bay
15 Mobile Bay
16 Mississippi Sound
17 Breton/Chandeleur Sounds
18 Mississippi River
19 Barataria Bay
20 Terrebonne/Timbalier Bays
21 Atchafalaya/Vermilion Bays
22 Calcasiu Lake
23 Sabine Lake
24 Galveston Bay
25 Brazos River
26 Matagorda Bay
27 San Antonio Bay
28 Aransas Bay
29 Corpus Christi Bay
30 Upper Laguna Madre
31 Lower Laguna Madre

6.1 Current Status and Stresses

There are 31 major estuarine watersheds in the GOM (Figure 1). The Mississippi River and the Atchafalaya River (formed from the Red River and

Table 1 Wetland area (km²) and open water area (km²) for 125 major estuaries in the US. From Turner 2001.

	Wetland Area (km²)			Open Water Area (km²)		
		Average			Average	
Region	N	(% total)	Range	N	(% total)	Range
Northeast	13	252 (4%)	36 - 616	14	395 (7%)	16 - 1419
Middle Atlantic	11	848 (11%)	57 - 4033	21	1103 (28%)	52 - 9920
South Atlantic	17	1399 (28%)	101 - 4579	20	619 (15%)	23 - 7638
Gulf of Mexico	26	1654 (28%)	80 - 8762	35	945 (41%)	5 - 5403
Pacific	14	332 (6%)	5.2 - 2343	33	236 (9%)	3 - 2411
All	81	1079 (100%)	5.2 - 8762	123	666 (100%)	3 - 9920

the diverted one-third of the Mississippi River) drain 41% of the US. The other estuaries are largely regional watersheds of much smaller size. The coastal wetland and open water area in the GOM is 28 and 41 % of the US total, respectively (Table 1). Louisiana has 55% of the total wetland area in the GOM, most of which is marsh habitat (Table 2).

Estuaries in the southeast/Gulf of Mexico region tend to have lower freshwater turnover times than other US estuaries (Figure 2). The time it takes to turnover the freshwater content of these estuaries could decrease further with climate change. In other words, the flushing rate will increase. Further, some chaotic and episodic climate changes are likely introduced, e.g., drought and floods (Knox, 1993). As wetland losses accumulate, then the flushing rates may decrease as open water habitat increases and the estuary deepens. A lower flushing rate (e.g., from increased open water area) could lead to more harmful algal blooms (because of a longer residence time) or higher salinities (because of increased seawater

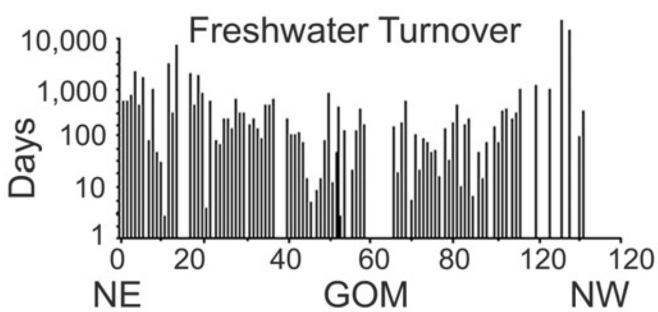

Figure 2. Variations in freshwater turnover times for US estuaries from the Northeast (NE) to the Gulf of Mexico (GOM) to the Northwest (NW). (Adapted from Turner, 2001).

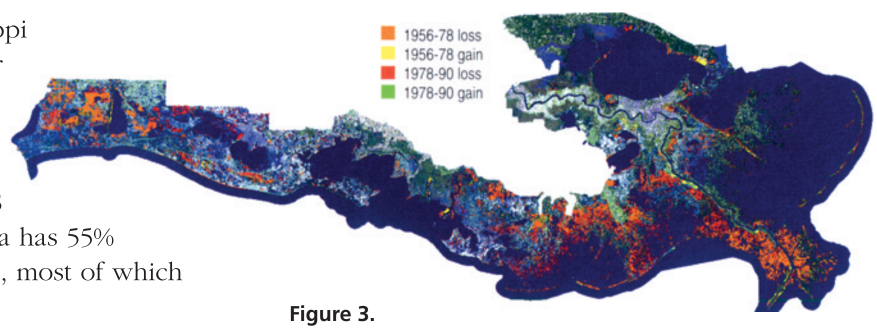

Figure 3.
Coastal landloss in Louisiana. From the USGS in Lafayette, Louisiana.

mixing through the estuarine mouth. We do not know if these factors will compensate for each other and balance the effects of each so that equilibrium is maintained.

Two major habitat changes whose management will be further complicated by the anticipate global climate changes are wetland losses and barrier island erosion. Wetland losses are particularly severe in the northern Gulf of Mexico (Figure 3) because of a variety of human influences, including hydrologic change, eutrophication, and impoundment. Louisiana's wetland losses, for example, were 69% of the nation's coastal wetland losses from

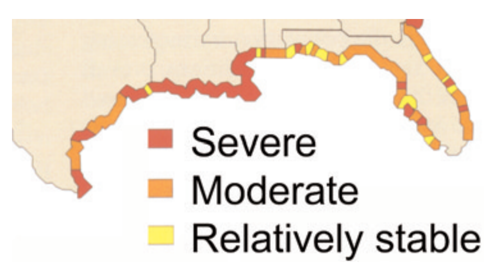

Figure 4. Annual shoreline change in the Gulf of Mexico. Adapted from USGS, 1985.

Table 2 Gulf of Mexico coastal wetland inventory (hectares). From NOAA, 1991.

	Marsh	Estuarine scrub-shrub	Forested and scrub-shrub	Total	% Total
Texas	183,900	1,100	3,000	188,000	14
Louisiana	723,500	4,100	1,900	729,500	55
Mississippi	23,800	400	-	24,200	2
Alabama	10,400	1,100	800	12,300	1
Florida	108,100	255,100	13,100	363,900	28
Total	1,049,700	255,100	13,100	1,317,900	100

1978 to 1990. Barrier islands form legal, physical and hydrological boundaries of importance to both natural and economic worlds. Barrier islands in the GOM are under considerable stress compared to the rest of the US because of either their use or their instability, including retreat (Figure 4).

6.2 Climate Variability and Change

Climate models predict an increase in temperature, variations (higher and lower) in precipitation, and higher riverine flow in major rivers. A summary of the predicted precipitation, temperature, and streamflow changes, by season expected to occur by the year 2100 as a result of global climate changes is in Table 3 (Swenson, Chapter 9). The scale of these changes is sufficient to anticipate impacts on the coastal ecosystems, although the magnitude and spatial distribution of impacts is somewhat speculative, given the sometimes conflicting model outputs for regional predictions. This uncertainty is an important area for research attention, since the interpretation of climate change impacts is driven by the magnitude of these changes, some of which might be synergistic, and others could be compensatory.

6.2.1 Estuarine salinity and climate change

Water turnover rates within the estuarine receiving basin will have two important effects on the physical environment of estuaries: the salinity regime will be altered, and the constituents will be diluted. The distribution and magnitude of effects will be indirectly realized through changes in estuarine salinity. A higher freshwater inflow will lower estuarine salinity and a lower net precipitation will raise salinities *if all other factors remain the same.*

Salinity in the northern Gulf of Mexico estuaries is influenced by (1) water exchange between the estuarine entrance and the coastal zone; and (2) local forcing (river discharge, precipitation) occurring

Table 3 Summary of predicted precipitation, temperature, and streamflow changes, by season expected to occur by the year 2100. The predictions are from the Hadley Model (HadCM2) as summarized by Ning and Addollahi (1999). Adapted from Swenson, Chapter 9.

Season	Parameter	Texas	Louisiana	Mississippi	Alabama	Florida
Winter	Precipitation	5-30% decrease	no change	no change	no change	no change
Spring	Precipitation	10% increase	no change	10% increase	10% increase	no change
Summer	Precipitation	10% increase	10% increase	15% increase	15% increase	no change
Fall	Precipitation	10% increase	10% increase	15% increase	15% increase	no change
Winter	Temperature	4° F increase	$<3^\circ$ F increase	2° F increase	2° F increase	<3-4° F increase
Spring	Temperature	3° F increase	3° F increase	3° F increase	3° F increase	3-4° F increase
Summer	Temperature	4° F increase	3° F increase	2° F increase	2° F increase	3-4° F increase
Fall	Temperature	4° F increase	$<3^\circ$ F increase	4° F increase	4° F increase	3-4° F increase
Winter	Streamflow	35% decrease	unknown	unknown	increase	unknown
Spring	Streamflow	35% decrease	unknown	unknown	increase	unknown
Summer	Streamflow	35% decrease	decrease	decrease	decrease	decrease
Fall	Streamflow	35% decrease	unknown	unknown	unknown	unknown

within the estuary proper. The Mississippi-Atchafalaya discharge dominates the input in the central portion of the Gulf, while the western (Texas) and eastern (Mississippi to Florida) portions of the Gulf are more heavily influence by local river flow (Table 4). The northern Gulf of Mexico precipitation-evaporation exhibits a general decrease in precipitation from east (Florida) to west (Texas), while surface evaporation rates generally increase from east to west across the Gulf. The sum of these two patterns results in an overall precipitation deficit in the western part of the Gulf (and southern Florida) and a precipitation surplus in the central portion of the Gulf.

The results of various climate change model predictions suggest that there will be increases in precipitation on the order of 10% for all of the Gulf states, except Florida. The predicted changes for streamflow are, in most cases, still uncertain. The effect of climate change on Mississippi River discharge is the most important consideration for the Louisiana estuaries, whose salinity is strongly affect-

Table 4 Summary of the major and secondary freshwater sources influencing salinities in the 26 northern Gulf of Mexico estuaries. The original data was taken from Orlando et al. (1995).

State	Estuarine system	Major freshwater source	Other freshwater source
Texas	Laguna Madre	Rainfall (65%)	Local riverflow (17%)
Texas	Corpus Christi Bay	Local riverflow (92%)	Rainfall (8%)
Texas	Aransas Bay	Local riverflow (54%)	Rainfall (46%)
Texas	San Antonio Bay	Local riverflow	Rainfall
Texas	Matagorda Bay	Local riverflow (25-80%)	Rainfall
Texas	Brazos River	Local riverflow	
Texas	Galveston Bay	Local riverflow	
Texas	Sabine Lake	Local riverflow	
Louisiana	Calcasieu Lake	Local riverflow	
Louisiana	Mermentau River	Local riverflow	
Louisiana	Atchafalaya/Vermilion	Atchafalaya River flow	
Louisiana	Terrebonne/Timbalier	Mississippi River flow	Rainfall
Louisiana	Barataria Bay	Mississippi River flow	Rainfall
Louisiana	Breton Sound	Mississippi River flow	Pearl River flow
Louisiana	Pontchartrain/Borgne	Local riverflow (90%)	Rainfall (5%)
Mississippi	Mississippi Sound	Local riverflow	Mississippi River flow
Alabama	Mobile Bay	Local riverflow	
Florida	Perdido Bay	Local riverflow	
Florida	Pensacola Bay	Local riverflow	
Florida	Choctawhatchee Bay	Local riverflow	
Florida	St. Andrew Bay	Rainfall	
Florida	Apalachicola Bay	Local riverflow	
Florida	Apalachee Bay	Local riverflow	
Florida	Suwannee River	Local riverflow	Groundwater flow
Florida	Tampa Bay	Local riverflow	Rainfall
Florida	Sarasota Bay	Rainfall	Local riverflow

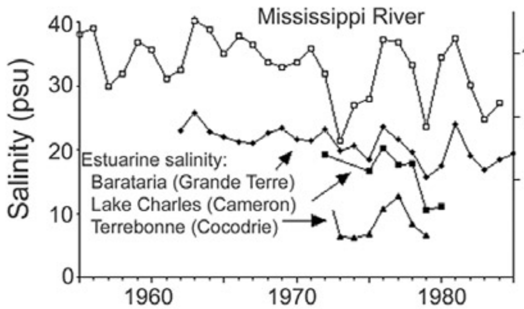

Figure 5. Time series plots of the combined annual mean flow of the Mississippi and Atchafalaya Rivers (open square) and plots of mean annual salinity from selected Louisiana Wildlife and Fisheries sampling stations within three Louisiana estuaries. River flow is in thousands of cubic feet per second (cfs) with a 15,000 cfs offset and is turned vertically to enhance visualization of the coherent patterns with estuarine salinity. It shows the effects of the river discharge variations on salinity in the estuarine bays. The relationship is dependent on freshwater entering through the open ocean passes during tidal excursions. Adapted from Wiseman et al., 1990.

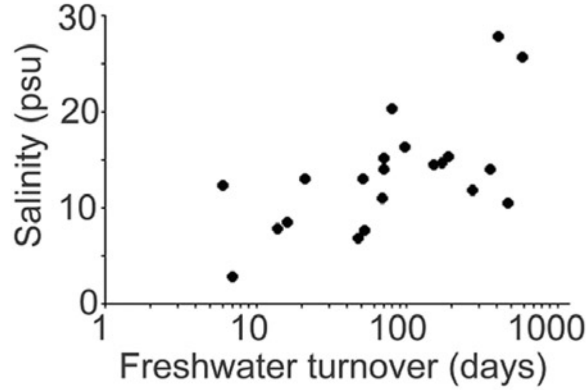

Figure 6. Freshwater inflow and salinity in Gulf of Mexico estuaries. Freshwater turnover is the estuarine volume divided by the freshwater inflow (from streams and precipitation) into the estuary. Increasing freshwater inflow will decrease the freshwater turnover time, leading to salinity reductions in the estuary. Adapted from Turner, 2001.

ed by salinity variations in the offshore waters (Figure 5). Boesch et al., (2000) present data indicating that the Hadley model predicts an increase of ~5%, and the Canadian Model predicts a decrease of ~35% for the Mississippi River discharge from 2025 through 2034. They further state that the Hadley model predicts an increase of ~50%, and the Canadian Model predicts a decrease of ~30% for the Mississippi River discharge from 2000 through 2099, and sea level is predicted to increase on the order of 30 centimeters by 2100.

Statistical models (Swenson Chapter 9) were developed describing the observed salinity at three stations (a “coastal station”, a “mid-estuary station”, and an “upper estuary station”) in the Barataria estuary, Louisiana, in terms of the major forcing functions (Mississippi River discharge, local precipitation, and coastal water levels). The most successful models used an autoregressive term in addition to the forcing function values. These models were able to account for 72, 74, and 63 percent of the observed salinity signal at the coast, mid-estuary, and upper estuary stations, respectively. The non-autoregressive portion of the model accounted for 48, 41, and 16 percent of the observed salinity signal at the coast, mid-estuary, and upper estuary stations, respectively.

The models were then used to predict the average salinity for each station using the data from 1990 through 2000 as an “index” period. The models reproduced the average annual salinity at each of the stations. The potential salinity changes that might occur with global climate changes in the forcing functions were estimated by changing the forcing functions during the index period to correspond to various climate change scenarios (increased or decreased precipitation and Mississippi River discharge). The resulting change in the annual pattern was then compared to the baseline condition. The results yield a potential change of ~3 psu (= 3 ppt) for the salt marsh, and ~1 psu for the intermediate to brackish areas of the Barataria system.

A separate analysis of the relationship between freshwater inflow and average salinity supports these model predictions and inferences. A doubling of freshwater inflow decreases the time it takes to turnover the water volume of an estuary. The relationship between freshwater turnover (X) and salinity (Y) for 26 Gulf of Mexico (GOM) estuaries is shown in Figure 6. It suggests that halving the freshwater turnover time (a doubling of freshwater inflow) will result in a salinity decrease of only a few psu (on the average).

The potential impacts of these changes are difficult to assess because the present climate models give conflicting results on the expected changes in runoff (there is general agreement on precipitation changes). However, if changes are about 3 psu, then the potential impacts would most likely be limited to small scale vegetation community changes at the boundaries of the major vegetation types. Larger

Table 5 Classification for Gulf of Mexico estuaries based on salinity variability as it relates to the character of the forcing functions. Listed, for each estuary type, is the stability level the forcing function and salinity variability characteristics, and example estuaries. Adapted from Swenson, Chapter 9.

Type	Description	Characteristics	Examples
1	Stable	1. Salinity controlled by one factor 2. Lack of dominant and continuous freshwater sources. 3. Salinity always at or near Gulf Salinities. 4. Very low to low salinity variability at all time scales.	Tampa Bay, FL Corpus Christie Bay, TX Sarasota Bay, FL Laguna Madre, TX
2	Variable 1	1. Salinity controlled by multiple factors. 2. Riverflow component important, tidal flow dominates. 3. Medium to high variability at day-week time scales. 4. Low variability at day-week time scales. 5. Low to medium salinity variability at yearly time scales.	San Antonio Bay, TX Terrebonne/Timbalier, LA Aransas Bay, TX Barataria Bay, LA Apalachee Bay, FL
3	Variable 2	1. Salinity controlled by multiple factors. 2. Riverflow and tidal flow are equal. 3. Medium variability at day-week scales. 4. High variability at day-week time scales. 5. Medium salinity variability at yearly time scales.	Suwannee River, FL Perdido Bay, FL Pensacola Bay, FL Apalachicola Bay, FL Mermantau River, LA
4	Variable 3	1. Salinity controlled by multiple factors. 2. Tidal flow component important, river flow dominates. 3. Low variability at day-week time scales 4. Medium variability at day-week time scales. 5. Low to medium salinity variability at yearly time scales.	Sabine Lake, LA-TX Mobile Bay, AL Breton Sound, LA Galveston Bay, TX Calcasieu Lake, LA
5	Stable	1. Salinity controlled by one factor. 2. Lack of dominant saltwater source. 3. Salinity values always quite low except for extreme events. 4. Low salinity variability at all time scales.	Atchafalaya Bay, LA Lake Pontchartrain, LA Chandeleur Sound, LA Mississippi Sound, MS

salinity changes would be needed in order to see dramatic vegetation shifts in the coastal salt marshes.

The two climate models (Hadley and Canadian) used for the basis for this study give conflicting estimates of the potential changes in the hydrologic cycle (Boesch et al., 2000). In general, there is low confidence in the predicted precipitation changes on a regional level (Adams and Gleick, 2000). This makes it difficult to assess the impacts around the Gulf of Mexico without detailed data from each estuarine system as was utilized in the Barataria assessment. However, some general statements regarding possible impacts can be made (Table 5). Stable systems such as Laguna Madre, Texas, or Atchafalaya Bay, Louisiana should not be affected by changes in the forcing functions that may result from global climate change, provided the changes are on the order of those predicted for the Barataria estuary (1 - 3 psu). These systems will only be effected by extremely large changes in the environmental forcing functions. The Types 2, 3, and 4 systems are the systems that would exhibit the greatest response to climate change due to their dynamic nature. In these systems, however, a negative change in one forcing function may be offset by a positive change in another forcing function. For example, in the Barataria System, a decrease in the local precipitation would lead to an increase in estuarine salinity, however, an increase in Mississippi River discharge occurring at the same time could offset this hypothetical salinity increase.

6.2.2 Sustaining salt marshes amidst climate changes

Salt marshes, located at the seaward edge of the estuary must maintain their relative elevational position as sea level rises. If the plant is flooded too often, then the soil salt marsh plants grow on may become a hostile environment, and the plants will become physiologically stressed. If the soils do not accumulate enough organic and inorganic materials to compensate for both sea level rise and for the lowering of the marsh soil (subsidence), then the marsh becomes open water. A healthy salt marsh accumulates just enough sediment over several years to survive the seasonal and annual fluctuations in

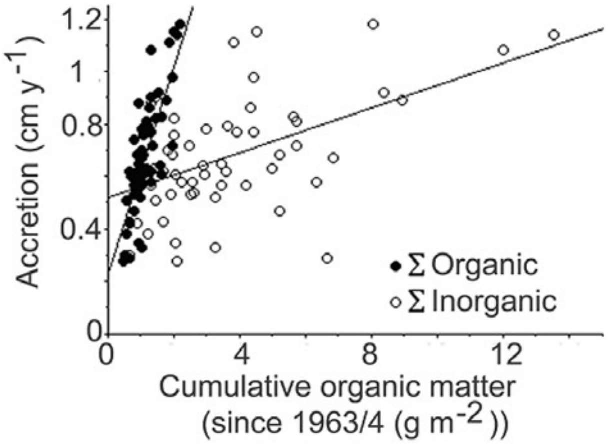

Figure 7. The relationship between the vertical accretion rate and the accumulated organic (left panel) and inorganic material (right panel). The data are for post 1963/4 accumulations. Adapted from data in Turner et al., 2001b.

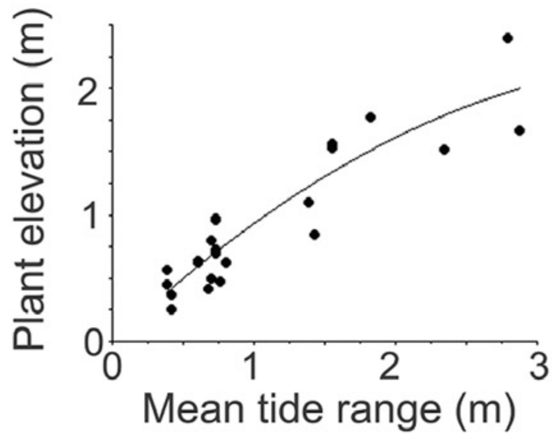

Figure 8. The relationship between the tidal range (X axis) and the elevation range within which the emergent salt marsh macrophyte Spartina alterniflora occupies. The tidal range at different locations within the Gulf of Mexico varies between 30 to 100 cm. Adapted from data in Mckee and Patrick, 1988.

water level. Most of this material is organic matter, not inorganic matter. Inorganic material makes up less than 5% of the soil volume in salt marshes. The rest of the soil is water, which is held there by the organic material. Thus the relationship between vertical accretion and organic matter is stronger than between vertical accretion and inorganic material (Figure 7).

GOM salt marshes occupy a rather narrow range (30 to 100 cm) within the intertidal zone, which is smaller than on the East Coast (Figure 8). A small change in a plant's elevation can make a big difference on whether or not its habitat is suitable, especially for plants living near the limits of its physiological tolerances. GOM salt marshes appear to be more susceptible to changes in subsidence, and sea level rise - a climate induced change. The marsh, in other words, is responsive to the seen (above ground) and unseen (belowground) environmental factors affecting plant health.

What this means is that the health of the salt marsh plant, especially belowground, is probably the major factor determining whether or not salt marshes can survive in the face of rising sea level and the sinking of the land upon which the plant is embedded. Most of the vertical adaptations that salt marsh plants must make are for subsidence, which is dominated by changes in the upper 2 meters (Turner 1991). The changes from global sea-level rise (present and future) are usually less than half of this subsidence rates (Figure 9). However, not all plants occupy an 'average' position in the landscape. Plants on the lower end of the tidal range shown in Figure 8 can be quite susceptible to even small changes in their flooding frequency.

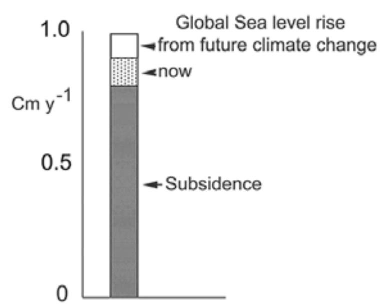

Figure 9. An example of the relative water level changes in a salt marsh due to subsidence from soil compaction and geological shifts and sinking (dark fill), present sea level rise (gray fill) and projected additional future sea level rise resulting from global climate change (unfilled). The total relative water level changes varies around the Gulf of Mexico, from zero to >1.3 cm y^{-1}.

There are other factors that interact with climate to influence the survivability of salt marshes. Some striking and novel results of other effects on coastal marshes arose from field experiments by Silliman and Zieman (2001) who demonstrated control of salt marsh macrophytic vegetation by snails. The common periwinkle, Littorina irrorata, has a profound effect on the health of the living salt marsh plant by grazing periphytic algae off the leaves that are damaged in the process. This effect increased with increasing nitrogen availability. Presumably, predation on periwinkles affects the amount of damage done by the whole snail population, and this predation could be influenced by commercial fishing pressure or interspecific competition by crabs, birds and fish (all of which might be influenced by climate). In addition, nutrient availability, including too much nitrogen, can increase the decomposition of the belowground organic material (Morris and Bradley, 1999), perhaps leading to marsh collapse. Thus, the survivability of salt marshes is not dependent on one factor, but the interaction of many factors, including those affected by global climate changes. These complex relationships between habitat sustainability and ecosystem health can be cumulative and long-term in nature.

The upland side of the salt marshes is also sensitive to flooding, and also other factors, reflecting the interactive nature of multiple influences. For example, Sasser (1977) documented how four brackish and salt marsh plants were sensitive to both salinity and flooding (Figure 10). A plant might exist, or not, because of either too high a salinity, or an intolerance to the in situ flooding regime.

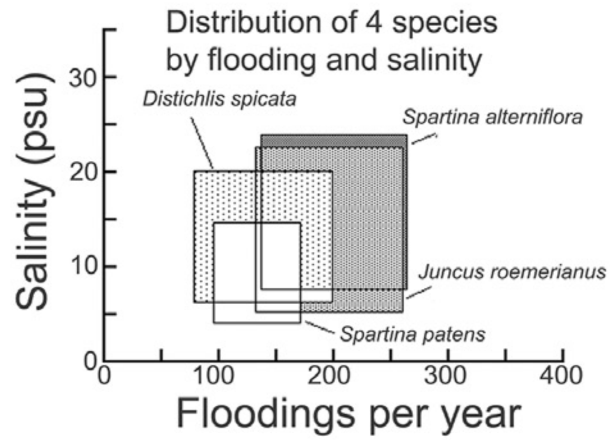

Figure 10. The distribution of four species of emergent estuarine plants described according to the flooding frequency and average salinity at each site. Note the close overlap for some species, and that a change in either salinity or flooding can change the competitive outcome for two species trying to occupy one location. Adapted from Sasser, 1977.

6.2.3 Commercial Shrimp Harvests and Climate Change

There has been considerable research on how temperature and salinity govern estuarine communities, especially species of substantial economic interest. Estuaries are often called 'nursery grounds' because of the role they play in providing juveniles a relatively food-rich niche of reduced predation pressure. A slight reduction in mortality while young can be quite important in determining the size of the adult population. Thus estuarine conditions have been used to predict future harvest success. Empirically-defined analyses of species composition, survival, or harvest over varying salinity and temperature ranges in Gulf of Mexico estuaries have been quite successful (e.g., Gunter, 1950; Gunter et al., 1964, Copeland and Bechtel, 1974; Armstrong, 1982). Based on these analyses, it is quite clear that the effects of climate change will be significant. The temperature of slow moving or stagnant shallow waters is strongly influenced by air temperatures, which are postulated to increase by 3 – 5°F as atmospheric carbon dioxide doubles. Estuaries with limited mixing will be more stratified as temperature rises (also affecting bottom water oxygen concentration), especially during summer.

The commercial shrimp fisheries of the northern Gulf of Mexico are based on the capture of brown and white shrimp, and much smaller quantities of pink and red shrimp. The general life cycle of brown and white shrimp includes an offshore spawning stock. One female may release one million eggs, which suggests a very high mortality rate. The free-floating larvae make their way into coastal estuaries and may have some ability to move vertically to maximize differential current flows within a stratified water column. Once in the estuary they live at the wetland edge and within the wetland (depending on water levels) where they grow large enough over several months to eventually migrate offshore as post-larvae or juveniles and be caught, eaten and/or reproduce. The entire cycle from birth to harvest is ordinarily 12 months.

The large annual variations in shrimp harvest from year to year are associated with changes in estuarine conditions when the juveniles are in the estuary. Variation in estuarine salinity and temperature at the time of estuarine use by the shrimp is documented world-wide for significant climatic influence on shrimp mortality (Table 7), although the frequency and intensity of passages of meteorological fronts, may also be important. Copeland and Bechtel (1974) analyzed the salinity and temperature preferences of several penaeid (shrimp) species in estuaries of the northern Gulf of Mexico. They clearly demonstrated the interactive optimal preferences by shrimp for temperature and salinity, rather than linear relationships dominated by one factor. The result is that several state fish and game agencies predict

Models of the effects of doubling sea-level rise on coastal wetland loss in Louisiana.

A computer model of the coastal Louisiana landscape was used to explore the effects of climate change on wetland loss rates (in Reyes et al., Chapter 7). Two watersheds were examined (Figure 11). One landscape (Western Basin) had a prograding delta and the other a regressive delta (Barataria). The 6100 km^2 Barataria estuarine system is located between the natural levees of the Mississippi River and Bayou Lafourche. The Western Basin is bordered by Freshwater Bayou on the west and the Atchafalaya River on the east and occupies about 6765 km^2. The models attempted to link habitat interactions within these two basins across spatial and temporal scales using three coupled modules: a vertically integrated hydrodynamic module; a process-based biological module of above and below ground primary productivity; and a module for soil dynamics.

The models were run using present sea-level rise rates and also a doubling of sea level rise (0.18 and 0.40 cm y^{-1}, respectively). The assumptions inherent to the model have varying levels of confidence, and there is no direct experimental mechanism to test their accuracy. Hindcasting model results against pre-1988 conditions is used, therefore, to test the model's accuracy. A minimum usefulness of the model is to teach scientists about the uncertainties in the model's assumptions, and, to predict the relative proportional changes in the two basins, and to estimate the relative changes in land loss with and without a doubling of sea level rise. The predictions (Table 6) suggest that the two basins behave differently, which the authors attribute to the presence of the Atchafalaya River debouching into the Western Basin, in contrast to the Mississippi River delta's retreat in the other site (located offshore of the Barataria Estuarine system). Interestingly, land loss in the Western Basin is predicted to be less than 5 % from 1988 to 2058 (70 years), and also that coastal land loss therein is unlikely to be dramatically affected by a doubling of sea level rise. Land loss in the Barataria Basin was predicted to be 37% over the same interval, and to increase by and additional 9% if sea level rise doubles (and additional 25% above the rates with a stable sea level rise).

Figure 11. Location of the two basins included in the computer model of coastal land loss and sea level rise changes.

Table 6 Results from a computer model that explores the effects on coastal wetland loss using two assumptions: with and without a doubling of sea level rise (SL) from 0.17 to 0.4 cm y^{-1}.

From 1988 to 2058:	Total Land (KM^2)	Open Water (KM^2)	Land loss 1988-2058	
Western Basin				
1988	2157	6465		
projected without 2X SL rise in 2058	2057	6565	4.64%	Difference
projected with 2X SL rise by 2058	2056	6566	4.68%	+ 0.05%
Barataria Basin				
1988	2971	2952		
projected without 2X SL rise in 2058	1866	4057	37.19%	Difference
projected with 2X SL rise by 2058	1604	4319	46.01%	+ 8.82%

Table 7 Examples of the effects of climate on coastal penaeid shrimp stocks. Adapted from Turner, 1989.

Location	Species	Effect on yields
North Carolina	*P. duorarum*	temperature (-)
Louisiana	*P. setiferus*	salinity (-) temperature (+)
	P. aztecus	salinity (+) temperature (+)
Northern Gulf of Mexico (USA)	*P. setiferus*	salinity (-) temperature (+)
	P. aztecus	salinity (+) temperature (+)
Florida	*P. duorarum*	water level (+)
Laguna Madre, Texas (periodically hypersaline)	*P. fluviatilis* *P. aztecus*	rainfall (+)
Australia	*P. merguiensis*	rainfall (+)
Indonesia	*P. merguiensis* *P. monodon*	riverflow (+)
Senegal	*P. duorarum*	salinity (+)

shrimp fisheries harvest on the basis of spring salinity and temperature, or from surrogate measures of salinity, such as riverflow. An example is the annual variations in the Gulf of Mexico shrimp catch which are negatively related to annual variations in riverflow (Figure 12), implying a riverine control on estuarine salinity. The higher yield at the same discharge in recent years may be the result of the greater fishing effort, gear changes, improved fishing knowledge, increased wetland 'edge' (resulting from wetland fragmentation), economic incentives, or, improved reporting of the actual catch. These predictive efforts are successful because larval recruitment from the spawning sites offshore into estuaries is so high that postlarval growth and survival in the estuary are probably the most important factors affecting the harvestable adult population size. Estuarine salinity and temperature changes affect the variations in annual postlarval survival, perhaps for physiological reasons, or for the indirect influences on food supply or predators. Nevertheless, it is clear that variations in climate affect fisheries yields.

Although postlarval growth and survival in the estuary are the most important factors affecting the harvestable adult population size from year-to-year, the long-term yields are directly related to both the quantity and quality of intertidal habitat. This conclusion is supported by the strong linear relationship between shrimp and the area of estuarine vegetation, from Louisiana to Florida (Figure 13). There is no obvious relationship between harvest and open estuarine water surface area, except for a possible inverse relationship. In addition, the species of shrimp caught are directly related to the kinds of intertidal coastal vegetation within that hydrologic unit. The implication of this conclusion is that habitat changes in the estuary (e.g., from any source including climate change) will affect shrimp yields.

Model predictions for climate change in the northern Gulf of Mexico suggest that both temperature and riverflow will increase. The present relationship between riverflow and commercial yields is negative (Figure 12). The short term effect of higher discharge rates will be a decrease in overall yields, therefore. There may be some adjustments as the estuarine watershed vegetation changes with lower salinities. The longer term prospects are, however, even worse. This result will because of the consequential dependency of the shrimp on the intertidal vegetation. It might seem that the fresher part of the estuary will move inland. However, the elevation gradient increases in many parts of the Gulf of Mexico, which will cause a squeezing of space for intertidal habitat. The result of these interacting forces will be lower shrimp yields for the same amount of fishing effort. The implication of the relationship between riverflow and shrimp yields shown in Figure 12 is that a 30% rise in river discharge might result in a 15 to 20 % reduction in shrimp yields in the northern Gulf of Mexico.

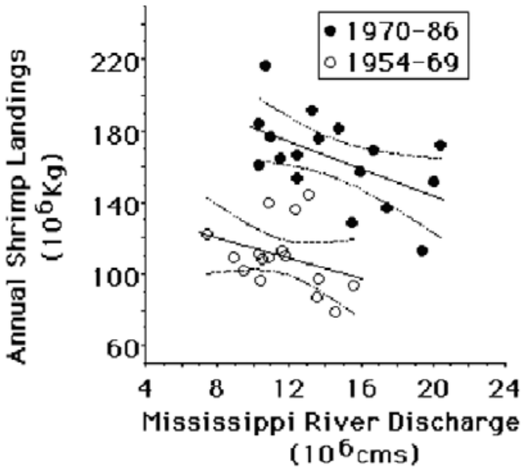

Figure 12. The relationship between the annual yields of shrimp in the Gulf of Mexico and discharge of the Mississippi river. The 95% confidence limit for the y value of each linear regression is shown. Temperature is also an important covariable. (Adapted from Turner, 1992).

6.2.4 Hypoxia and climate change

Hypoxia occurs when the oxygen content of bottom waters fall below 2 mg l^{-1}. This cut-off point is the empirically-defined limit below which shrimp and fish are usually absent. Anoxia occurs where there is no oxygen in bottom layers.

What Causes Hypoxia

Two principal factors lead to the development and maintenance of hypoxia in coastal waters: (1) a physically stratified water column, and, (2) decomposition of organic matter in the bottom layer. The water column must be stratified so that the bottom layer is isolated from the surface layer with the result that normal diffusion of oxygen from surface to bottom layers is reduced. Fresher waters derived from rivers and seasonally-warmed surface waters are less dense and reside above the saltier, cooler and more dense water masses near the bottom. This isolation reduces the reaeration of oxygen from atmosphere to surface layer to bottom waters. The stratified system may be interrupted by wind-mixing events, notably tropical storms and winter cold fronts.

The decomposition of organic matter in the bottom layer consumes oxygen, but stratification prevents an equilibrium concentration that is sufficient to maintain oxygen concentrations sufficient to support many life forms, including fish and shrimp. The source of this organic matter is mostly from phytoplankton growth in surface water. Phytoplankton not incorporated into the food web and fecal material generated via the food web sink into bottom waters where they are decomposed by aerobic bacteria, and oxygen is depleted. The concentrations and total loads of nitrogen, phosphorus and silica influence the quantity and quality of phytoplankton community and, ultimately, the flux of phytoplankton-derived organic matter.

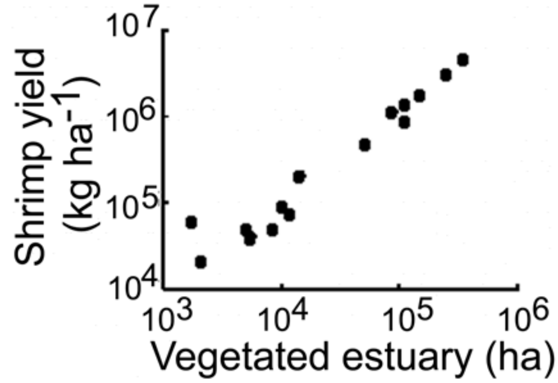

Figure 13. The relationship between intertidal vegetation and penaeid shrimp yields from the estuaries of the northern Gulf of Mexico (adapted from Turner, 1977).

The relative influence of the physical features of the system and the progression of biological processes varies spatially and over an annual cycle. In the northern Gulf of Mexico the physical and biological processes are complexly inter-related and directly linked with the dynamics of rivers, atmospheric sources, and groundwater.

Where is Hypoxia/Anoxia in the Gulf of Mexico

Decreased concentration of dissolved oxygen (=hypoxia) occurs in many parts of the world's aquatic environments. Hypoxic and anoxic (no oxygen) waters have existed throughout geologic time and presently occur in many of the ocean's deeper environs, but their occurrence in shallow coastal and estuarine areas appears to be increasing, most likely accelerated by human activities (Diaz and Rosenberg, 1995).

The second largest zone of coastal hypoxia (= oxygen depleted waters) in the world is found on the northern Gulf of Mexico continental shelf adjacent to the outflows of the Mississippi and Atchafalaya rivers (Figure 14). The mid-summer bottom areal extent of hypoxic waters (< 2 mg l^{-1} O_2, or ppm) in 1985 – 1992 averaged 8,000 to 9,000 km^2, but increased to 16,000 to 20,000 km^2 in 1993 - 1999 (Rabalais and Turner, 2000). The estimated extent was 12,500 km^2 in mid-summer of 1998, and 4,400

km^2 in 2000 and reached a record size of 20,700 km^2 in mid-summer 2001 (Rabalais 2001). Hypoxia is not found just a thin lens overlying bottom sediments, but occurs well up into the water column depending on the location of the pycnocline(s). Depending on the depth of the water, hypoxia may encompass from 10% to over 80% of the total water column, but is normally only 20 to 50% of the water column. At the high end of this range, hypoxic waters may reach to within 2 m of the surface in a 10-m water column, or to within 6 m of the surface in a 20-m water column.

Hypoxia or anoxia is also found in most of the Gulf of Mexico estuaries (Figure 15). When hypoxia occurs in Mobile Bay or nearby coastal waters, fish can be trapped along the shore where they are easily capture (and sometimes moribund). These events are called "Jubilees" if the fish are moribund when captured, but not dying. Jubilees also happen in Louisiana along barrier island beaches.

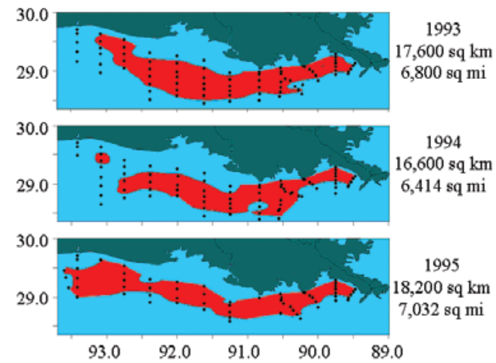

Figure 14. Hypoxia in bottom waters during the summer west of the Mississippi River delta. Graphics provided by N. N. Rabalais and colleagues and are described in Rabalais et al., 1999.

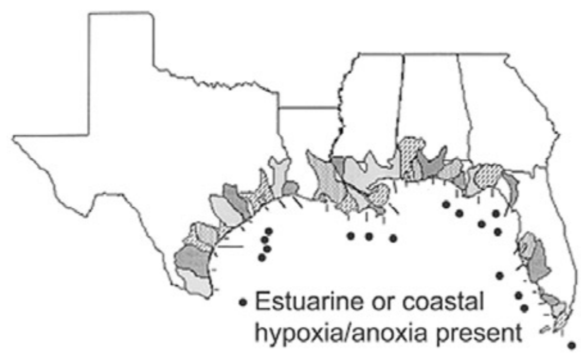

Figure 15. Estuaries in the Gulf of Mexico that have a record of periodic hypoxia or anoxia.

Some Biological Effects of Hypoxia

The hypoxic zone off Louisiana is often referred to as the "Dead Zone" in the popular press and literature. The term "dead zone" refers to the failure to capture fish, shrimp, and crabs in bottom-dragging trawls when the oxygen concentration falls below 2 mg l^{-1} in the water covering the seabed (Leming and Stuntz, 1984; Renaud, 1986). The numbers of stressed or dying benthic infaunal organisms within the sediments increase substantially when the oxygen levels remain low for prolonged periods (Rabalais et al. 2001). Higher up in the water column and in the surface mixed layer, however, there is sufficient oxygen to support sizable populations of swimming fish and crabs. Also, there are anaerobic or hypoxia-adapted organisms that survive in sediments overlain by hypoxic or anoxic waters, so that the term "dead zone" is not entirely applicable to the whole of the area designated "hypoxic" (several chapters in Rabalais and Turner, 2001). Still, the area is large, approaching the size of the state of Massachusetts in 2001, and garners public attention primarily because of the loss of catchable fish and shrimp.

Mass mortalities are likely if they are trapped against the shore by a large anoxic water mass. Heavy mortalities occur in the benthic infauna and species diversity is drastically reduced when ambient oxygen concentrations decrease below 0.5 mg l^{-1} (Gaston, 1985; Boesch and Rabalais, 1991; Rabalais et al. 1993, 2001). There is some recovery of the benthic community after hypoxic events are over. However, the overall structure of the benthic community is shifted in species composition and age structure, to a smaller-sized, lower biomass, polychaete dominated fauna. An increase in areal extent and severity of hypoxia will decrease recovery rates and also reduce food resources (infauna) for recolonizing demersal groups, such as the commercially important penaeid shrimps. Further, alterations in benthic community structure will have implications for sedimentary processes, benthic pelagic coupling, and energy flow. Major alterations in benthic communities due to hypoxia stress, especially a reduction in diversity and biomass, will certainly alter the productivity base that leads to fishery stocks. Further, fishers have to travel farther to catch the migrating fisheries stocks that avoid hypoxic areas, thus reducing net economic returns.

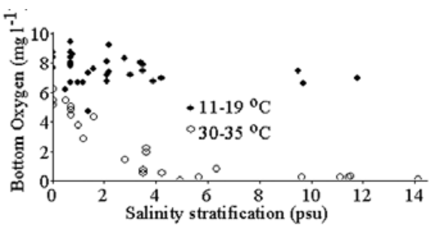

Figure 16. The relationship between salinity stratification between surface and bottom water (X axis) and bottom water oxygen concentration (X axis; (mg l^{-1}) in upper Charlotte Harbor, Florida. Data are for June-October from sampling by the South Florida Water Management District. Two portions of the data are included: where temperature in the surface water is 30°C or higher (open circles) and between 11 and 19°C (filled circles). From Turner et al., 2001.

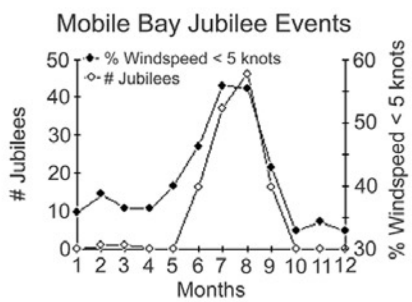

Figure 17. The percent monthly occurrence of low winds (< 5 knot wind speeds, 1974 – 1984) and the historical record of the total number of "jubilees" in Mobile Bay by month from 1946 – 1971. Adapted from Turner et al., 1987.

Climate Change and Hypoxia

Freshwater discharge and seasonal atmospheric warming control the strength of stratification necessary for the development and maintenance of hypoxia. The combined long-term average annual discharge for the Mississippi and Atchafalaya Rivers to the Gulf of Mexico is 19,920 $m^3 s^{-1}$ (1930 – 1997 period) (Bratkovich et al., 1994; Goolsby et al. ,1999). The long-term peak flow occurs in March, April and May, and the long-term low flow is in summer and early fall. Although flow is reduced in summer, large-scale circulation patterns facilitate the retention of the fresh water on the shelf (Rabalais et al. 1999). There is significant interannual variability in discharge, but the long-term average discharge for the lower Mississippi River is remarkably stable near 14,000 $m^3 s^{-1}$ (Turner and Rabalais, 1991; Bratkovich et al., 1994). Less obvious is a statistically significant and increasing trend in the Mississippi River discharge for 1900 – 1992 as measured at Tarbert Landing (Bratkovich et al. 1994). It appears to be due to a tendency for increasing discharge in September through December. This period, however, is much less important in the coastal ocean than spring and summer in the timing of important biological processes that lead to the development of hypoxia or the physical processes important in its maintenance. If a longer period of annual discharge were considered, e.g., for the early 1800s to present, the trends since the 1950s are obvious but are concealed within high interannual variability and no long-term change over a century and a half (Rabalais et al., 1999).

The projected global climate changes in the Gulf of Mexico includes higher temperatures, altered seasonal variations in river discharge and precipitation, and increased precipitation and (probably) Mississippi River discharge. Both increased temperature and freshwater discharge will affect the size and severity of hypoxic water masses in the Gulf of Mexico. Climate changes in the Gulf of Mexico will affect both of these factors, and often in a negative way. An example of the interrelationship between temperature (which is directly related to organic-decomposition rates), stratification and hypoxia is shown in Figure 16. Hypoxia in Charlotte Harbor is most likely to occur at higher temperatures and during periods of water column stratification. A lack of wind mixing of the water column may also encourage the likelihood of hypoxic events. Jubilees in Mobile Bay, for example, occur during the summer when wind speed is relatively low (Figure 17).

6.3 Response/Coping/Adaptation Options Information and Research Needs in the future

The preceding discussion illustrated several ways in which the anticipated climate changes will affect coastal ecosystems. The physical structure of coastal systems may be changed through alterations in salinity and temperature, and by habitat changes resulting in the replacement of emergent vegetation with open water. These changes can affect fisheries. Further, nutrient reduction strategies meant to reduce the severity and frequency of hypoxic events can be compromised by increased riverflow.

The seemingly direct consequences of climate change, therefore, are not the only stressor on ecosystems. Anthropogenic stress from one factor (e.g., sea level rise) can be additive to existing stres-

Models of Climate Change Effects on Hypoxia

Because model projections for the Mississippi River runoff are highly variable, the assessments of future climate change scenarios for the northern Gulf of Mexico are complicated. The Canadian and the Hadley model projected a 30% decrease and a 40% increase, respectively, by the year 2099. Justić (Chapter 8) developed an eutrophication model to describe changes in surface and bottom oxygen concentrations within the core of the Gulf of Mexico hypoxic zone. A plot of the model results and the actual data are shown in Figure 18. A sensitivity analysis revealed that the model is highly sensitive to external forcing, yet sufficiently robust to withstand order of magnitude changes in the nitrate flux of the Mississippi River.

Model simulations suggest that altered freshwater and nutrient fluxes would have important implications for water column stability, net productivity and global oxygen cycling in the northern Gulf of Mexico. A doubling of atmospheric carbon dioxide would lead to higher temperatures, increased runoff and longer, more severe and larger hypoxic zones in the northern Gulf of Mexico (Figure 19). Nominal model simulation for the period 1954-2000, for example, predicted 19 years with moderate hypoxia (< 2 mg O_2 l^{-1}) and 16 years with severe hypoxia (< 1 mg O_2 l^{-1}). A 30% decrease in the Mississippi River discharge for the same period would have significantly reduced the number of years with moderate and severe hypoxia to 8 and 4, respectively. For a scenario with 4°C increase in the average annual temperature and a 20% increase in the average Mississippi River discharge, the model predicts 31 year with moderate and 26 years with severe hypoxia. Importantly, model simulations suggest that pronounced hypoxia would not develop if the nitrate concentrations would had remained unchanged with respect to the period 1954 – 1967 (0.61 mg N l^{-1}). Thus, depending on future climate change scenarios and nutrient control strategies, hypoxia in the northern Gulf of Mexico may become more or less severe.

Model simulations indicated that bottom water hypoxia in the northern Gulf of Mexico has intensified in recent historical time, as a probable consequence of increased net productivity and an increase in the vertical flux of the organic carbon. Apparently, the long-term increase in riverine nutrient fluxes has been the primary factor controlling this historical decline in oxygen concentrations. Nevertheless, the influence of climatic factors on nitrate flux has been significant and may further increase as a result of global climate change (Figure 20).

In contrast to a relatively high degree of confidence associated with the projected temperature increases, the effects of global climate change on hydrological cycle are less certain, particularly on regional scales. The annual Mississippi River runoff, for example, was projected to decrease by 30% for the Canadian model, but increase by 40% for the Hadley model by the year 2099. Model simulations further suggest that altered freshwater and nutrient fluxes would have important implications for water column stability, net productivity and global oxygen cycling in the northern

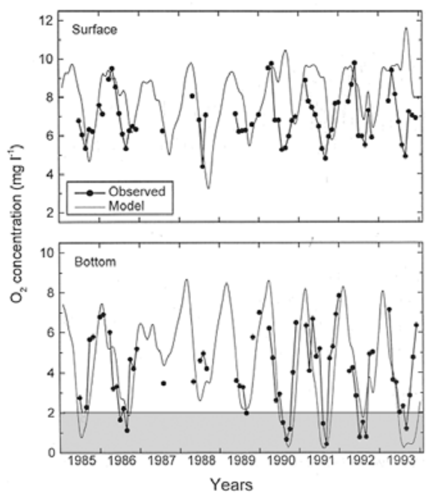

Figure 18. Observed and predicted monthly averages of surface (0-10 m) and bottom (10-20 m) oxygen concentrations at station C6 for the period June 1985 – November 1993. From Justić, Chapter 8.

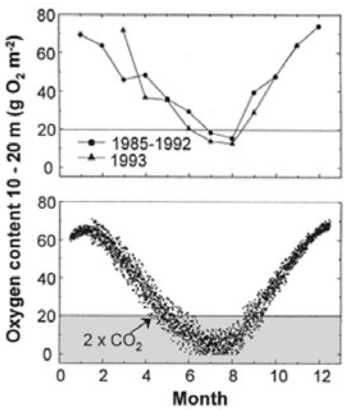

Figure 19. Seasonal changes in the integrated subpycnoclinal oxygen content (10-20m) at station C6 in the core of the hypoxic zone. Observed monthly averages for 1985 – 1992 and 1993 are compared to a Monte-Carlo simulation for a 2xCO_2 climate. The 2xCO_2 probability plot is comprised of 2880 points. From Justić et al. 1996.

Gulf of Mexico. Direct and indirect fisheries losses would likely be exacerbated if hypoxia expands in space or time as a result of global climate change.

The results of this model suggest that a large-scale reduction (~30%) in nitrogen concentration of the Mississippi River would eventually diminish the severity of hypoxia in the northern Gulf of Mexico. Nevertheless, the areal extent and the severity of hypoxia are very sensitive to climate-induced changes in freshwater and nutrient fluxes. If, for example, the Mississippi River discharge increases by 20%, as predicted in some climate change model scenarios, then a reduction in nitrate flux in excess of 20% would be required only to prevent the eutrophication from worsening. Consequently, nutrient control efforts for the Mississippi River watershed that are based solely on achieving a specific reduction in the non-point source loading, may have a limited success in controlling the eutrophi-

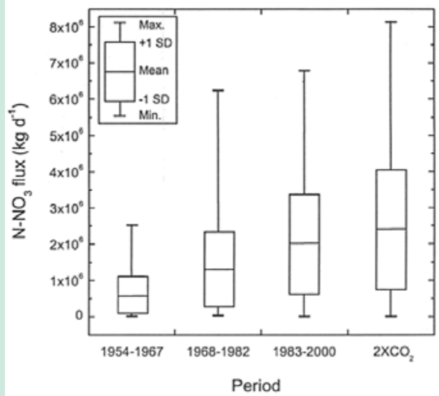

Figure 20. Box-plots showing nitrate flux (N-NO_3 flux) statistics for 1954 – 1967, 1968 – 1982, and 1983 – 2000, as well as projections for a 2xCO_2 climate based on a 20% increase in the Mississippi River runoff (Miller and Russell 1992). From Justić, Chapter 8.

cation and hypoxia in the northern Gulf of Mexico.

sors (e.g., eutrophication). In this context, managing the consequences of climate change become more complicated, not less complicated (Figure 21). Human activities cause some parts of the climate change "problem", but the resulting implications for ecosystems and climate change are also tied to each other, and then to new types or amounts of human uses.

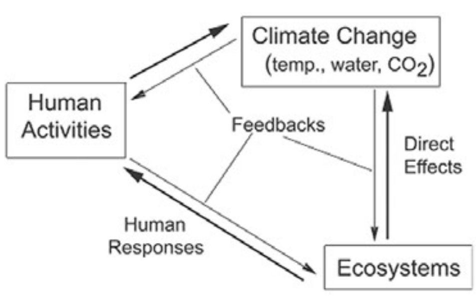

Figure 21. The effects and feedbacks in the interacting systems of climate, ecosystems and human societies. Adapted from Mulholland et al. 1997.

A long-term and integrated perspective is helpful, in this regards. It is widely understood that restoration of habitats is more difficult than sustaining them, at least from a non-political point of view. Climate change impacts are generally understood to add to, not subtract from, the total suite of coastal ecosystem stressors. Thus, preventing habitat change and loss is more cost-effective than rehabilitation and restoration.

However, it is also prudent to consider that some stressor impacts can be rolled back, but only reduced. Sea-level rise, for example, will probably continue, but at a lower rate than expected as a result of the anticipated from global climate changes. Under these circumstances, prevention is not enough, and future adjustments should be planned and anticipated. That type of planning and adjustment requires a substantial improvement in our knowledge and experience. The highlighted issues brought forth in this review suggest that this improvement should include long-term and comprehensive (integrated) programs that promote understanding of:

(1) wetland soil sustainability within the context of the entire organic and inorganic framework, and how the marsh ecosystem is affected by multi-year exposure to varying nutrients, altered food webs, and freshwater inflow management meant to provide single-problem solutions - e.g., oyster harvests or salinity management.

(2) the interactions between the social/political structure and function and the ecosystem attributes. The involvement of educators, social scientists, and natural scientists is required to find successfully-implement solutions to these complex problems.

(3) scenario testing approaches to strategically analyze the anticipated problems before their impact overwhelms abilities to react. Some approaches might involve computer modeling, others experimental field testing of contrasting methods, and still others comparative analyses of social and natural systems outside of the immediate region.

(4) control and management options for land use, harvest management, and water quality, with attention to the evaluation of unusual events (and subsequent management pressures) and competing resources claims.

(5) mechanisms and models of how build a better "tool kit" which has alternative options and support to try things, with the knowledge that, for some resources, we will only get one chance to fix the problem before it is unmanageable. We must be open to all kinds of solutions.

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Chapter 7

Impacts of Sea-Level Rise on Coastal Landscapes

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Summary

Two landscape explicit models were used to investigate habitat shifts in coastal Louisiana due to varying river forcing and sea-level rise. Land loss and yearly shifts of marsh habitats in two contrasting watersheds were examined, one a prograding and the other a regressive delta. The models linked several modules dynamically across spatial and temporal scales. Both models consisted of 3 coupled modules: a vertically integrated hydrodynamic module; a process-based biological module of above and below ground primary productivity; and a module for soil dynamics. The models explored future effects of possible sea-level rise and river diversion plans for a 30-year and a 70-year projection starting in 1988. Results suggested that increased river forcing (flow) had large land preservation impacts, and healthy functioning of the Mississippi Delta depends largely on freshwater inputs. This type of model is a useful tool for research and management for predicting causes and effects of regional impacts and structural landscape level changes.

7.1 Introduction

The Mississippi River is the source of sediment for most of the Louisiana coastal marshes. This contribution serves to maintain and create coastal marsh habitats. Opposite to this process, and since the beginning of the 20th century, natural processes, such as subsidence and sea-level rise, in combination with human activities including canal dredging, sediment diversion and extensive levee construction along the Mississippi River have overturned the natural balance. To date, the river now funnels sediments over the continental shelf and no longer contributes to the coastal areas. Coastal wetlands across southeastern

Louisiana have contracted and are being lost as they are converted to open water (Wells, 1996), serving as models for the effects of accelerated sea-level rise (Day and Templet, 1989). Annual variability in mean sea-level (MSL) can be several centimeters per year (Baumann, 1980), and high MSL can result in increased penetration of salinity into wetlands (Penland et al., 1988). Wetlands naturally sink as the soft sediments deposited on them by rivers consolidate and compress under their own weight. Such changes are believed to underlie the general pattern of displacement of freshwater vegetation by more salinity tolerant communities, and vegetation die-off followed by conversion to open water (Wells, 1996; Roberts, 1997). In contrast, active sediment deposition when associated with river discharge leads to land progradation (Roberts, 1997). An example of this active land building can be found in the Atchafalaya delta at the mouth of the Atchafalaya River (Fig. 1).

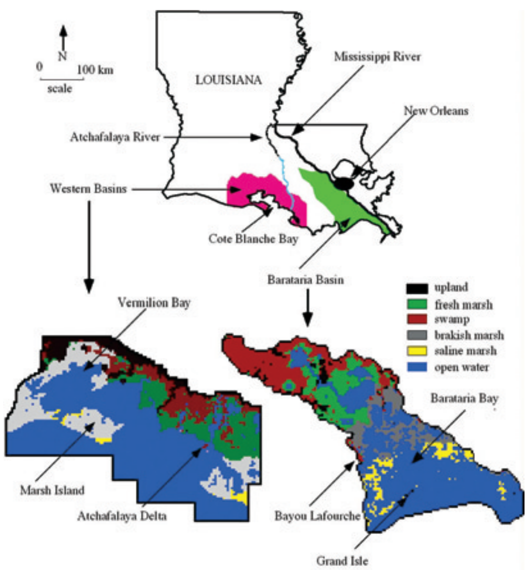

Figure 1. The State of Louisiana showing location for the Barataria and Western Basins.

Most wetlands in the Mississippi Delta estuarine complex are losing elevation to MSL at variable rates (Penland and Ramsey, 1990). These rates vary not only spatially but also temporally. We present two contrasting regions: the Barataria Basin and the watershed comprised by the Vermilion, Cote Blanche Bays, and the Atchafalaya delta, here defined as the Western Basins (Fig. 1). Calculated mean annual land loss rates in Barataria and the Western Basins for three different periods are presented in table 1, with a mean for all periods of 57.3 km^2 and 10.68 km^2, respectively (Britsch and Dunbar, 1993). Reed (1995) estimated that indirect land loss due to canal dredging alone could account for more than 30% in the Barataria Basin. This finding indicates that local anthropogenic modifications have had different effects in each basin making it difficult to assess changes on a regional basis.

Understanding these land loss rates and impacts (e.g. habitat change) is critical for assessing the long-term effects of evolving forcing functions (e.g., river discharge) to restoration approaches. The objectives of this study were to (1) construct a multiple scale process model for the Barataria and the Western Basins to understand and predict regional habitat change; and (2) assess wetland response to long-term indirect and cumulative impacts of different river forcing.

To address these issues we used spatially articulated landscape models under diverse scenarios (Sklar et al., 1985; Costanza et al., 1990; White, 1991; White et al., 1991; Reyes et al., 1994; Martin et al., 2000; Reyes et al., 2000). These dynamic spatial interaction models incorporate location specific algorithms that allow feedback between the local processes and the landscape dynamics, so that both the landscape and the intensity of the processes affecting it change throughout time (Boumans and Sklar, 1990). In this chapter we present the results of varying the environmental functions, namely river discharge and rates of sea-level rise, and the effects of those variations on two different watersheds.

7.2 Study Area

The Barataria estuarine system is an estuarine-wetland system located between the natural levees of the Mississippi River and Bayou Lafourche. It is roughly triangular in shape with an area of 6100 km2. The Western Basins are bordered by Freshwater Bayou on the west and the Atchafalaya River on the east and occupies about 6765 km^2 (Fig. 1).

Both basins are dynamic systems undergoing change due to natural and human processes. The Barataria basin has been closed to direct river inflow since 1904. Precipitation provides its main source of freshwater; however, the Mississippi River exerts an indirect influence on salinity in the lower basin by reducing salinity in the nearshore Gulf of Mexico (Perret et al., 1971). The Western Bays basins are directly influenced by the Atchafalaya River (Penland and Ramsey, 1990). As a result, these basins are examples of the few locations in southern Louisiana that have experienced net land gain (Boesch et al., 1994).

7.3 Methods

A landscape habitat prediction model was built for each watershed. Each is a dynamic spatial model under variable time and spatial scales, using a finite difference, 2-dimensional and vertically integrated hydrologic module coupled with a primary productivity module. Output from the hydrodynamic and productivity modules are submitted to a soil module and then evaluated by a habitat switching module that redefines the habitat mosaic on a biannual basis. Specific details for the modules and their interactions have been documented previously (White et al., 1997; Martin, 2000; Reyes et al., 2000).

Forcing functions to the models consist of an historical data series spanning 1956 through 1995 that include climatic variables (precipitation, wind, temperature), river flow and sediment concentration, relative sea-level rise (RSLR-comprised of subsidence and eustatic sea-level rise), tides, and salinity.

7.4 Calibration

Both models were calibrated by comparing results against historical conditions. The models were run for the 1978 to 1987 decade using habitat classified maps prepared by U.S. Fisheries & Wildlife Service (USFWS) to set initial conditions and final spatial comparison. This calibration exercise examined how much the simulated ecological processes across the landscape compensate for all the land loss processes implicit in the real landscape dynamics. Large scale dynamics, as the ones performed by this landscape model, do not explicitly incorporate local processes (e.g., effects of small canals and spoilbanks), however the calibration of regional parameters incorporates whatever regional effects these local processes might have.

The landscape calibration required a match in habitat distribution. The resulting habitat classified maps are presented in Figure 2 for both the Barataria Basin Model (BBM) and the Western Basins Model (WBM). A useful estimate of habitat agreement can be calculated as the percentage of change of the total wetland area (i.e., the sum of marshes and swamp habitats). These values are 3% for BBM and 2% for WBM, however these percentages don't take in to consideration the spatial agreement nor the different habitat types. Thus, for the agreement between each of the two simulated maps to be quantified, we used a goodness-of-fit, a spatial statistics routine comparing the spatial pattern of habitat cells at multiple

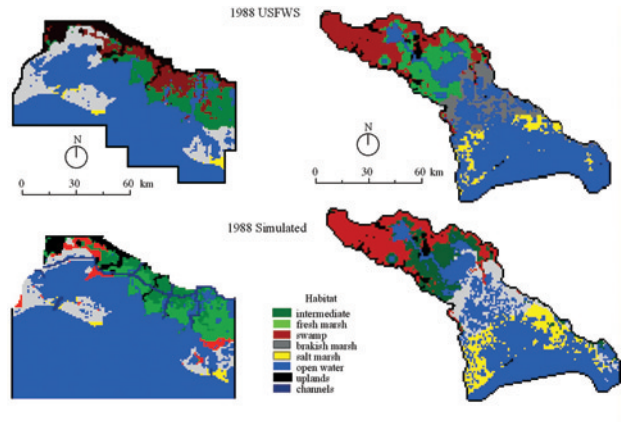

Figure 2. Habitat classified USFWS maps for 1988 and resulting maps from the calibration exercise.

resolutions (Costanza, 1989), which gave a value above 85 for both basins (Martin, 2000; Reyes et al., 2000) out of a possible 100, where 0 is no match to 100 is a perfect match.

7.5 Sea-level Rise and River Discharge Scenarios

Landscape models of this type are one of the few tools that can be used to predict the effects of complex spatial interactions and cumulative, long-term effects of global changes. Simulations, from 1988 to 2018, were performed for a series of scenarios (Table 2). The first scenario, referred to as Normal Conditions (NC), simulated a future continuation of current trends. Later simulations are evaluated by comparing results against this NC scenario.

7.5.1. Normal Conditions Scenario

The NC scenario consisted of a 30-year simulation for each basin (a 70-year prediction is also presented for the WBM). To run simulations into the future, theoretical time series and boundary conditions need to be selected. We repeated the original time series in reverse order, because climate tends to be cyclic (Thomson 1995). The forcing functions and boundary conditions are actual data for years 1955 – 1992, but when the year 1993 was simulated, the climate from 1991 was used, 1994 simulation used climate from 1990, and so on.

The resulting habitat distribution for the BBM (Fig. 3) converted 1,105 km^2 to open water during 1988 to 2018 (Table 2) or about a loss of 48% total wetland area. The largest decline (498 km^2) was for brackish marsh, while only 5 km^2 of swamp were lost. The model identified large portions of the mid-

Table 1 Annual loss rates (km²) for three different periods in the Western Bays and Barataria Basins.

Interval	Western Bays km² yr-1			Barataria km² yr-1		
1931-1958	2.41			7		
1956-1978	3.41[a]	3.3		16[a]	21.55	25.50
1978-1988	2.57[b]	4.4	0.8	19[b]	35.40	27.11
Source:	(Britsch and Dunbar 1993)	USFWS	Model output	(Dunbar et al. 1992)	USFWS	Model output

Note: [a]1956-74 and [b]1983-1990 intervals.

Table 2 Summary of scenario results performed in each basin.

Resulting Habitat Coverage (km²)

Scenario Name	Intermediate Marsh	Fresh Marsh	Swamp	Brackish Marsh	Salt Marsh	Open Water	Calibration Fit
Western Basins 1988 USWFS map	219	727	461	674	76	6465	
Calibration (1977-87)	238	737	462	701	77	6407	94.93
Normal Conditions (1988-2018)	172	1185	462	442	55	6306	
(1988-2058)	300	1383	461	152	58	6268	
High River Forcing (1988-2018)	302	1588	468	110	22	6132	88.64
(1988-2058)	216	1793	462	79	30	6042	86.84
No River Forcing (1988-2018)	289	1159	465	301	53	6355	92.39
(1988-2058)	225	1264	460	50	58	6565	89.25
Twice SLR rate (1988-2018)	289	1264	465	196	53	6355	91.67
(1988-2058)	225	1263	460	50	58	6566	88.06
Barataria Basin 1988 USWFS map		755	1022	734	460	2952	
Calibration (1977-87)		723	1002	722	634	2854	89.32
Normal Conditions (1988-2018)		396	1017	236	217	4057	
High River Forcing (1988-2018)		1022	1022	293	159	3427	85.63
Low River (1988-2018)		612	1022	567	389	3335	76.74
Twice SLR rate (1988-2018)		240	1014	150	200	4319	94.77

Notes: USWFS = U.S. Wildlife & Fisheries Service; SLR = sea-level rise. Fit values for Base Case scenarios were computed against 1988 USWFS habitat map. Fit values for river forcing options were computed against the 2018 normal conditions habitat map.

dle and lower brackish marsh that converted to open water, whereas the upper basin, dominated by swamp habitat, remained relatively unchanged. The land change in the middle basin was due to increased water levels and a diminishing plant productivity while the lower basin suffered from rising sea-level and increased salinity.

The WBM study area experienced a 7.37% gain in wetland during the 30-year NC (9.13% for the 70-year run) which was due to the expansion of freshwater marsh coverage (458 km^2) associated with the progradation of the Atchafalaya Delta (Fig. 3, Table 2). The areas around the Atchafalaya Delta sustained their original habitat, in contrast with areas that started to break up such as the ocean side of Marsh Island. Although only 30% of the Mississippi River discharge was used as flow for the Atchafalaya River (nominal U.S. Army Corps of Engineers discharge values), the capacity of this forcing to deposit sediments resulted in a noticeable delta growth.

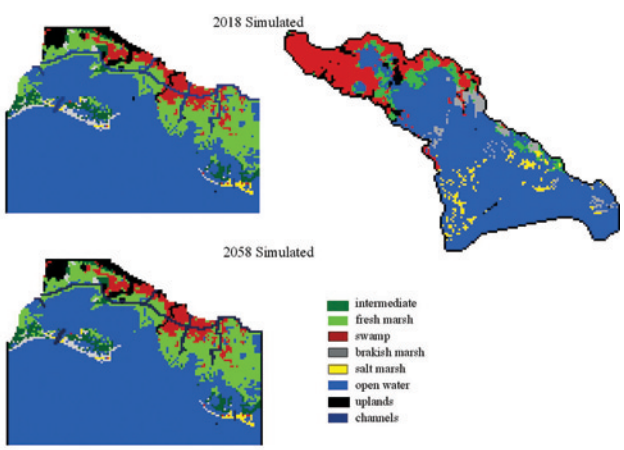

Figure 3. Resulting habitat distribution of Western and Barataria Basins under the Normal Conditions scenario for years 2018 and 2058.

7.5.2 Additional River Discharge Scenario

This scenario simulated a two-fold increase of river water into the basins. Under a global warming scenario, the discharge from the Mississippi has been computed to increase as a direct result of modifications to the hydrologic cycle such as increased precipitation (Justic et al., 1996). Based on these studies and the possibility of increased water flow through river structures and land runoff, we considered this a plausible scenario.

For the BBM, the main inflow was through the southeastern boundary, as the Mississippi River discharges into the Gulf. A smaller percentage of the input water, however, gets delivered through the West Point la Hache and Namoi siphons (i.e., water pumps). Land loss in this scenario was 630 km^2 less than the NC (Fig. 4). The overall change was gain of 33 % for the wetlands. The freshwater marsh had the least losses (626 km^2 were preserved), in contrast to salt marsh which showed a 27% decline (58 km^2 loss) from the NC scenario (Table 2).

Historically, the Atchafalaya River discharge has gone from unimportant to about 30% of the total flow of the Mississippi and Red rivers over the past two centuries (Roberts 1997). This increased discharge now is coupled with efforts to control the flow of the Mississippi River. Simulations for the WBM, using twice the Atchafalaya River discharge, increased both, the water and sediment delivered to the estuary, and increased the growth of the deltas by 174 km^2 compared to the NC for 2018 and by 226 km2 for 2058 (Fig. 4). By doubling river input brackish and salt marshes were subject to freshwater influence. This freshening of the habitat resulted in a transformation of 506 km^2 into a combination of intermediate freshwater marsh and open water across the study area (Table 2).

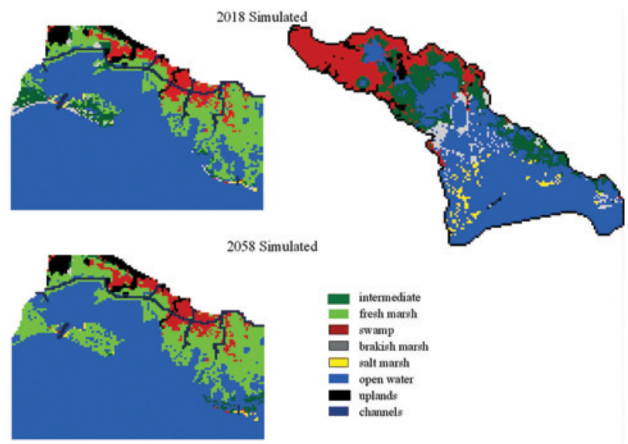

Figure 4. Resulting habitat distribution of Western and Barataria Basins under the high river discharge scenario for years 2018 and 2058.

7.5.3 Restricted River Discharge Scenario

A restriction of river inputs is exemplified by the current situation in the Barataria basin. Since 1904 the Barataria basin has been isolated from river inflow. However, presently in addition to restricted river inputs other factors such as, oil and gas exploration, salt water intrusion, and weirs and locks affect the wetland functioning (Condrey et al., 1995). For an increased restriction of river discharge scenario in this basin, a low river discharge year (1964) was used. The results of this low-river scenario paint a complex picture (Fig. 5). A total of 722 km² of wetlands were preserved from the NC scenario, with 92 km² more than in the "Additional River" scenario. Most of these gains were in brackish marshes that almost doubled in extension (Table 2), showing, perhaps, a homogeneous influence of water conditions for all the landscape. That is, constant salinity influence and little flooding seem to favor salt tolerant communities.

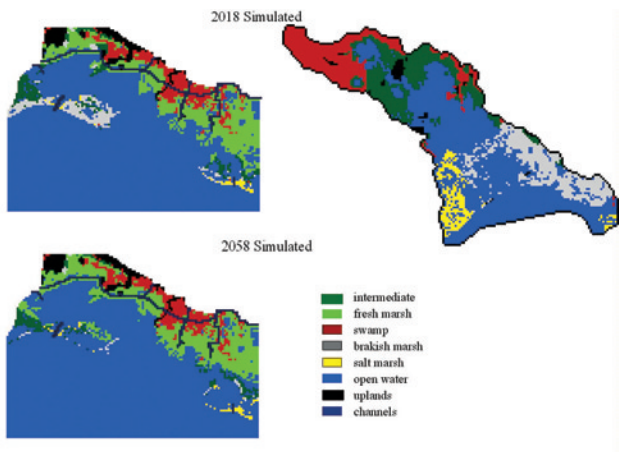

Figure 5. Resulting habitat distribution of Western Basins under no flow scenario and Barataria Basin under the low river flow scenario for years 2018 and 2058.

The scenario for WBM comprised reducing the Atchafalaya River flow to one half normal discharge, resulting in decreased growth of the deltas and leading to increased land loss (Fig. 5). Habitat extension for 2018 is similar as in BBM, brackish and salt marsh extension is higher than with the Increased River Discharge scenario. This behavior, however, changes to substantial losses (about 300 km²; Table 2) for the year 2058. Elimination of river input increased land loss and salt intrusion to the area.

7.5.4 Increased Sea-Level Rise Scenario

Future scenarios of coastal areas must consider the possibility of an increased Sea-Level Rise (SLR) rate due to global climate change and/or increased subsidence. In the previous scenarios the SLR rate used was 0.18 cm/yr (an average for the values reported by Gornitz et al., 1982). The increased SLR scenario considered a rate of 0.4 cm/yr, double the standard rate, but well within the range of values calculated by several authors (Hoffman, 1984; Emery and Aubrey, 1991; Gornitz, 1995), and representative of the "best guess" rates estimated by the IPCC (Gornitz, 1995).

Increasing the SLR rate, for both watersheds, resulted in extensive losses of inland habitats (Table 2). While for Barataria the total land loss was of 262 km² by 2018, the Western Bays show a slower decline of 55 km² by 2018 and 298 km² by 2058. Presenting a clear image of the pernicious influence of saltwater intrusion in both basins (Fig. 6).

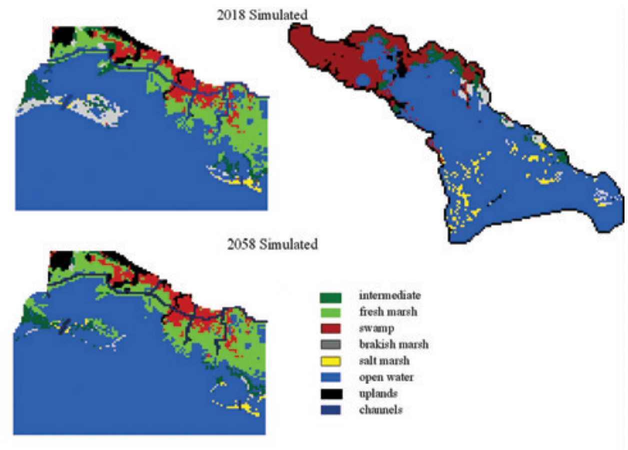

Figure 6. Resulting habitat distribution of Western and Barataria Basins under the double sea-level rise rate scenario for years 2018 and 2058.

Overall, fresh and brackish marshes lost from 30 to 50% of the area remaining in the Normal Conditions scenario. Salt marshes on Barataria basins decreased by 17 km². However, under the Additional River Discharge scenario, these salt marshes were the only habitat that expanded (an increase of 41 km².)

For the WBM, the same decreasing trend of marsh area can be observed when compared with the NC value (Fig. 6). By 2018 fresh marsh increased to 79 km² but at the end of the simulation this value becomes a net loss of 120 km². Salt marshes, however, keep the same coverage. When open water extension is compared with the Additional River Discharge scenario it becomes evident how accentuated the marsh loss can be (Table 2).

7.6 Discussion

The principal regional factors driving long-term trends in land-loss and habitat change in coastal Louisiana are (1) sea-level rise and subsidence, (2) changes in the introduction of freshwater and sediments from the Mississippi and Atchafalaya Rivers, and (3) modifications to internal hydrology (Gagliano et al., 1981; Baumann et al., 1986; Salinas et al., 1986; Coleman, 1988; Day and Templet, 1989; Boumans and Day, 1993; Reed, 1995; Day et al., 1997; Turner, 1997). Our landscape models are driven by these same dominant regional processes and were sensitive to factors that affect how land and water surfaces evolve interactively through time. This means the models are less sensitive to local human factors such as canal dredging or natural factors such as nutria destruction or fires.

Simulation results indicated the importance of river discharge forcing. Overall, increased river input to both basins resulted in net gains or preservation of marsh areas. Although the flow alterations presented here may seem extreme, they do have a historical and future relevance. Reductions in riverine inputs mimic trends that have taken place in the past, as the Barataria present conditions indicate. Increased river discharge is now occurring in the Western Bays area, as the Atchafalaya discharge has risen from minimal to 30% of that of the Mississippi River. Compounding these changes in river flow, the amount of sediments reaching the Mississippi is about 75% less than historical conditions due to natural and anthropogenic changes (Cahoon et al., 1995; Wells, 1996).

It was our intention to test the long-term effects of climate in both basins. As the climate conditions became more extreme (i.e., increased SLR scenario) habitats changed and overall land loss increased (Table 2). Relatively high rates of loss, on the order of 30 to 40 km^2/yr, are predicted for all river forcing scenarios. The comparisons of the variability of the fit indices in both basins (Table 2) suggest that Barataria is more susceptible to habitat changes (the range of values is larger) than the Western Bays marshes. The Western Bay marshes are currently influenced by flow of the Atchafalaya River, resulting in habitats more resistant to changes in weather and sea-level rise effects. Using the goodness-of-fit index as an indicator of beneficial processes was not straightforward. Lower values only indicate the amount of discrepancies between the resulting map and the NC scenario. Thus, both high and low river forcing scenarios had low values for both basins, in contrast with the high values for the increased SLR scenario. These values argue for the use of the fit number along with a visual interpretation of the resulting map to determine the net benefits of a management strategy. These results, along with the NC scenario, also indicate that weather might be responsible for the largest changes in marsh stability. Across basin processes such as, accretion, vegetation productivity and sediment inputs alone can not compensate for the effects of increased sea-level rise (as high as 10 cm interannually; Penland and Ramsey, 1990), acute weather conditions (hurricanes and winter storms), and natural subsidence (Baumann et al. 1986; Coleman, 1988; Day and Templet, 1989; Nyman et al., 1990; Cahoon, 1994; Wells, 1996).

7.7 Conclusions

Two dynamic landscape models for coastal Louisiana were developed to combine hydrodynamic and biological processes at different time and space scales. These mechanistic models included feedback among four different modules (water, soil, plant, and habitat switching) demonstrating the ability to accurately reproduce historical conditions and forecast the consequences of climate change scenarios.

River forcing scenario results demonstrated the importance of increasing water delivery and throughput into both basins. As these areas are subject to restricted freshwater inflows, the rate of land loss increases, but not necessarily in a linear fashion.

The use of these landscape models allows evaluation of natural processes across regions and investigation of cause and effect related to climate change scenarios at specific locations.

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Chapter 8

Climate Change Impacts on Low Oxygen Zones and its Effects on Fisheries

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Summary

A large-scale hypoxic zone (< 2 mg O_2 l^{-1}) in the coastal waters of the northern Gulf of Mexico, recently exceeding 20,000 km^2, overlaps with habitat and fishing grounds of commercial fish and shrimp species. We have developed a simple eutrophication model that accurately describes changes in surface and bottom oxygen concentrations for a station within the core of the Gulf of Mexico hypoxic zone. A sensitivity analysis revealed that the model is highly sensitive to external forcing, yet sufficiently robust to withstand order-of-magnitude changes in the nitrate flux of the Mississippi River. Model simulations indicated that bottom water hypoxia in the northern Gulf of Mexico has intensified in recent historical time, as a probable consequence of increased net productivity and an increase in the vertical flux of the organic carbon. Apparently, the long-term increase in riverine nutrient fluxes has been the primary factor controlling this historical decline in oxygen concentrations. Nevertheless, the influence of climatic factors on nitrate flux has been significant and could further increase as a result of global climate change.

In contrast to a relatively high degree of confidence associated with the projected temperature increases, the effects of global climate change on the hydrological cycle are less certain, particularly on regional scales. The annual Mississippi River runoff, for example, was projected to decrease by 30% for the Canadian model, but to increase by 40% for the Hadley model by the year 2099. Model simulations further suggest that altered freshwater and nutrient fluxes would have important implications for water column stability, net productivity and global oxygen cycling in the northern Gulf of Mexico. Direct and indirect fisheries losses would likely be exacerbated if hypoxia expands in space or time as a result of global climate change.

8.1 Introduction

General circulation models (GCMs) forced by enhanced greenhouse gas concentrations have projected a global temperature increase of 2 to 6 ^{o}C over the next 100 years (IPCC, 1996). In contrast to a relatively high degree of confidence associated with the projected temperature increases, the effects on the global hydrological cycle are less certain, particularly on regional scales. Miller and Russell (1992) examined the impact of global warming on the annual runoff of the world's 33 largest rivers using a limited area model nested in a GCM. For a CO_2 climate, the runoff increases were detected in all studied rivers in high northern latitudes, with a maximum of +47 %. At low latitudes there were both increases and decreases, ranging from +96% to –43%. Importantly, the model results projected an increase in the annual runoff for 25 of the 33 studied rivers. The northern Gulf of Mexico (Figure 1), which receives inflows of the Mississippi River - the sixth largest river in the world (Milliman and Meade, 1983), is one of the coastal areas that would experience increased freshwater input under the simulated $2x/CO_2$ scenario. The annual Mississippi River runoff would increase 20%, and a higher runoff would occur during the May-August period (Figure 2). Wolock and McCabe (1999) estimated the potential effects of climate change on mean annual runoff for U.S. rivers based on Canadian and Hadley model projections. The estimates for the Mississippi River differed greatly between the two models. The annual Mississippi River runoff was projected to decrease by 30% for the Canadian model, but increase by 40% for the Hadley model by the year 2099.

The northern Gulf of Mexico would likely be highly sensitive to changes in freshwater inflow, because the combined discharges of the Mississippi and Atchafalaya Rivers account for 98% of the total freshwater inflow into the northern Gulf of Mexico (Dinnel and Wiseman, 1986). The nutrient-rich plumes of these two rivers rapidly form the Louisiana Coastal Current that flows predominantly westward along the Louisiana coast, and then southward along the Texas coast. Riverine nutrients are confined within the upper 10 m by a strong seasonal pycnocline ($\Delta\sigma_t$ = 4 - 10 kg m^{-3}), which persists from April through October (Rabalais et al., 1991). Given this physical setting, it is not surprising that biological processes in the northern Gulf of Mexico are strongly influenced by the pattern and relative magnitude of riverine freshwater runoff (Justić et al., 1993). Changes in the areal extent of hypoxic (< 2 mg O_2 l^{-1}) bottom waters provide a representative example of the riverine influence on coastal productivity processes (Figure 1). The northern Gulf of Mexico is presently the site of the largest (up to 22,000 km^2) and most severe coastal hypoxic zone in the western Atlantic Ocean (Rabalais et al., 1999). Hypoxia normally occurs from March through October in waters below the pycnocline, and extends between 5 and 60 km offshore (Rabalais et al., 1996). During the drought of 1988 (a 52-year low discharge record of the Mississippi River), however, bottom oxygen concentrations were significantly higher than normal, and formation of a continuous hypoxic zone along the coast did not occur in midsummer (Figure 1). The opposite occurred during the Great Flood of 1993 (a 62-year maximum discharge for August and September), when the areal extent of summertime hypoxia doubled with respect to the average hydrologic year (Rabalais et al., 1998). Hypoxia in the coastal bottom waters of the northern Gulf of Mexico develops as a synergistic product of high surface primary productivity, which is also manifested in a high carbon flux to the sediments, and high stability of the water column. Likewise, the 1993 event was associated with both an increased stability of the water column and nutrient-enhanced primary productivity, as indicated by the greatly increased nutrient concentrations and phytoplankton biomass in the coastal waters influenced by the Mississippi River (Dortch, 1994; Rabalais et al., 1998).

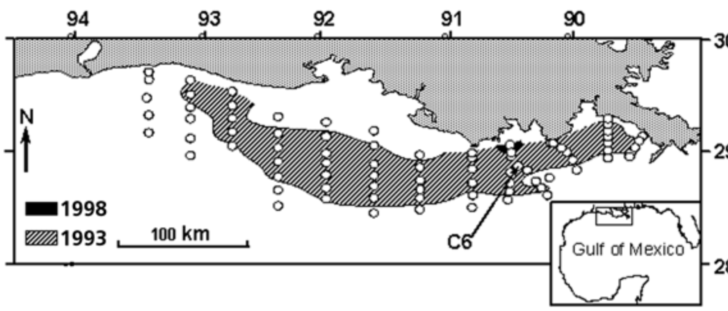

Figure 1. Map of the northern Gulf of Mexico showing station grid and location of station C6. Shaded areas represent the distribution of hypoxic (< 2 mg O_2 l^{-1}) bottom waters during August 1988 and July 1993.

Climate change, if manifested by increasing riverine freshwater inflow, could affect coastal and estuarine ecosystems in several ways. First, changes

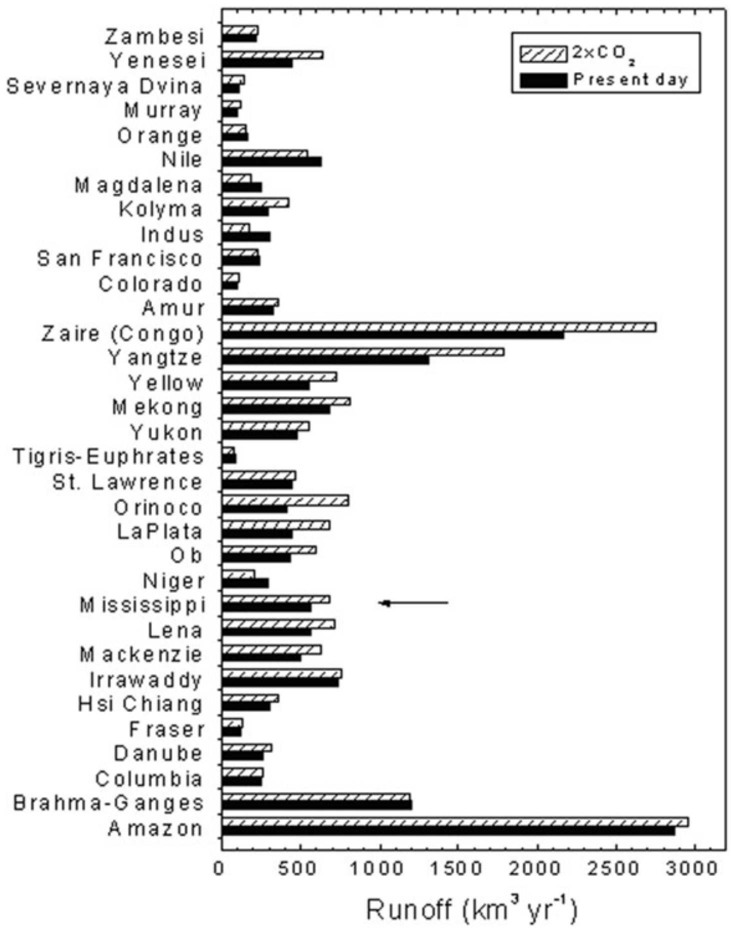

Figure 2. Average annual discharges and projected $2xCO_2$ discharges for 33 world's major rivers (data obtained from Miller and Russell 1992). Mississippi River is indicated by an arrow.

in freshwater inflow will affect the stability of the water column, and this effect could be enhanced due to changes in sea surface temperatures. Vertical density gradients are likely to increase, which could decrease vertical oxygen transport and create conditions in the bottom water favorable for the development of severe hypoxia or anoxia (Justić et al., 1996). Second, the concentrations of nitrogen (N), phosphorus (P), and silicon (Si) in riverine freshwater inflows are typically an order of magnitude higher than those in coastal waters (Justić et al., 1995a; 1995b). The mass fluxes of riverine nutrients are generally well correlated with integrated runoff values (Turner and Rabalais, 1991; Goolsby et al., 1999). Consequently, the nutrient inputs to the coastal ocean are expected to increase as a result of the increasing riverine runoff, which could have an immediate effect on the productivity of coastal phytoplankton. Third, the stoichiometric ratios of riverine nutrients, Si:N, N:P and Si:P, may differ from those in the coastal ocean (Justić et al., 1995a). Increased freshwater inflow, therefore, may also affect coastal phytoplankton communities by increasing or decreasing a potential for single nutrient limitation and overall nutrient balance (Smayda, 1990; Dortch and Whitledge, 1992; Justić et al., 1995a; 1995b; Turner et al., 1998). A decrease in freshwater inflow would have the opposite effects to those described above.

Here we review probable implications of climate change for the Gulf of Mexico hypoxic zone and its effects on fisheries. In this report we are focusing on two areas: (1) coupling between climate variability, freshwater runoff of the Mississippi River, and hypoxia in the coastal northern Gulf of Mexico, and (2) potential implications of global climate change for coastal fisheries in the hypoxic zone. In this analysis we use our previously published physical-biological model (Justić et al., 1996; 1997) and extensive long-term data sets collected at a station within the core of the Gulf of Mexico hypoxic zone (C6; Figure 1).

8.2 Methods

8.2.1 The Study Area

The study area encompasses the Louisiana coastal waters (Figure 1). Station C6, located in the inner section of the hypoxic zone, was used as a reference site for studies of impacts of climate change. This site was chosen because of the longest and most consistent oceanographic data records (1985 – present) that are available for the northern Gulf of Mexico. Three distinct oceanographic features of this region facilitated the application of a two-box modeling scheme. First, between the beginning of April and the end of October, a strong pycnocline ($\Delta\sigma_t$ = 4 - 10 kg m^{-3}) is typically found at the average depth of 10 m (Rabalais et al., 1991). Because the depth is only about 20 m, the pycnocline virtually divides the upper and the lower water column into two distinct water bodies of approximately equal volumes. Second, the horizontal oxygen transport in the inner section of the hypoxic zone appears to be of lesser importance than the vertical oxygen transport. This is suggested by a high coherence between changes in vertical temperature gradients and changes in bottom oxygen concentration. In contrast, a strong tidal signal, which would indicate horizontal transport, is not present in the periodograms of oxygen data series from station C6 (Rabalais et al., 1994). Also, maximum lateral displacement of water parcels that can be expected due to diurnal and semidiurnal currents is only about 3 km (Rabalais et al., 1994), which is not likely to affect the inner section of a 60 km wide hypoxic zone. Third, because of the high turbidity of the continental shelf waters near the Mississippi River, primary productivity below the depth of 10 m is low (Lohrenz et al., 1990), and may be considered insignificant when compared to vertical oxygen transport.

8.2.2 Data Sources

The data on temperature, salinity, and dissolved oxygen concentration were obtained from a series of monitoring cruises conducted during the period June 1985 - October 1993. Our sampling station (C6; Figure 1) was occupied on a biweekly to monthly basis. Standard water column profile data were obtained from a Hydrolab Surveyor or a SeaBird CTD system with SBE 13-01 (S/N 106) dissolved oxygen meter. The dissolved oxygen measurements were calibrated with Winkler titrations (Parsons et al., 1984) that were periodically carried out during deployment of the instruments. Continuous (15 - min intervals) temperature and oxygen measurements were also obtained at station C6 from July 1990 onward, using an Endeco 1184 pulsed dissolved oxygen sensor. The instrument was deployed at the depth of 19 m, approximately 1m above the seabed. Predeployment and postdeployment calibrations of the pulsed dissolved oxygen sensors were performed in accordance with factory specifications. Continuous oxygen measurements were controlled during hydrographic surveys of the study area, by comparison with Winkler titrations, Hydrolab Surveyor, or a SeaBird CTD data.

The daily-averaged discharge values for the lower Mississippi River at Tarbert Landing (August 1954 - May 2000) were provided by the U.S. Army Corps of Engineers. Those daily-averaged discharges are inferred from data-adaptive models of discharge versus water level, whose accuracy is normally higher than 90% (Bratkovich et al., 1994). Monthly discharge averages, used in the nitrate flux calculations, were computed from the daily-averaged discharge values. Monitoring station Tarbert Landing is located in Mississippi, 13 km downstream from the inlet channel to the Old River control structure, where one-third of the Mississippi River is diverted to the Atchafalaya River. The discharge at Tarbert Landing, therefore, accounts for about 70% of the total Mississippi and the Atchafalaya River discharge.

In this analysis, we used the monthly records (August 1954 - May 2000) of nitrate concentration at St. Francisville. St. Francisville is located in Louisiana, approximately 430 km upstream from the Mississippi River Delta. The average monthly nitrate fluxes were computed by multiplying the average monthly nitrate concentrations with the respective monthly discharge averages. Data sources and analytical methods used to determine nitrate concentrations are discussed in Turner and Rabalais (1991) and Goolsby et al. (1999). Nitrogen is often considered to be the limiting nutrient for the growth of the estuarine and coastal phytoplankton (e.g. D'Elia et al., 1986). The data from the northern Gulf of Mexico indicate that the frequency of stoichiometric nitrogen limitation is on the order of 30% (Justić et al., 1995a).

8.2.3 Model Formulation

We adopted our previously published two-box modeling scheme (Justić et al., 1996), which assumes uniform properties for the layers above and below the average depth of the pycnocline. The model includes mathematical descriptions of relevant physical and biological processes that affect oxygen cycling in shallow, river-dominated, coastal waters (Justić et al., 1996, 1997). The oxygen concentration in the upper water column changes as a result of biological oxygen production and consumption, oxygen transport in the horizontal and vertical direction, and atmospheric exchanges. By neglecting horizontal oxygen transport due to advection and diffusion, the oxygen balance in the upper water column (O_{ts}, g O_2 m^{-2}, 0 – 10 m) may be described by the expression

$$\partial O_{ts} / \partial t = - F_{Ot} - D_O + NP \qquad (1)$$

where t is time (d), F_{Ot} is the total air-sea oxygen flux (g O_2 m^{-2} d^{-1}), D_O is the diffusive oxygen flux through the pycnocline (g O_2 m^{-2} d^{-1}), and NP is the net primary productivity expressed in terms of oxygen equivalents (g O_2 m^{-2} d^{-1}). Because of the high turbidity of the continental shelf waters near the Mississippi River, primary productivity below the depth of 10 m is low (Lohrenz et al., 1990), and may be considered an insignificant term when compared to vertical oxygen transport. Thus, the balance equation for oxygen in the lower water column (O_{tb}, g O_2 m^{-2}, 10 – 20 m) includes only two terms: oxygen uptake due the benthic and water column respiration (R), and oxygen resupply from the upper water column via turbulent diffusion (D_O):

$$\partial O_{tb} / \partial t = -R + D_O. \qquad (2)$$

A description of the individual model terms from Eqs. 1 and 2 is discussed below.

Oxygen transport through the sea surface is dependent on the difference in the partial pressure of the gas in the surface layer and in the atmosphere. The transfer velocity across the air-sea boundary is thought to be a function of the temperature and the wind speed. In our calculations we used the formulation proposed by Stigebrandt (1991), which takes into account the effect of gas transfer due to bubbles:

$$F_{Ot} = V\,(O_s - 1.025\, O_2'). \qquad (3)$$

Here F_{Ot} is the total air-sea oxygen flux (g O_2 m^{-2} d^{-1}), V is transfer velocity (m d^{-1}), O_s is the average surface oxygen concentration (g O_2 m^{-3}, 0-10 m), and O_2' is the oxygen saturation value (g O_2 m^{-3}). Negative F_{Ot} values obtained from Eq. 3 indicate that the oxygen flux is directed towards the water column. The O_s value was computed by dividing the O_{ts} value (Eq. 1) with the thickness of the upper water column (10 m). The oxygen saturation value was computed from the observed temperature data and estimated salinity values using the equation of Weiss (1970). Surface salinity values for station C6 were calculated from the Mississippi River runoff data, using a time-delayed linear model (τ = 2 months; r^2 = 0.8; $p <$ 0.001) developed by Justić et al. (1996). The transfer velocity was computed from a formula given by Liss and Merlivat (1986),

$$V = 5.9\, Sc^{-0.5}\, (aW + b) \qquad (4)$$

where Sc is Schmidt number, and W is wind speed (m s^{-1}). The values of constants a and b depend on the wind speed. In the interval where $3.6 < W < 13$ m s^{-1} these constants are equal to 2.85 and –9.65, respectively (Liss and Merlivat, 1986). At oxygen saturation levels above 125%, a modification of Eq. 4. was used that takes into account the oxygen surplus,

$$V = 5.9\, Sc^{-0.5}\, (aW + b)\, (O_s / O_2')^2 \qquad (5)$$

where O_s is the ambient surface oxygen concentration (g O_2 m^{-3}, O-10 m), and O_2' is the oxygen saturation value (g O_2 m^{-3}). Schmidt numbers for oxygen were computed from surface temperature data (T_s), using a simple analytical expression derived by Stigebrandt (1991):

$$Sc = 1{,}450 - 71\, T_s + 1.1\, T_s^2. \qquad (6)$$

The vertical diffusive flux of oxygen (DO) was estimated from the equation:

$$D_O = - K_z\, (\partial O_2 / \partial z) \qquad (7)$$

where K_z is the vertical eddy diffusivity (m^2 s^{-1}), O_2 is ambient oxygen concentration (g O_2 m^{-3}), and z is depth (m). The model assumes that the only properties of the stratified water column controlling K_z are the turbulent kinetic energy dissipation rate (ε), and the buoyancy frequency (= Brunt-Väisälä frequency) (N):

$$K_z = a\, \varepsilon\, N^{-2}. \qquad (8)$$

Various values for parameter a have been suggested (e.g., Denman and Gargett, 1983). Because of the high stability of the water column in the northern Gulf of Mexico (Rabalais et al., 1999), we adopted the value of 0.8 (Weinstock, 1978). This value is thought to be valid for strong and intermediate stratification, where the Cox number is less than 2500 (Caldwell et al., 1980). We assumed that the turbulent energy dissipation rate (ε) at the depth of 10 m is in the range of 10^{-7} m^2 s^{-3}, which is likely to be an upper estimate. Corresponding values were obtained from microstructure measurements in the upper ocean during high winds (Dillon and Caldwell, 1980). Buoyancy frequency N (s^{-1}) was calculated from the expression

$$N^2 = (g/r_w)\ (\partial\rho/\partial z) \qquad (9)$$

where g is the acceleration due to gravity (9.81 m s^{-2}), ρ_w is the average density of the water column (kg m^{-3}), and $\partial\rho/\partial z$ is the vertical density gradient (kg m^{-4}) between the upper (0-10 m) and the lower (10-20 m) water column. Vertical density gradients were computed from a multiple regression of $\partial\rho$ on salinity and temperature (r^2 = 0.85; p < 0.001), as explained in Justić et al. (1996).

The net productivity of the surface water column (NP; gC $m^{-2}d^{-1}$) was computed from the time-delayed regression model developed by Justic et al. (1996):

$$NP_t = -0.34 + 3.93 \times 10^{-7}\ (N\text{-}NO_3)_{t-1} \qquad (10)$$

where $N\text{-}NO_3$ is the nitrate flux of the Mississippi River (10^6 kg d^{-1}), and subscripts t and $t-1$ denote the current and the preceding month, respectively. The Eq. 10 was developed based on the Mississippi River nitrate flux data for the period 1985-1992 and net productivity estimates at station C6. The cross correlation coefficient (ccc) indicated that the two time series are highly coherent (ccc = 0.73; p < 0.01), and that a time-delay of one month is justified (Justić et al., 1997). Conversion of carbon to oxygen equivalents, so that Eq. 1 is dimensionally correct, was carried out using a ratio of 3.47 by weight (mol. C: mol. O_2 = 106 : 138, Redfield et al., 1963).

The rate of respiration (R) in the lower water column is proportional to the amount of detritus present, and may be described by the first order decay relation

$$R = -k\ C_s \qquad (11)$$

where k is the decay constant, or respiration constant, (d^{-1}), and C_s is the pool of sedimentary organic carbon that is available for decomposition (g C m^{-2}). Vertical flux of organic detritus to the bottom waters is described as a function of surface net productivity at some earlier time. For the northern Gulf of Mexico, Justić et al. (1993) showed that there is a significant coherence (r = 0.85; P < 0.01) between the net productivity of the upper water column (0-10 m) and the oxygen deficit in the lower water column (10-20 m), implying a time-lag of 1 month. Thus, the respiration rate (R) in the lower water column at any given time t may be expressed in terms of the net productivity rate $NP(t)$ at some earlier time t_0 (Officer et al. 1984, 1985), so that

$$R(t) = k(t) \int_{-\infty}^{t} a\ NP(t_0)\ exp\left[-\int_{t_o}^{t} k(t_1)\ dt_1\right] dt_0 \qquad (12)$$

where the proportionality constant α describes the fraction of NP that reaches the lower water column. Carbon uptake during respiration was converted to oxygen equivalents using a ratio of 3.47 by weight (mol. C : mol. O_2 = 106 : 138, RQ = 0.77, Redfield et al. 1963). Rabalais et al. (1991) suggested that around 50% of surface primary production may be reaching the bottom (~ 20 m on average) in the northern Gulf of Mexico. Based on the data for the period 1985-1992, Justić et al. (1997) estimated that the average respiration rate (R) of the lower water column (10-20 m) at station C6 accounted for 47% of the NP in the upper water column (0-10 m). Accordingly, a value of α = 0.47 was used in this study. The respiration constant k is often described by an empirical relationship of the form

$$k = k_0\ (T_b/10)^a\ \ (O_b/6)^b \qquad (13)$$

where k_0 is the multiplying factor (d^{-1}), T_b is the average temperature of the lower water column (10-20 m, ^oC), O_b is the average oxygen concentration (g O_2 m^{-3} = mg O_2 l^{-1}) in the lower water column, and a and b are constants. The O_b value was computed by dividing the O_{tb} value (Eq. 2) with the thickness of the lower water column (10 m). In this study, we have adopted the values of k_0 = 0.008, a = 1.1, and b = 0.4. The later two values were originally proposed for the Chesapeake Bay (Officer et al., 1985), while the k_0 value of 0.008 was the upper limit of the range of values for this constant proposed for Patuxent estuary (Boynton et al., 1980). Those estimates for k_0 a and b provided a good fit to the benthic and epibenthic respiration rates observed in the coastal waters of the northern Gulf of Mexico.

Eq. 12. defines the net productivity as a surrogate for excess carbon in the upper water column (0-10 m) that is available for export to the lower water column (10-20 m). The instantaneous vertical carbon flux (S_f, gC m^{-2}d^{-1}) due to the sedimentation of organic material from the upper water column may be described as

$$S_f(t) = \alpha\, NP(t_0) \qquad (14)$$

Accordingly, the balance equation for organic carbon in sediments (C_s, gC m^{-2}) may be written as

$$\partial C_s / \partial t = S_f(t) - R(t) - E_c \qquad (15)$$

where $R(t)$ is the respiration rate in the lower water column, expressed here in terms of carbon equivalents (gC m^{-2} d^{-1}), and E_c (gC m^{-2} d^{-1}) is the loss of sedimentary carbon due to resuspension and export. The continental shelf of the northern Gulf of Mexico is a highly dynamic system where wind-driven sediment resuspension may be a driving force in exporting sediments to the outer shelf and slope. Seasonal deposition rates can be locally high, but decadal sediment accumulation rates are significantly lower (Wiseman et al., 1999). In computing the organic carbon accumulation rates, we assumed that 50% of the sedimented organic carbon that is not subsequently decomposed is ultimately exported from the study area.

Equations 1, 2 and 15 represent a system of coupled, non-linear, ordinary differential equations. In simulations experiments, the equations were solved using the Runge-Kutta integration method of the fourth order, and an integration step of 0.01 month (0.3 days).

8.3 Results

8.3.1 Trends in the Mississippi River Discharge and Nitrate Flux 1954-2000

The average nitrate flux of the lower Mississippi River increased 3.3-fold between 1954-1967 and 1983-2000 (Figure 3). During the same time period, the average nitrate concentration increased 2.3-fold while the average discharge increased 40%. Partitioning of the observed trend in nitrate flux among the two flux components, nitrate concentration and discharge, revealed that about 80% of the observed increase in flux could be explained by only the increase in nitrate concentration (Figure 4). This indicates that historical increase in the anthropogenic nutrient inputs has had a far greater impact on the lower Mississippi River nitrate flux then a change in climate. Nevertheless, the influence of climatic factors on nitrate flux has been significant and may further increase as a result of global climate change. This argument is supported by two lines of evidence: First, the residual component of nitrate flux, obtained by removing a trend from the time-series, is controlled primarily by the variability in discharge, i.e. climatic factors. Also, there is a highly significant relationship between discharge and nitrate flux for the period 1983-2000 (Figure 5). Linearity in discharge-flux relationships was also observed in the 1954-1967 and 1968-1982 data subsets. The regression slopes for 1954-1967 (α=62.35; R=0.81; $p<0.01$) and 1968-1982 (α=96.12; R=0.69; $p<0.01$), however, were significantly lower ($p<0.01$) in comparison with the slope for the 1983-2000 (α=146.76; R=0.86; $p<0.01$). Clearly, these differences between the three periods are attributable to historically lower nitrate concentrations during 1954-1967 and 1968-1982 (Figure 3).

Sensitivity of nitrate flux to altered discharge was estimated by computing the percent increase in flux that corresponds to a 1% increase in the average discharge for the 1983-2000 (15,874 m^3 s^{-1}). Our estimated flux sensitivity value was 1.16%, which was somewhat higher than a value of 1.1% that was reported for the lower Mississippi River by Alexander et al. (1996). In general, flux sensitivity values above 1% are indicative of rivers where runoff, either from agricultural, urban, or forested lands, is the predominant source of nitrate (Alexander et al. 1996). Because of the amplified influence of discharge on nitrate flux in these rivers (Figure 5), nutrient management efforts for the Mississippi River (Brezonik et al., 1999; Goolsby et al., 1999) may be more challenging.

While a detailed discussion of complex watershed processes affecting nitrate flux remains beyond the scope of this paper, there are several ways in which these anticipated changes in precipitation and increases in discharge may influence nitrate flux. First, the higher precipitation would leach more

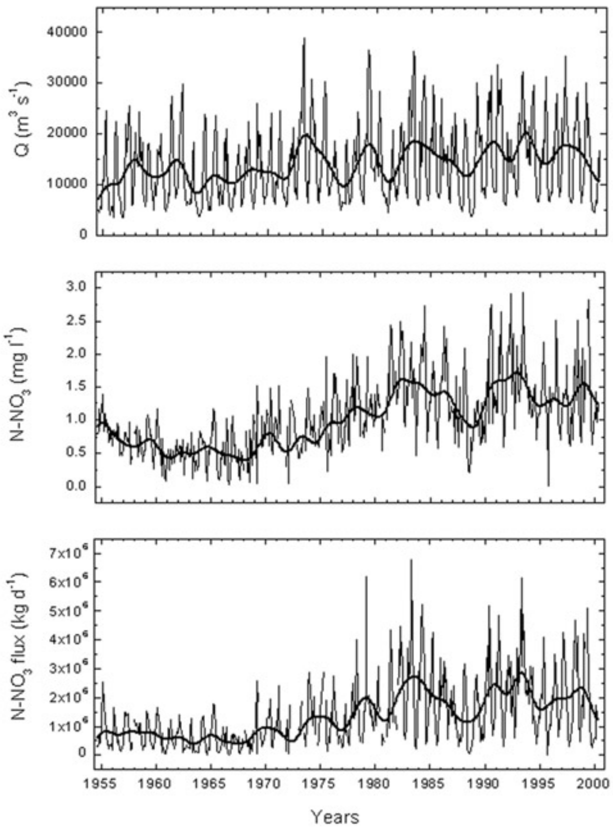

Figure 3. Monthly averages (1954-2000) of the lower Mississippi River discharge (Q), nitrate concentration (N-NO_3), and nitrate flux (N-NO_3 flux). Smoothed curves are estimated third order polynomial fits on 12-month weighted averages.

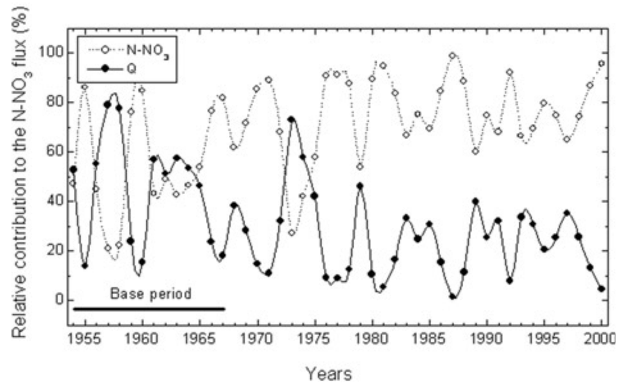

Figure 4. Partitioning of observed trends in the N-NO_3 flux of the lower Mississippi River into anthropogenic (N-NO_3 concentration) and climatic (discharge, Q), components. Symbols indicate relative contributions (%) of the two flux components, based on deviations from averages of the base period 1954-1967.

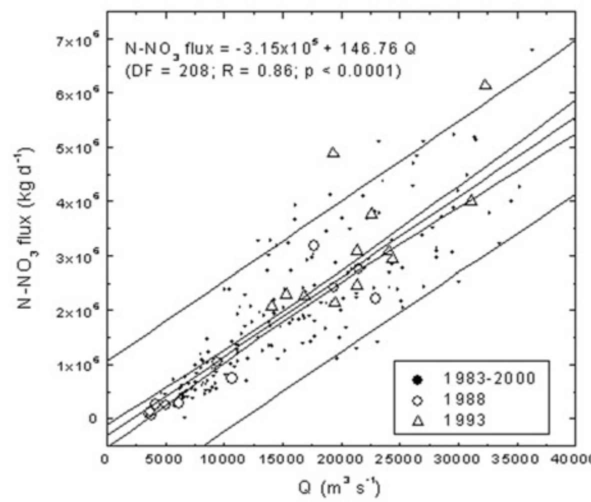

Figure 5. Regression of nitrate flux (N-NO_3 flux) on discharge (Q) for the period 1983-2000. The values for the drought of 1988 and the flood of 1993 are shown in different symbols. The two pairs of lines parallel to the regression line denote the 95% confidence limits and the 95% prediction limits, respectively.

nitrates from soils into tributaries and the mainstem of the Mississippi River (Goolsby et al., 1999). Second, unless riverine nitrate concentrations are reduced, the higher discharge would necessarily lead to an increased nitrate flux (Figure 5). Lastly, the higher discharge would decrease the water residence times in canals, lakes and small streams in the upper parts of the watershed. This would substantially reduce nitrogen losses due to denitrification (Howarth et al., 1996; Alexander et al., 2000), and ultimately result in a higher nitrate concentration in the mainstem of the Mississippi River. Thus, it is impossible at this time to reliably predict future trends in nitrate concentration of the lower Mississippi River. Nevertheless, a hypothetical 20% increase in the Mississippi River discharge (Miller and Russell, 1992) would result in a nitrate flux that greatly surpasses the historical flux values for the period 1954-2000 (Figures 3 and 6).

8.3.2 Model Simulations

Calibration results for surface and bottom oxygen concentrations are illustrated in Figure 7. The model was calibrated on the basis of a 1985-1993 data set for the Mississippi River and the Northern Gulf of Mexico. The 1985 – 1993 period included three average hydrologic years (1985, 1986 and 1989), a record flood year (1993, a 62-yr record high discharge), two years with above average discharge (1990 and 1991), three years with below average discharge (1987, 1988 and 1992), and a record drought year (1988, a 52-yr record low discharge). Given the time-span of the data, we considered the 1985 – 1993 data subset to be suitable for model calibration. A sensitivity analysis revealed that the model is highly sensitive to

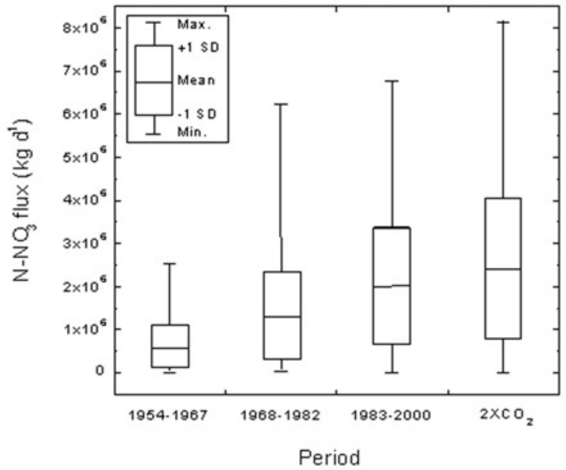

Figure 6. Box-plots showing nitrate flux (N-NO_3 flux) statistics for 1954-1967, 1968-1982, and 1983-2000, as well as model projections for a 2xCO_2 climate.

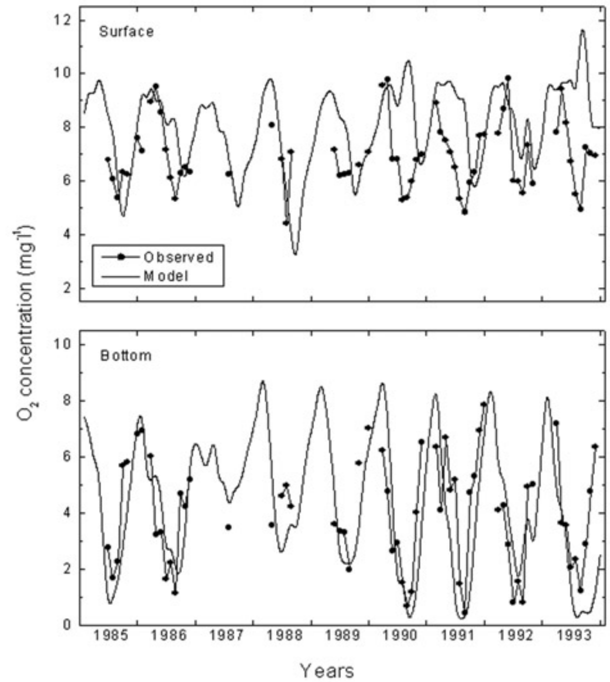

Figure 7. Observed and predicted monthly averages of surface (0-10 m) and bottom (10-20 m) oxygen concentrations at station C6 for the period June 1985-November 1993.

external forcing, yet sufficiently robust to withstand an order of magnitude change in the nitrate flux between successive months, such as those encountered during the flood of 1993. For the bottom layer (10 – 20 m), the model agrees exceptionally well with the observed values, both in terms of the annual and interannual variability. The agreement between the model and the data is also very good for the surface layer (0 – 10 m), with the exception of 1990, 1991, and 1993, for which the predicted summertime oxygen concentrations were somewhat higher than observed.

Model simulations for a station within the core of the present day hypoxic zone (C6; Figure 1) indicated a decadal trend of increase in the oxygen concentrations in the upper water column (0 – 10 m) and decrease in the lower water column (10 – 20 m) (Figure 8). The annual average oxygen concentration at 10-20 m depth decreased from 6.6 mg l^{-1} in 1955 – 1965 to 4.2 mg l^{-1} during 1990 – 2000. As expected, the differences in summertime oxygen concentrations between those periods are even greater. The average oxygen concentration in the lower water column during August decreased from 5.8 mg l^{-1} in 1955 – 1965 to 0.9 mg l^{-1} during 1990 – 2000. The model has identified the mid 1970s as a start of the recurring hypoxia (< 2 mg O_2 l^{-1}) in the lower water column. This result should, however, be interpreted with caution, because the model only predicts the average oxygen concentration for the entire lower water column. It is probable that hypoxia in the near bottom waters was sporadically present during the late 1960s and early 1970s, and perhaps even earlier than that (Figure 8). The model results also suggest that the annual average oxygen concentration of the upper water column (0 – 10 m) increased from 7.0 mg l^{-1} in 1955 – 1965 to 8.4 mg l^{-1} during 1990 – 2000.

8.3.3 Future Scenarios: An Inverse Approach to Scientific Controversy

Assessments of future climate change scenarios for the northern Gulf of Mexico are complicated by the fact that model projections for the Mississippi River runoff are highly variable. The Canadian and the Hadley models projected a 30% decrease and a 40% increase, respectively, by the year 2099. In a series of modeling studies we investigated the impacts of various climate change scenarios and different nutrient control strategies for the Mississippi River (Table 1) on the Gulf's hypoxic zone. Model simulations were conducted in a hindcast mode, by increasing or decreasing the Mississippi River discharge, nitrate concentration, and nitrate flux relative to the observed monthly averages for the period 1954-2000 (Figure 3). Model results are summarized in Table 2. Nominal model simulation for the period 1954-2000 predicted 19 years with moderate hypoxia (< 2 mg O_2 l^{-1}) and 16 years with severe hypoxia (< 1 mg O_2 l^{-1}). A 30% decrease in the Mississippi River discharge for the same period would have significantly reduced the number of years with moderate and severe hypoxia to 8 and 4, respectively (Table 2). For a scenario with 4°C increase in the average annual temperature and a 20% increase in the average Mississippi River discharge, the model predicts 31 year with moderate and 26 years with severe hypoxia. Importantly, model simulations suggest that pronounced hypoxia would not develop if the nitrate concentrations would had remained unchanged with respect to the period 1954 – 1967 (0.61 mg N l^{-1}). Thus, depending on future climate change scenarios and nutrient control strategies, hypoxia in the northern Gulf of Mexico may become more or less severe.

Nutrient reductions in the Mississippi River and their effects on the Gulf of Mexico hypoxic zone are currently high-profile concerns in scientific and public forums (e.g., Brezonik et al., 1999; Goolsby et al., 1999; Rabalais et al., 1999). There are examples of successful nutrient control programs, whose implementation in coastal and estuarine ecosystems under stress have resulted in a reversal of the eutrophication trend (Rosenberg, 1976; Cherfas, 1990; Johansson and Lewis, 1992). Those nutrient control programs, however, have been implemented in circumstances where external nutrient inputs were much lower than that of the Mississippi River, and their results may not be applicable to the northern Gulf of Mexico. Nevertheless, model results (Table 2) suggest that a large-scale reduction (~30%) in nitrogen concentration of the Mississippi River would eventually diminish the severity of hypoxia in the northern Gulf of Mexico. Because of the sensitivity of riverine nitrate flux to climatic influences, global climate change would likely have important implications for the northern Gulf of Mexico. Consequently, nutrient control efforts for the Mississippi River watershed that would be based solely on achieving a specific reduction in the non-point source loading, may have a limited success in controlling the eutrophication and hypoxia in the northern Gulf of Mexico. If, for example, the Mississippi River discharge would increase 20%, as predicted in some model scenarios (Miller and Russell, 1992), a reduction in nitrate flux in excess of 20% would be required only to prevent the eutrophication from worsening.

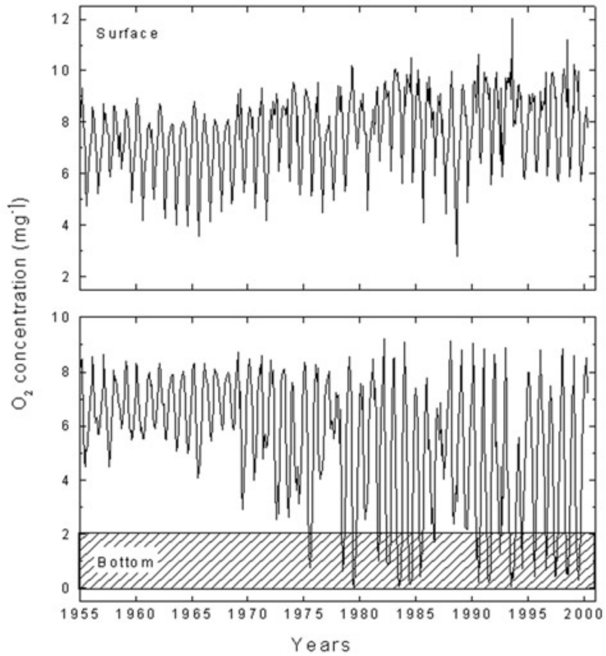

Figure 8. Simulated changes in the average surface (0-10 m) and bottom (10-20 m) oxygen concentration at station C6 for the period January 1955-May 2000. Shaded area in the lower chart denotes hypoxic conditions (< 2 mg O_2 l^{-1}) in bottom waters.

8.3.4 Implications for Fisheries Food Webs

The effects of hypoxia on demersal and benthic communities will likely intensify as hypoxia stress worsens, due to either increase in areal extent, severity, or duration. Catches in trawls are negligible when the bottom dissolved oxygen concentration falls below 2 mg l^{-1} (Pavela et al., 1983; Renaud, 1986). Motile fishes and invertebrates migrate from the area or into the upper water column. Mass mortalities are likely, however, if they are trapped against the shore by a large anoxic water mass. This could become a serious problem in the northern Gulf of Mexico, if the areal extent of hypoxia increases. Heavy mortalities occur in the benthic infauna and species diversity is drastically reduced when ambient oxygen concentrations decrease below 0.5 mg l^{-1} (Gaston, 1985; Boesch and Rabalais, 1991; Rabalais et al., 1993; Rabalais et al., 2001). Presently, there is some recovery of the benthic community in the fall, and further recruitment in the subsequent spring. However, the overall structure of the benthic community is shifted in species composition and age structure, to a smaller-sized, lower biomass, polychaete dominated fauna. An increase in areal extent and severity of hypoxia will decrease recovery rates and also reduce food resources (infauna) for recolonizing demersal groups, such as the commercially important penaeid shrimps. Further, alterations in benthic community structure will have implications for sedimentary processes, benthic pelagic coupling, and energy flow. Major alterations in benthic communities due to hypoxia stress, especially a reduction in diversity and biomass, will certainly alter the productivity base that leads to fishery stocks.

Pelagic species could also be impacted if hypoxic conditions extend high into the water column affecting their distribution and movement patterns. From August 1995 to February 1997, for example, dual beam hydroacoustics were employed on quarterly research trips to measure the density and in situ target strengths of fishes associated with a petroleum platform, South Timbalier 54 (Stanley and Wilson, 1998). During the survey in July 1996, observed dissolved oxygen levels were below 2 mg O_2 l^{-1} in depths of 15 – 22 m. Within these depths fish density was essentially zero while from the surface to 15 m elevated fish densities were observed. Other potential fisheries impacts include: concentrated fishing effort with increased bycatch, local nearshore mortality of finfish and shellfish, and decreased recruitment due to impacts on zooplankton assemblages (Hanifen and Romaire, 1998; Craig et al., 2001).

Freshwater runoff, via its negative effect on salinity, is a critical parameter governing biological processes in the northern Gulf of Mexico estuaries and coastal waters. The annual yield of penaeid shrimp in the Gulf of Mexico is inversely related to the annual discharge of the Mississippi River, perhaps because of reduced estuarine salinities at high river flows (Turner, 1992; Mulholland et al., 1997). Penaeid shrimp postlarvae are mostly limited to estuarine habitats with salinities greater than 10 psu. In the case of Louisiana, salinities are primarily influenced by river flow and precipitation. Mississippi River discharge affects the lower estuaries, while rainfall affects the upper bays and estuaries. With heavy rains or high river flow, salinities in the marshes are reduced. If salinities are reduced beyond acceptable conditions, postlarvae do not move as high into the marshes, ultimately influencing adult stock. This is important because if the freshwater runoff increases as a result of global warming, estuarine salinities could decrease, possibly leading to reduced yields of shrimp and other species favoring higher estuarine salinities. Temperature also influences growth. Growth is inhibited in waters with a temperature below 20°C. Global warming may expand this region of high shrimp yield northwards, increasing shrimp harvest throughout the region, assuming that salt

Table 1. Investigated model scenarios. Changes denote deviations from the observed monthly averages for the period 1954-2000.

Nominal model	Observed monthly averages (1954-2000) of the Mississippi River discharge, nitrate concentration and nitrate flux.
Scenario 1.	30% decrease in the average Mississippi River discharge (Wolock and McCabe, 1999).
Scenario 2.	20% increase in the average Mississippi River discharge (Miller and Russel, 1992; Wolock and McCabe, 1999).
Scenario 3.	4°C increase in the average annual temperature of the northern Gulf of Mexico.
Scenario 4.	4°C increase in the average annual temperature of the northern Gulf of Mexico and 20% increase in the average Mississippi River discharge.
Scenario 5.	Mississippi River nitrate concentration remains unchanged with respect to the average for the period 1954-1967 (0.61 mg N L^{-1}).
Scenario 6.	30% reduction in the Mississippi River nitrate concentration (proposed management scenario).

Table 2. Model results for selected scenarios described in Table 1. The simulation interval was 45 years (1954 – 2000).

	Number of years with moderate hypoxia (< 2 mg O_2 l^{-1})	Number of years with severe hypoxia (< 1 mg O_2 l^{-1})
Nominal model	19	16
Scenario 1.	8	4
Scenario 2.	26	20
Scenario 3.	25	19
Scenario 4.	31	26
Scenario 5.	0	0
Scenario 6.	12	7

marsh nursery areas are not negatively affected by other factors, such as water level changes.

Louisiana commercial and recreational fisheries depend on life cycles of species located within shallow continental shelf waters that overlap with the hypoxic zone. Fishery-independent surveys reveal reduction or absence of shrimp in hypoxic waters (Craig et al., 2001). Both abundance and biomass of fishes and shrimp are significantly reduced where oxygen concentrations in bottom water fall below 2 mg l^{-1} (Renaud, 1986). Under experimental conditions, white shrimp avoid water with dissolved oxygen concentrations below 1.5 mg l^{-1} and brown shrimp are even more sensitive, avoiding water with oxygen concentrations below 2.0 mg l^{-1}. The ability to detect and avoid hypoxic water leads to an observed blocking effect on juvenile shrimp emigrating from inshore nurseries to offshore feeding and spawning grounds. The life cycle of shrimp involves offshore (Gulf shelf) and inshore (estuarine) phases. Adults spawn on the Louisiana and Texas shelf. Resulting larvae immigrate as plankton via currents into coastal estuaries. Within the estuaries, postlarvae metamorphose into small juvenile shrimp that are benthic in habit. After about two months, intermediate size juveniles emigrate from the nursery and return to the outer shelf to complete their growth into adults. The life cycle from egg to adult takes about 6 months. Larval, postlarval, sub-adult, and adult shrimp utilize habitats overlapping with the hypoxic zone, and, depending on the stage within the life cycle, their spawning grounds, feeding grounds, or migratory pathways could be impacted. A negative correlation between shrimp catch and the presence of hypoxia corroborates interference with shrimp migration (Zimmerman and Nance, 2001). In areas where hypoxia is widespread and persistent, shrimp catch is always low. In Louisiana, the nearshore concentration of shrimp is always higher than offshore, possibly because hypoxia impedes offshore movement. Since nearshore catches are comprised of young shrimp, productivity in growth to a larger size is lost. Production models conservatively estimate that several million pounds of shrimp are lost annually due to early harvest. Since hypoxia blocks access of migrating juvenile shrimp to offshore feeding grounds, losses in production due to lost feeding are also predictably large. These direct and indirect fisheries losses would be exacerbated if hypoxia expands in space and time as a result of global climate change.

8.4 Conclusions

The average nitrate flux of the lower Mississippi River increased from about 0.6×10^6 kg d^{-1} in 1954-1967 to about 2×10^6 kg d^{-1} in 1983-2000, which is a 3.3-fold increase. During the same time period, the average nitrate concentration increased 2.3-fold (from 0.61 mg N-NO_3 l^{-1} to 1.37 mg N-NO_3 l^{-1}), while the average discharge increased 40% (from 11,381 m^3 s^{-1} to 15,874 m^3 s^{-1}). Partitioning of the total increase in nitrate flux among the two flux components revealed that about 80% of the observed increase in flux may be explained by the increase in nitrate concentration. Nevertheless, the residual component of nitrate flux is controlled primarily by the variability in runoff, i.e., climatic factors. Nitrate concentration is also highly correlated with discharge at the low end of the discharge spectrum, up to about 13,000 m^3 s^{-1}. This peculiar relationship is clearly affecting nitrate flux, primarily by amplifying variations in flux between flood and drought years. Consequently, future changes in the frequency of droughts or floods, or an overall change in freshwater discharge, may substantially alter the flux of nitrate to the northern Gulf of Mexico. Model simulations for the northern Gulf of Mexico indicated that bottom water hypoxia intensified about 30 years ago, as a probable consequence of increased net productivity and increase in the vertical flux of the organic carbon. Apparently, the long-term increase in riverine nutrient fluxes has been the primary factor controlling this historical decline in oxygen concentrations. Thus, riverine nutrient fluxes, via their influence on net productivity of the upper water column, play a major role in controlling the development of bottom water hypoxia and accumulation of organic carbon in coastal sediments.

Assessment of future climate change scenarios for the northern Gulf of Mexico is complicated by the fact that model projections for the Mississippi River runoff are highly variable. The Canadian and the Hadley models projected a 30% decrease and a 40% increase, respectively, by the year 2099. Nevertheless, model simulations suggest that altered freshwater and nutrient fluxes would have important implications for water column stability, net productivity, and global oxygen cycling in the northern Gulf of Mexico. Nominal model simulation for the period 1954-2000, for example, predicted 19 years with moderate hypoxia (< 2 mg O_2 l^{-1}) and 16 years with severe hypoxia (< 1 mg O_2 l^{-1}). A 30% decrease in the Mississippi River discharge for the same period would have significantly reduced the number of years with moderate and severe hypoxia to 8 and 4, respectively. For a scenario with 4^oC increase in the average annual temperature and a 20% increase in the average Mississippi River discharge, the model predicts 31 years with moderate and 26 years with severe hypoxia. Importantly, model simulations suggest that pronounced hypoxia would not develop if the nitrate concentrations would had remained unchanged with respect to the period 1954-1967 (0.61 mg N l^{-1}). Thus, depending on future climate change scenarios and nutrient control strategies, hypoxia in the northern Gulf of Mexico may become more or less severe.

Nutrient reductions in the Mississippi River and their effects on the Gulf of Mexico hypoxic zone are currently high-profile concerns in scientific and public forums, largely because of the potentially negative consequences that hypoxia may have for habitat functionality and sustainability of the Gulf's coastal fisheries. Our model results suggest that a large-scale reduction (~30%) in nitrogen concentration of the Mississippi River would eventually diminish the severity of hypoxia in the northern Gulf of Mexico. Nevertheless, the areal extent and the severity of hypoxia are very sensitive to climate-induced changes in freshwater and nutrient fluxes. If, for example, the Mississippi River discharge would increase 20%, as predicted in some model scenarios, a reduction in nitrate flux in excess of 20% would be required only to prevent the eutrophication from worsening. Consequently, nutrient control efforts for the Mississippi River watershed that are based solely on achieving a specific reduction in the non-point source loading, may have a limited success in controlling the eutrophication and hypoxia in the northern Gulf of Mexico.

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Chapter 9

Assessing the Potential Climate Change Impact on Salinity in the Northern Gulf of Mexico Estuaries: A Test Case in the Barataria Estuarine System

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Summary

Statistical models were developed which described the observed salinity at three stations (a coastal station, a mid-estuary station, and an upper estuary station) in the Barataria estuary, Louisiana in terms of the major forcing functions (Mississippi River discharge, local precipitation, and coastal water levels). The most successful models used an autoregressive term in addition to the forcing function values. These models were able to account for 72, 74, and 63 percent of the observed salinity signal at the coast, mid-estuary, and upper estuary stations respectively. The non-autoregressive portion of the model accounted for 48, 41, and 16 percent of the observed salinity signal at the coast, mid-estuary, and upper estuary stations respectively.

The models were then used to predict the annual salinity pattern for each station using the data from 1990 through 2000 as an index period. The models were able to reproduce the annual signal at each of the stations. The potential salinity changes that could occur with global climate changes in the forcing functions were estimated by changing the forcing functions, during the index period, to correspond to various climate change scenarios (increased or decreased precipitation and Mississippi River discharge). The resulting change in the annual pattern was then compared to the baseline condition. The results yield a potential change of ~3 ppt for the salt marsh, and ~1 ppt for the intermediate to brackish areas of the Barataria system. An analysis of literature data for twenty six estuaries around the northern Gulf of Mexico indicated that fairly small salinity changes are expected under most of the climate change scenarios for the northern Gulf of Mexico estuaries.

The potential impacts of these changes are difficult to assess since the present climate models give conflicting results on the expected changes in runoff (there is general agreement on precipitation changes). However, should the resulting changes in salinity be on the order of 3 ppt, then potential impacts would most likely be limited to small scale vegetation community changes at the boundaries of the major vegetation types. Larger salinity changes would be needed in order to see dramatic vegetation shifts in the coastal salt marshes.

9.1 Introduction

The purpose of this Case Study was to assess the potential changes that could occur in the salinity of northern Gulf of Mexico estuaries due to global climate changes. This was accomplished through a "Test Case" approach by analyzing the observed salinity patterns in the Barataria Bay Louisiana estuarine system in relation to known forcing functions. This present study has updated the work of Swenson and Turner (1995) to make predictions of probable salinity changes in the Barataria system resulting from global climate change. The analysis presented in this report quantifies the relationship between rainfall, Mississippi River discharge, coastal water levels, and salinity, using the available time series data. The results were then used (with the literature) to assess the likely changes that could occur in other Northern Gulf of Mexico estuaries.

Estuarine gravitational circulation is, in many cases, influenced by flows occurring as a result of other processes (e.g. wind forcing). Wind forcing causes the formation of buoyant effluent plumes, which influence shelf chemistry and biology as well as physics (Wisemann, 1986). These exchanges are bi-directional with significant transfers of mass, momentum, chemical, and geological constituents occurring between the shelf and the estuary (Wisemann, 1986). Meteorological forcing in estuaries along the northern Gulf of Mexico can be considered in terms of: (1) exchange between the estuarine waters and the waters in the coastal zone; and (2) local forcing occurring within the estuary proper. At time scales of a few days, the along-estuary wind stress drives an estuarine-shelf exchange; at longer time scales Ekman convergence/divergence driven by the alongshore wind stress drives the estuarine-shelf exchanges (Schroeder and Wiseman, 1986). Work by Kjerfve (1975) in Caminada Bay, Louisiana, demonstrated that the diurnal tidal influence, in addition to the wind forcing, can be important in controlling the internal dynamics of these systems. The most pronounced effect of wind forcing on the central Northern Gulf of Mexico systems is the difference between a northerly and a southerly wind. Strong winds from the south "push" water towards the coast forcing water into the estuaries, raising water levels about 0.3 – 0.5 m above normal. Conversely, winds from the north force water out of the estuaries depressing the water levels 0.3 – 0.5 m below normal. The "set up" of water usually occurs as a front approaches the area from the west and the

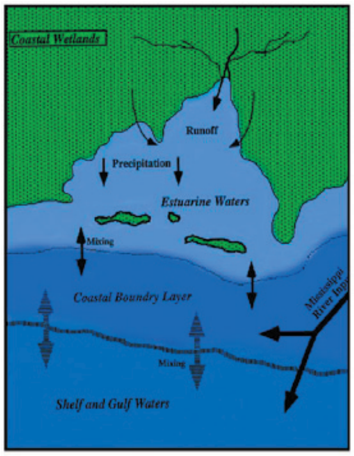

Figure 1. Schematic of an estuarine system illustrating the major pathways of fresh water and coastal ocean water inputs to the system.

Western Gulf of Mexico	Central Gulf of Mexico	Eastern Gulf of Mexico
19 Sabine lake	11 Mississippi Sound	1 Sarasota Bay
20 Galveston Bay	12 Lakes Pontchartrain/ Borgne and Chandeleur Sound	2 Tampa Bay
21 Brazos River and San Bernard Rivers/ Cedar Lakes	13 Breton Sound	3 Suwanee River
22 Matagorda Bay	14 Barataria Bay	4 Apalachee Bay Estuaries
23 San Antonio Bay	15 Terrebonne-Timbalier bays	5 Apalachicola Bay
24 Aransas Bay	16 Atchafalaya/Vermilion Bays	6 St. Andrew Bay
25 Corpus Christi Bay	17 Mermentau River	7 Choctawhatchee Bay
26 Laguna Madre	18 Calcasieu lake	8 Pensacola Bay
		9 Perdido Bay
		10 Mobile Bay

Figure 2. Map of the Gulf of Mexico showing the estuaries characterized by Orlando, et. al. (1993).

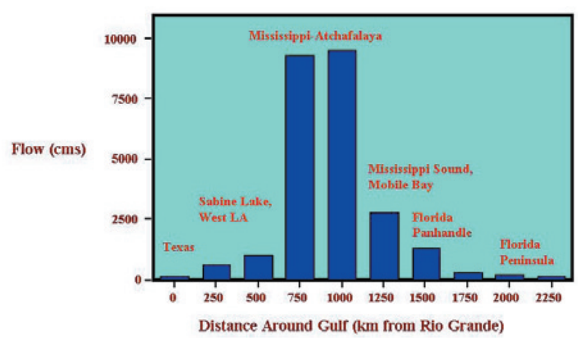

Figure 3. Distribution of river input into the Northern Gulf of Mexico. Modified from Orlando et. al. (1993).

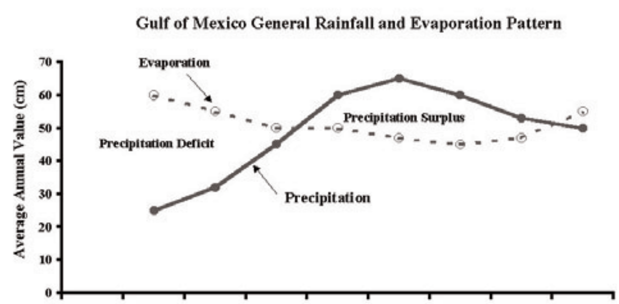

Figure 4. Distribution of annual average precipitation and evaporation around the Northern Gulf of Mexico. Modified from Orlando et. al. (1993).

southerly winds pile water along the coast, then after the front passes the winds shift to a more northerly direction. This situation results in a rapid drop in the estuarine water levels. Hart and Murray (1978) describe this type of situation occurring in Chandeleur-Breton Sound. These events result in substantial fluxes of water into, and out of, estuarine systems, and can have dramatic effects on the salinity distribution within the system. Thus, the salinity signal in these estuarine systems is fairly complex. A schematic detailing the major forcing functions discussed above is shown in Figure 1.

Orlando et. al. (1993) described the factors influencing salinity in 26 estuarine systems in the northern Gulf of Mexico (Figure 2). The distribution of freshwater input into these Northern Gulf of Mexico estuaries is presented in Figure 3. The Mississippi-Atchafalaya discharge dominates the input in the central portion of the Gulf, while the western (Texas) and eastern (Mississippi to Florida) portions of the Gulf are more heavily influence by local river flow. The overall precipitation and evaporation pattern of the Gulf is presented in Figure 4. In general, the Gulf of Mexico is characterized by a decrease in precipitation from east (Florida) to west (Texas), while surface evaporation rates generally increase from east to west across the Gulf. This results in an overall pattern in which there is a rainfall deficit (evaporation exceeds precipitation) in the western part of the Gulf (and southern Florida) and a rainfall surplus (precipitation exceeds evaporation) in the central portion of the Gulf. The overall result is that some of the estuaries in the northern Gulf have the highest freshwater input per unit estuarine volume (Ward, 1980). Orlando et. al., (1993) concluded that high Mississippi River flows reduced the salinities in the lower portion of the estuaries in the central gulf (Louisiana) due to advection of Mississippi River water into the estuaries. During times of high river flow the local precipitation is unimportant. Conversely, at times of low Mississippi River flow, the salinities in the lower bays increase, and local precipitation becomes more important. The major freshwater sources for the 26 Gulf of Mexico estuaries described by Orlando et. al., (1993) are presented in Table 1.

Table 1 Summary of the major and secondary freshwater sources influencing salinities in the 26 northern Gulf of Mexico estuaries presented in Figure 2. Data was taken from Orlando et. al. (1995).

State	Estuarine system	Major freshwater source	Other freshwater source
Texas	Laguna Madre	Rainfall (65%)	Local riverflow (17%)
Texas	Corpus Christie Bay	Local riverflow (92%)	Rainfall (8%)
Texas	Aransas Bay	Local riverflow (54%)	Rainfall (46%)
Texas	San Antonio Bay	Local riverflow	Rainfall
Texas	Matagorda Bay	Local riverflow (25-80%)	Rainfall
Texas	Brazos River	Local riverflow	
Texas	Galveston Bay	Local riverflow	
Texas	Sabine Lake	Local riverflow	
Louisiana	Calcasieu Lake	Local riverflow	
Louisiana	Mermentau River	Local riverflow	
Louisiana	Atchafalaya/Vermillion	Atchafalaya River flow	
Louisiana	Terrebonne.Timbalier	Mississippi River flow	Rainfall
Louisiana	Barataria Bay	Mississippi River flow	Rainfall
Louisiana	Breton Sound	Mississippi River flow	Pearl River flow
Louisiana	Pontchartrain/Borgne	Local riverflow (90%)	Rainfall (5%)
Mississippi	Mississippi Sound	Local riverflow	Mississippi River flow
Alabama	Mobile Bay	Local riverflow	
Florida	Perdido Bay	Local riverflow	
Florida	Pensacola Bay	Local riverflow	
Florida	Choctawhatchee Bay	Local riverflow	
Florida	St. Andrew Bay	Rainfall	
Florida	Apalachicola Bay	Local riverflow	
Florida	Apalachee Bay	Local riverflow	
Florida	Suwannee River	Local riverflow	Groundwater flow
Florida	Tampa Bay	Local riverflow	Rainfall
Florida	Sarasota Bay	Rainfall	Local riverflow

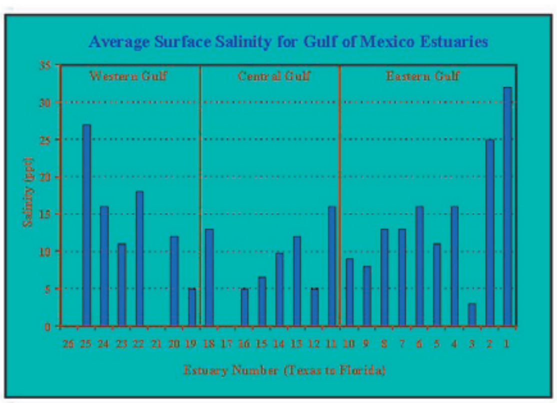

Figure 5. Distribution of surface salinity for 26 estuaries around the Gulf of Mexico. Data is from Orlando et. al. (1993), and updated as part of this study.

The salinity of the estuaries around the Gulf of Mexico shows a fairly large range of values as a result of the freshwater input distribution. The average surface salinity for the 26 Gulf of Mexico estuaries studied by Orlando et. al. (1993) is presented in Figure 5 (the data for Barataria and Terrebonne-Timbalier was updated as part of this study). In general the central Louisiana estuaries exhibit lower salinities due to the effect of the Mississippi River discharge. The south Texas estuaries and the south Florida estuaries exhibit the highest salinities due to the general pattern of rainfall deficits in these locations.

9.2 Methods

9.2.1 The Data base

The data used are from time series data sets that were readily available in a computer compatible format (usually an ASCII data file). The data came from the following sources:

1. Hourly salinity data from recording gages maintained by the Louisiana Department of Wildlife and Fisheries (LDWF). The gage locations are indicated in Figure 6.

2. Daily Mississippi River discharge data from the United States Army Corps of Engineers (USACE).

3. Climatic data (Palmer Drought Severity Index, Precipitation) from the Louisiana Office of Climatology at Louisiana State University and from the National Oceanic and Atmospheric Administration (NOAA). These data are available for various climatic regions in the Gulf of Mexico states. The climatic regions for each of the states are shown in Figure 7.

4. Water level data from the National Ocean Survey (NOS) of the National Oceanic and Atmospheric Administration). The gage location is indicated in Figure 6.

The data files were transferred to a desktop computer for analysis using Statistical Analysis System (SAS 1990 a, b, c, d, e). Because all the data were in time series format, the same basic techniques were used for all sites. The data sets were inventoried, checked for data quality, and put into the final form for analysis using the following general procedures:

A. Data Inventories
- Total Observations in data set
- Sampling Frequency

B. Descriptive Statistics
- Mean
- Standard Deviation
- Minimum
- Maximum

C. QA/QC checks
- Investigate potential outliers
- Raw data plots

D. Plots of monthly means for each station and variable

E. Data editing
- remove erroneous data points
- compute monthly means

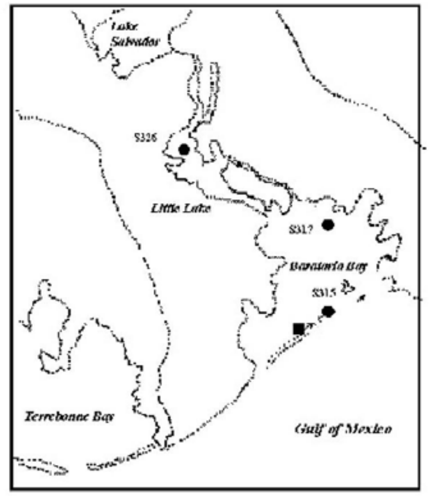

Figure 6. Map of the Barataria Estuarine system, Louisiana showing the locations of the gages used in the analysis. The Louisiana Department of Wildlife and Fisheries salinity gages located at the coast (S315 at Grand Terre), mid-estuary (S317 at St. Marys' Point), and upper estuary (S326 at Little Lake) are indicated by the filled circles. The National Ocean Survey water level gage at Grand Isle is indicated by the filled square.

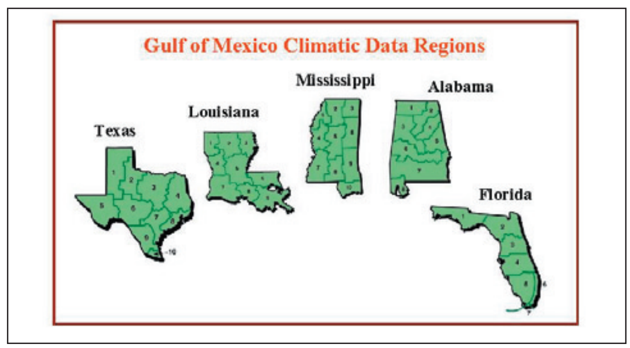

Figure 7. Map of the states around the Gulf of Mexico, indicating the Climate Division for which climate summaries (precipitation, Palmer Drought Severity Index, etc.) are available.

Any needed correction factors (for conversion to metric units, calculation of salinity from chloride or conductivity) were applied during these checks.

9.2.2 Barataria Bay Louisiana: A Test Case

Introduction

The Barataria Estuarine system just to the west of the Mississippi River consists of a series of lakes and bays surrounded by low lying marshes. These marsh systems are characterized hydrologically by numerous interconnecting lakes, channels, and bayous. The flows through these channels and bayous are coupled with extensive overland flooding, thus exchanging water between the marsh surface and the surrounding water bodies. The circulation patterns, and salinity structure within these estuaries is controlled internally by a combination of tidal dynamics, riverine input, and wind forcing. The Barataria Estuary system was used as a test case to develop statistical models which would explain the observed estuarine salinity as a function of the major forcing functions (Mississippi River flow, local precipitation, and coastal water levels).

In one of the first comprehensive studies of the hydrologic characteristics of the Barataria Estuarine system (Baumann 1987) the changes in the spatial and temporal salinity patterns in Barataria Estuary system were attributed to three basic factors:

1. The seasonal evapotranspiration and precipitation regime,
2. Mississippi River discharge,
3. Seasonal water level cycle.

Barrett (1971) and Gagliano et. al. (1973) described an inverse relationship between Mississippi River flow and coastal salinities in Louisiana. Their results were based upon linear statistics. Wiseman et. al., (1990) used Auto-Regressive Moving Average (ARMA) to analyze the relationship between weekly discharge of the Mississippi River and Louisiana coastal salinities based upon long term records, and time series modeling. This type of analysis assumes that the present state of a system is a function of the present and past values of its inputs. Thus, the model is able to account for lags in the system, with the larger lags having less effect than the more recent. The total models were able to account for 70 to 86% of the observed variance in the salinity signal. The river discharge portion of the model accounted for 30 to 50% of the variance of the observed salinity data. The remainder (the Auto-Regressive portion) described processes not directly related to the river flow (tidal dispersion, wind-driven estuarine-shelf exchange). Their analysis also indicated an increase in the lag between the Mississippi River flow and coastal salinity as one moved either into the estuary or downstream along the coast (westward). Although these are statistical models, the results were consistent with a conceptual model in which Mississippi River discharge alters coastal salinities, which in turn propagates up-estuary and westward along the coast (Wiseman et. al., 1990).

Assumptions

The approach in this study is a statistical approach (regression) to explaining the observed salinity in the Barataria estuary, there is no attempt to model the actual physical processes that control the salinity. This imposes some restrictions on what can be inferred (or predicted) using the results of the analysis:

1. The statistical model approach is useful for looking at possible changes in salinity under different forcing function scenarios (e.g. what if the river had been higher during the time period the data were collected). The statistical results will give a general idea of the range of values that can be expected with changes in the forcing functions under the present hydrological configuration of the Barataria estuary.
2. The predictions made in this report are to be used as a guide only since they do not take into account the impact of the Davis Pond diversion. This diversion, a structure that will divert up to 10,000 cubic feet per second (cfs) of freshwater into the upper portions of the Barataria system, (~ 50 km north of the Little Lake gage) will begin operation later this year. The operaton of this structure will significantly alter the hydrologic configuration of the Barataria system during the months that it operates. In order to account for the diversion a dynamic hydrologic (and salinity) model would be needed. That approach is beyond the scope of this present study.
3. The statistical approach in this study does not fully describe the dynamic nature of the system. Swenson and Turner (1995) presented data showing that the location of the 5 ppt isohaline is highly variable, moving ~20 km in response to changes in forcing functions from year to year. In addition frontal passages and tropical storms often result in large magnitude (5 ppt or greater) but relatively short duration (~3 days) salinity pulses in the system (Swenson and Swarzenski, 1995). The affect of these events is averaged out in the approach taken in this analysis.
4. This analysis is not able to address the overall spatial distribution of the salinity changes in the Barataria estuary, only the possible magnitude of the change at a few locations. This spatial distribution of the change is also an important component in assessing the overall impact of salinity change.

Table 2 Classification matrix for the BES based upon the Palmer Drought Severity Index (PDSI) and Mississippi River discharge. The matrix classifies the upper (north of Little Lake) and lower portions of the system as either a "high salinity year" a "low salinity year" or a "normal year". Values of river discharge greater than 1 standard deviation (S. D.) above the mean were considered high river discharge years, and values of river discharge less than 1 standard deviation (S. D.) below the mean were considered low river discharge years. The Palmer Drought Severity Index classifies the years into drought conditions. The index has a numeric value with 0 indicating normal conditions. Values equal to, or less than, -4 indicate extreme drought conditions. Values equal to, or greater than, +4 indicate extreme moist conditions. Very moist (>3) was used as an indicator of a high local runoff year, and moderate drought (<-3) as an indicator of a low local runoff year.

	Palmer Drought Severity Index					
	Moderate Drought Index		Normal Drought Index		Very Moist Drought Index	
	Lower Estuary	Upper Estuary	Lower Estuary	Upper Estuary	Lower Estuary	Upper Estuary
Mississippi River Discharge >1 S. D. Above Mean	Low Salinity or "Wet Year"	Low Salinity or "Wet Year"	Low Salinity or "Wet Year"	"Normal Year"	Low Salinity or "Wet Year"	High Salinity or "Dry Year"
Mississippi River Normal River Discharge	Low Salinity "Normal Year"	or "Wet Year"	"Normal Year"	"Normal Year"	"Normal Year"	High Salinity or "Dry Year"
Mississippi River Discharge <1 S. D. Below Mean	High Salinity or "Dry Year"	Low Salinity or "Wet Year"	High Salinity or "Dry Year"	"Normal Year"	High Salinity or "Dry Year"	High Salinity or "Dry Year"

Table 3 Climatic classification for the Barataria Estuarine System based upon the Palmer Drought Severity Index (PDSI) and Mississippi River discharge.

Year Classification					
Year	Season	Drought Severity	River Flow	Upper Estuary	Lower Estuary
1980	Jan. - Jun.	very moist	normal	wet	normal
1980	Jul. - Dec.	mild drought	-1 SD	normal	dry
1981	Jan. - Jun.	mild drought	normal	normal	normal
1981	Jul. - Dec.	moderate drought	normal	dry	normal
1982	Jan. - Jun.	normal	normal	normal	normal
1982	Jul. - Dec.	normal	-1 SD	normal	dry
1983	Jan. - Jun.	very moist	+1 SD	wet	wet
1983	Jul. - Dec.	unusual moist	normal	wet	normal
1984	Jan. - Jun.	moist	+1 SD	normal	wet
1984	Jul. - Dec.	normal	normal	normal	normal
1985	Jan. - Jun.	mild drought	normal	normal	normal
1985	Jul. - Dec.	normal	normal	normal	normal
1986	Jan. - Jun.	mild drought	normal	normal	normal
1986	Jul. - Dec.	moderate drought	normal	dry	normal
1987	Jan. - Jun.	moist	normal	normal	normal
1987	Jul. - Dec.	incipient drought	normal	normal	normal
1988	Jan. - Jun.	moist	normal	normal	normal
1988	Jul. - Dec.	moist	-1 SD	normal	dry
1989	Jan. - Jun.	mild drought	normal	normal	normal
1989	Jul. - Dec.	mild drought	normal	normal	normal
1990	Jan. - Jun.	normal	+1 SD	normal	wet
1990	Jul. - Dec.	moderate drought	normal	dry	normal
1991	Jan. - Jun.	very moist	normal	wet	normal
1991	Jul. - Dec.	extreme moist	-1 SD	wet	dry
1992	Jan. - Jun.	extreme moist	normal	wet	normal
1992	Jul. - Dec.	very moist	normal	wet	normal
1993	Jan. - Jun.	extreme moist	+1 SD	wet	wet
1993	Jul. - Dec.	incipient drought	normal	normal	normal
1994	Jan. - Jun.	normal	+1 SD	normal	wet
1994	Jul. - Dec.	moist	normal	normal	normal
1995	Jan. - Jun.	moist	normal	normal	normal
1995	Jul. - Dec.	mild drought	normal	normal	normal
1996	Jan. - Jun.	normal	normal	normal	normal
1996	Jul. - Dec.	normal	normal	normal	normal
1997	Jan. - Jun.	moist	+ 1 SD	normal	wet
1997	Jul. - Dec.	normal	normal	normal	normal
1998	Jan. - Jun.	normal	+1 SD	normal	wet
1998	Jul. - Dec.	normal	normal	normal	normal
1999	Jan. - Jun.	normal	normal	normal	normal
1999	Jul. - Dec.	incipient drought	-1 SD	dry	dry
2000	Jan. - Jun.	extreme drought	-1 SD	dry	dry

Climatic Characterization

Swenson and Turner (1995) used an overall climatic characterization to identify high freshwater inflow years and low freshwater inflow years. The salinity data from these time periods was then compared to determine the overall magnitude of the climatic drivers on the position of various salinity isohalines in the Barataria System.

The climatic regime was classified into wet, dry and normal year classes for the upper and lower portions of the Barataria Estuary system using Mississippi River Discharge and the Palmer Drought Severity Index (PDSI) as classification variables. A value of +/- 1 standard deviation, was used for the cutoff point for Mississippi River flow for wet and dry years. The PDSI classifies the years into drought or moist conditions. The index has a numeric value, with zero indicating normal conditions, values equal to or less than -4 indicate extreme drought conditions, values equal to or greater than +4 indicate extreme moist conditions. The very moist (>3) condition was used as an indicator of a high local runoff year, and the moderate drought (<-3) category was used as an indicator of a low local runoff year. A classification matrix was developed (Table 2) which classified the upper and lower portions of the estuary into wet and dry years (based upon river discharge and the PDSI). The actual data were then used to classify the years from 1980 through 1995. Table 3 presents the yearly classification data from the Swenson and Turner (1995) study for the Barataria system. The Table has been updated through 2000 as part of the present study. The following discussion, however, is limited to the original Swenson and Turner (1995) time period (1980-1995). The data indicated that 1983 and 1993 were wet years. The first half (January - June) of each year was characterized by high river flow (>1 standard deviation above normal) with a PDSI indicating very moist (1983) or extremely moist (1993) local conditions. The latter half of the year (July - December) the river flow returned to normal for both years. It was more difficult to find a good example of a dry year during the 1980-1995 time period. There were no cases of low river flow and moderate drought conditions. The best candidate for a dry year was 1981 and this was used in a subsequent analysis. The salinity data from the Barataria Estuary for the wet and dry years determined above was then used by the Louisiana Department of Natural Resources to produce isohaline maps for the two contrasting conditions. The data indicated that a change from low rainfall to high rainfall shifts the 5 ppt isohaline ~15 km south, and the 15 ppt isohaline ~8 km south, and a change from low riverflow to high riverflow shifts the 5 ppt isohaline 20 km south, and the 15 ppt isohaline ~10 km south.

Forcing Function Salinity Relationships

The monthly mean Mississippi River stage and discharge and the de-trended monthly mean water levels at Grand Isle, from 1955 through 2000 are presented in Figure 8. The long term trend was removed from the water level data in order to more clearly show the seasonal pattern. The monthly Palmer Drought Severity Index (PDSI) for each of the three Louisiana Climate Regions from 1955 through 2000 are presented in Figure 9. The Mississippi River discharge exhibits a seasonal pattern in which the maximum discharge of ~22,000 $m^3 sec^{-1}$ occurs in April, and the minimum discharge of ~6,000 $m^3 sec^{-1}$ occurs in September. The mean monthly coastal water levels show a pattern in which there are two peaks. One is in May-June and the second (and larger) is in September-October. Although the standard deviation is large, a comparison of the monthly means using Duncans' multiple range test (SAS, 1988) indicated that all months are significantly different from each other with the exception of one grouping (August and November). September had the highest mean levels. The lowest water level values occurred in January. Linear regression was performed to investigate the temporal trends in each variable. The Mississippi River discharge shows a statistically significant increase of about 42 $m^3 sec^{-1} yr^{-1}$ over the time period from 1955 through 2000. The stage did not exhibit a statistically significant trend with time. The water level at Grand Isle exhibits a statistically significant trend (which is also a major portion of the signal) of ~1.17 cm yr^{-1} over the time period from 1955 through 2000.

The Louisiana Department of Wildlife and Fisheries (LDWF) salinity stations used in this study (Figure 6) will be referred to as a coastal station (Station S315 - Grand Terre); a mid-estuary station (Station S317 - St. Mary's Point), and an upper estuary station (Station S326 - Little Lake). Although the upper estuary station is not at the upper limit of the system (which is the fresh marshes and swamps), it is located at a point where the system has changed from open bays to more restricted water bodies. Time series plots of the salinity at the coast (Grand Terre Island), mid-estuary (St. Mary's Point) and upper estuary (Little Lake) are presented in Figure 10. The most obvious feature of the forcing functions

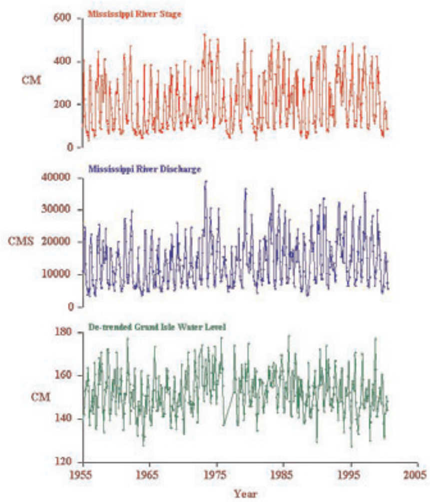

Figure 8. Plot of (top to bottom) monthly Mississippi River stage, monthly Mississippi River discharge, and de-trended monthly water levels at Grand Isle.

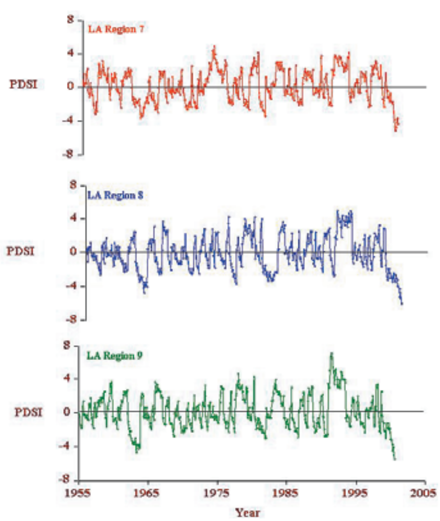

Figure 9. Plot of (top to bottom) monthly Palmer Drought Severity Index for (top to bottom) Louisiana climate division 7 (west Louisiana), climate division 8 (central Louisiana) and climate division 9 (east central Louisiana). Positive values indicate moist conditions and negative values indicate drought conditions.

plots (Figures 8 and 9) and the salinity plots (Figure 10) is the uniqueness of the 1999 – 2000 data. The time period from the fall of 1999 through the end of 2000 was characterized by an extended and severe drought, low Mississippi River discharge, and low coastal water levels. This time period was also characterized by the highest salinities on record. The Grand Isle station exhibits a statistically significant trend of -0.05 ppt y^{-1}, the St. Mary's Point station did

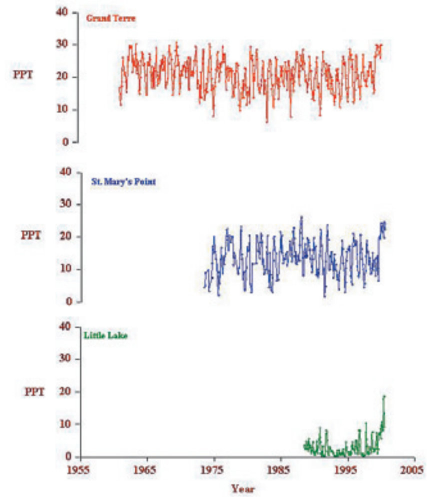

Figure 10. Plots of (top to bottom) monthly mean salinity for Grand Terre (a coastal station), St. Mary's Point (a mid-estuary station), and Little Lake (an upper estuary station) in the Barataria system. The monthly means were computed from hourly data.

not exhibit a statistically significant trend, and the Little Lake station exhibited a statistically significant trend of 0.29 ppt y^{-1}. The contribution of each of these forcing functions to the salinity will be discussed in the next section.

Statistical models for salinity prediction

Regression models (SAS, 1988) were used to look at the importance of Mississippi River discharge, the Palmer Drought Severity Index, rainfall, and coastal water levels. Coastal water levels (as defined by the water levels at Grand Terre) were included to account for the possibility of the "stacking up" of water at the coast which could influence the transport of water in and out of the Barataria system. Several models were run, using various lags for river flow, rainfall, and coastal water levels, in an approach that was similar to that of Gagliano et. al., (1973). Stepwise linear regression and Autoregressive models (SAS, 1988) were also used to produce a series of models using various combinations of variables (up to 9 variables). The results indicated that very little improvement in the model (5-7% improvement) was obtained by using more than three or four variables. In addition, any model used should be physically reasonable. A model using 1 month lag of the variables would be a physically reasonable model, whereas a model that used the 1 month lag and the 3 month lag, skipping the 2 month lag, would not be physically reasonable, although it might be statistically valid. Similar results were

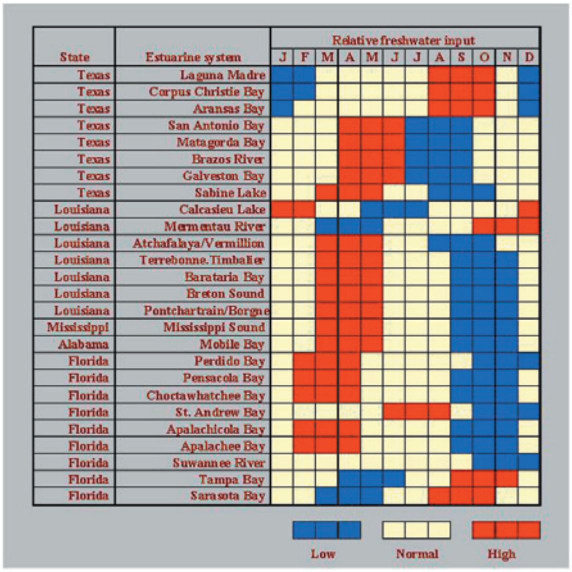

Figure 11. Monthly changes in relative freshwater input into estuaries around the Gulf of Mexico (Figure 2). Indicated, for each estuary, are the months during which high and low freshwater input occur. Adapted from Orlando et. al. (1993).

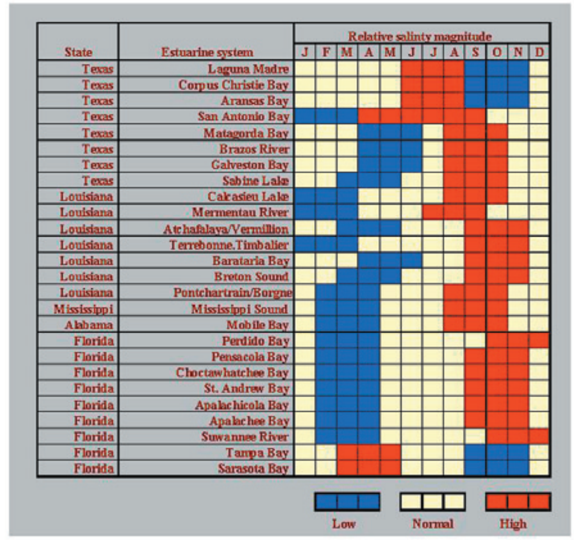

Figure 12. Monthly changes in relative salinity values for estuaries around the Gulf of Mexico (Figure 2). Indicated, for each estuary, are the months during which high and low salinity values occur. Adapted from Orlando et. al. (1993).

Table 4 Summary of predicted precipitation, temperature, and streamflow changes, by season expected to occur by the year 2100. The predictions are from the Hadley Model (HadCM2) as summarized by Ning and Addollahi, 1999.

Season	Parameter	Texas	Louisiana	Mississippi	Alabama	Florida
Winter	Precipitation	5-30% decrease	no change	no change	no change	no change
Spring	Precipitation	10% increase	no change	10% increase	10% increase	no change
Summer	Precipitation	10% increase	10% increase	15% increase	15% increase	no change
Fall	Precipitation	10% increase	10% increase	15% increase	15% increase	no change
Winter	Temerature	4°F increase	<3°F increase	2°F increase	2°F increase	<3-4°F increase
Spring	Temerature	3°F increase	3°F increase	3°F increase	3°F increase	3-4°F increase
Summer	Temerature	4°F increase	3°F increase	2°F increase	2°F increase	3-4°F increase
Fall	Temerature	4°F increase	<3°F increase	4°F increase	4°F increase	3-4°F increase
Winter	Streamflow	35% decrease	unknown	unknown	increase	unknown
Spring	Streamflow	35% decrease	unknown	unknown	increase	unknown
Summer	Streamflow	35% decrease	decrease	decrease	decrease	decrease
Fall	Streamflow	35% decrease	unknown	unknown	unknown	unknown

obtained by Wiseman et. al. (1990) in their analysis of Mississippi River flow and salinity. Because the overall goal is to obtain a model that is both parsimonious and physically reasonable, it was decided to limit the models to three or four variables.

The changes in relative freshwater input and relative salinity magnitude for 26 estuaries around the Gulf of Mexico (Orlando et. al., 1993) are summarized, on a monthly basis, in Figures 11 and 12. The data indicate that there are strong seasonal differences throughout the Gulf. In order to assess potential impacts, the measured and predicted salinity from the last five years was used as an index period to develop a baseline yearly salinity pattern for each of the stations as discussed below.

The potential changes in the salinity forcing functions for the Gulf of Mexico, by season, are summarized in Table 4 (based on Ning and Abdollahi (1999). The model predictions are for increases in precipitation on the order of 10% for all of the Gulf states, except Florida. The predicted changes for streamflow are, in most cases, uncertain (Boesch et. al., 2000). The effect of climate change on Mississippi River discharge is the most important consideration for the Louisiana estuaries. Boesch et. al. (2000) present data indicating that the Hadley model predicts an increase of ~5%, and the Canadian Model predicts a decrease of ~35% for the Mississippi River discharge over the time period from 2025 through 2034. They further state that the Hadley model predicts an increase of ~50%, and the Canadian Model predicts a decrease of ~30% for the Mississippi River discharge over the time period from 2090 through 2099. Data presented by Boesch et. al., (2000) project changes in sea level on the order of 30 centimeters by 2100. The actual forcing functions during the index period (1995-2000) were then altered to reflect these projected changes in precipitation and Mississippi River discharge. The statistical model was re-run and a new mean yearly pattern was produced for each station. These yearly patterns present what the salinity would have been during the 1990-1995 period if the forcing functions were at the levels predicted by the climate change models. The yearly salinity patterns were calculated for the following scenarios:

1. An increase of 30 % in Mississippi River dis charge.
2. A decrease of 30 % in Mississippi River discharge.
3. An increase of 10 % in local precipitation.
4. A decrease of 10% in local precipitation.
5. An increase of 30 cm in water levels.
6. Conditions 1, 3, and 5 combined.
7. Conditions 2, 4, and 5 combined.

The yearly salinity pattern from each of the above scenarios was then compared to the baseline conditions. The baseline conditions used were those generated by the best fit statistical model to the forcing function and salinity data. These conditions will yield a broad range of the possible salinity changes that may result from global climate change impacts on salinity forcing functions.

9.3 Results

9.3.1 Statistical Model Results

In all cases the most successful models were those that contained an autoregressive term. The models were run for the entire data record for each station (1961 – 2000 for Station 315, 1973 – 2000 for Station 317, and 1988 – 2000 for Station 326). The results of the final statistical models are presented in Table 5. The results of the model predictions for the time period from 1995-2000 are presented in Figure 13. The measured values are shown by the solid line and the predicted results from the statistical model are shown as a dashed line (with solid dots). The model for station 315 (coastal station at Grand Terre) explained a total of 72 percent of the observed signal, with the linear portion of the model explaining 48 percent, using Mississippi River discharge, precipitation from Louisiana climate division 9, Grand Isle water levels, and the previous month's salinity. The model for station 317 (mid-estuary station at St. Marys' Point) explained a total of 74 percent of the observed signal, with the linear portion of the model explaining 41 percent, using Mississippi River discharge, precipitation from Louisiana climate division 9, Grand Isle water levels, and the previous month's salinity. The model for station 326 (upper-estuary station in Little Lake) explained a total of 63 percent of the observed signal, with the linear portion of the model explaining 16 percent, using Mississippi River discharge, precipitation from Louisiana climate division 9, and the previous 3 month's salinity. The results show a decrease in the magnitude of the effect of the Mississippi River discharge and coastal water levels from the coast inland. The effect of precipitation is maximum mid-estuary (St. Mary's Point) and minimum at the upper station (Little Lake). This

Table 5 Summary of regression results to predict salinity in the Barataria system using Mississippi River discharge, precipitation at Louisiana climate region 9, and de-trended coastal water levels.

LDWF S315 Coastal Station at Grand Terre

Overall Model R-square = 0.72
Linear portion R-square = 0.48

Variable	Estimate	F-value	Probability > F
Intercept	19.99		
Mississippi Discharge	-0.00029	544.38	0.0001
Region 9 Precipitation	-0.2761	99.56	0.0001
Grand Isle Water Level	-0.0329	83.50	0.0001
1 month previous salinity	+0.5466	354.00	0.0001

LDWF S317 Mid-estuary station at St. Mary's Point

Overall Model R-square = 0.74
Linear portion R-square = 0.41

Variable	Estimate	F-value	Probability > F
Intercept	9.66		
Mississippi Discharge	-0.00024	277.17	0.0001
Region 9 Precipitation	-0.3806	88.96	0.0001
Grand Isle Water Level	-0.0065	22.74	0.0001
1 month previous salinity	+0.6297	330.94	0.0001

LDWF S326 Upper estuary station in Little Lake

Overall Model R-square = 0.63
Linear portion R-square = 0.16

Variable	Estimate	F-value	Probability > F
Intercept	2.916		
Mississippi Discharge	-0.00007	47.25	0.0001
Region 9 Precipitation	-0.1522	11.55	0.0009
Previous month salinity	+0.8728	145.63	0.0001
2 months previous salinity	-0.4220	7.37	0.0075
3 months previous salinity	+0.2511	6.96	0.0094

is not what would be expected but may be a result of the shorter data record at the Little Lake station. The autoregressive parameter seems to indicate a faster flushing in the lower portion of the system (one month lag at the coast and mid-estuary compared to three month lag at Little Lake).

The measured and predicted yearly salinity patterns for the statistical models are presented in Figure 14. The model reproduces the observed annual pattern at all stations with a fairly high degree of accuracy. The model is useful for looking at possible changes in salinity under different forcing function scenarios (e.g., what if the river had been higher during 1995 – 2000).

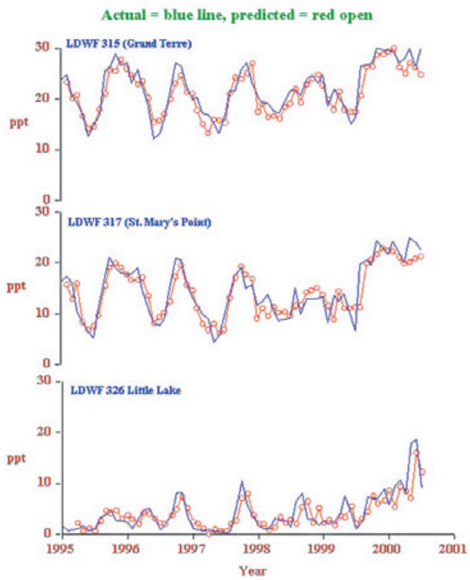

Figure 13. Plots of measured monthly mean salinity (blue line) and predicted monthly salinity (dashed red line with circles) for LDWF Station 315 (Top), LDWF Station 317 (middle) and LDWF Station 326 (bottom) in the Barataria system. The following models were used: Station 315: Salinity = 19.99 - 0.00029 Q - 2761 P - 0.0329 WL - 0.5466 S^{-1}; Station 317: Salinity = 9.66 - 0.00024 Q - 0.3806 P - 0.00655 WL +0.6297 S^{-1}, and Station 326: Salinity = 2.92- 0.00007 Q - 0.1522 P + 0.8728 S^{-1}, - 0.4220 S^{-2}, + 0.2511 S^{-3} where Q = total monthly Mississippi River Discharge (m^3s^{-1}), P = total monthly precipitation (cm), WL = de-trended water level at Grand Isle (cm), S^{-1} = salinity (ppt) of previous month, S^{-2} = salinity (ppt) two months previous, S^{-3} = salinity (ppt) three months previous.

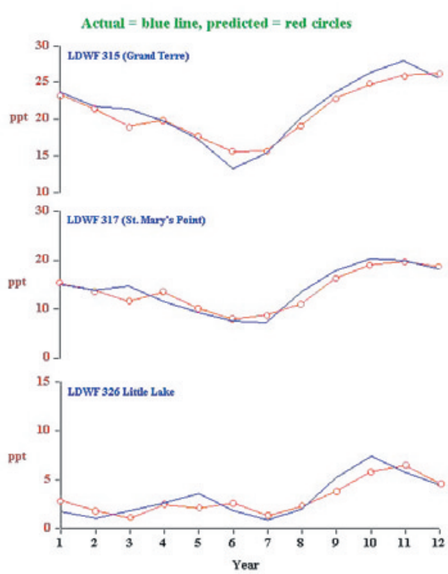

Figure 14. Measures (blue line) and predicted (dashed red line with circles) mean monthly salinity pattern for the LDWF Grand Terre station (top), the LDWF St. Mary's Point (middle) and the LDWF Littlt Lake station (bottom) in the Barataria estuary system in Louisiana. The values are the mean monthly values of data from 1995 through 2000.

9.3.2 Potential Salinity Changes in Barataria Bay, Louisiana

The model results are presented in Figures 15 through 17. These figures only present the results for changes in Mississippi discharge and changes in precipitation. The changes due to coastal water level changes were very small in all cases. The results were similar at all three stations, with changes in Mississippi River discharge resulting in the majority of the salinity changes. The greatest change occurs from January through July. Taking the worst case scenario (30 percent change in the Mississippi occurring with a 10 percent change in precipitation), the analysis predicts changes of ~3 ppt at Grand Terre, and St. Marys' Point, and ~1 ppt at Little Lake.

Orlando et. al., (1993), classified estuaries around the gulf into 5 major categories ranging from stable to highly variable depending upon whether or not the salinity is controlled by one dominant forcing function or multiple forcing functions (Table 6). The stable systems are characterized by two extreme cases: (1) Type 5 systems such as Atchafalaya Bay, Louisina that have an extremely large freshwater source which prevents significant saltwater intrusion, thus maintaining relatively low salinity variability, and (2) Type 1 systems such as Laguna Madre, Texas where the salinity is always close to the Gulf level and also exhibits relatively low salinity variability. The variable systems (Types 2 – 4) range between these two extreme cases depending upon the relative contribution of freshwater inflow and tidal forcing. The systems exhibiting the highest level of variability (Type 3) are those where the salinity is controlled by multiple factors with freshwater inflow and tidal forcing being of equal dominance (e.g. Apalachicola Bay, Florida). The Type 2 systems are those where the salinity is controlled by multiple forces, but the

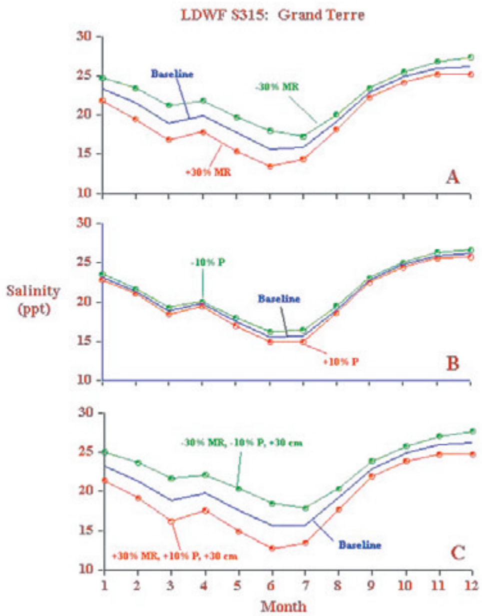

Figure 15. Grand Terre (LDWF S315) baseline salinity conditions, as defined by the autoregressive model (blue line) and predicted salinity changes due to: **(A)** a 30 percent increase (red circle) or a 30 percent decrease (green circle) in Mississippi discharge; **(B)** a 10 percent increase (red circle) or a 10 percent decrease (green circle) in precipitation; **(C)** a 30 percent increase in Mississippi discharge and a 10 percent increase in precipitation (red circle) or a 30 percent decrease in Mississippi discharge and a 10 percent decrease in precipitation (green circle).

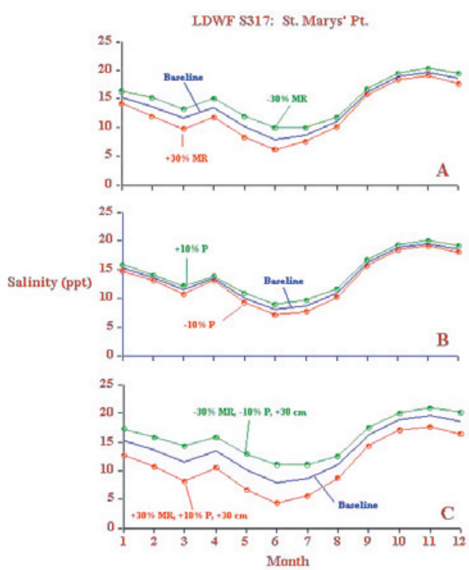

Figure 16. St. Marys' Point(LDWF S317) baseline salinity conditions, as defined by the autoregressive model (blue line) and predicted salinity changes due to: **(A)** a 30 percent increase (red circle) or a 30 percent decrease (green circle) in Mississippi discharge; **(B)** a 10 percent increase (red circle) or a 10 percent decrease (green circle) in precipitation; **(C)** a 30 percent increase in Mississippi discharge and a 10 percent increase in precipitation (red circle) or a 30 percent decrease in Mississippi discharge and a 10 percent decrease in precipitation (green circle).

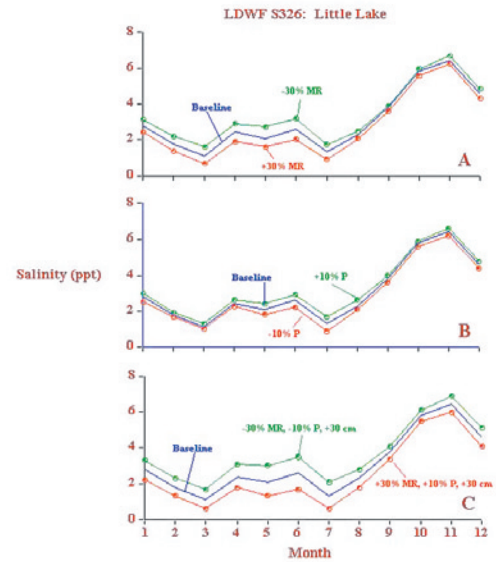

Figure 17. Little Lake (LDWF S326) baseline salinity conditions, as defined by the autoregressive model (blue line) and predicted salinity changes due to: **(A)** a 30 percent increase (red circle) or a 30 percent decrease (green circle) in Mississippi discharge; **(B)** a 10 percent increase (red circle) or a 10 percent decrease (green circle) in precipitation; **(C)** a 30 percent increase in Mississippi discharge and a 10 percent increase in precipitation (red circle) or a 30 percent decrease in Mississippi discharge and a 10 percent decrease in precipitation (green circle).

tidal forcing predominates (e. g. San Antonio Bay, Texas).). The Type 4 systems are those where the salinity is controlled by multiple forces, but the riverflow predominates (e. g. Mobile Bay, Alabama).

The data from Orlando et. al. (1993) were analyzed to look at salinity changes that occur in the Gulf of Mexico estuaries with current changes in freshwater for high and low freshwater input years. The overall data are shown in Figure 18 that pres-

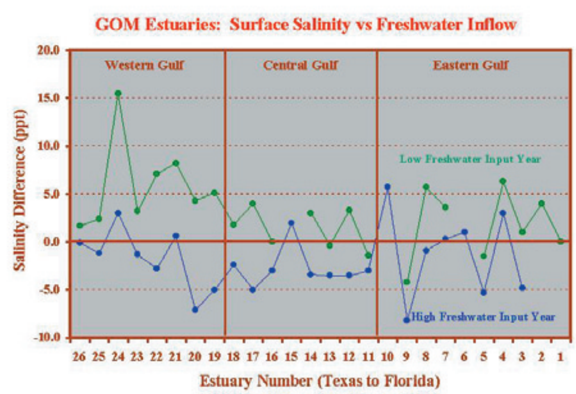

Figure 18. Changes in surface salinity (in ppt) for 26 estuaries around the Gulf of Mexico resulting from either a high freshwater input year (blue circles) or a low freshwater input year (green circles). Data are from Orlando et. al. (1993), and updated as part of this study.

Table 6 Classification for Gulf of Mexico estuaries based on salinity variability as it relates to the character of the forcing functions. Listed, for each estuary type, is the stability level the forcing function and salinity variability characteristics, and example estuaries. This Table was adapted from data found in Orlando et. al. (1993).

Type	Description	Characteristics	Examples
1	Stable	1. Salinity controlled by one factor. 2. Lack of dominant and continuous freshwater source 3. Salinity always at or near Gulf Salinities. 4. Very low to low salinity variability at all time scales.	Tampa Bay, FL Corpus Christie Bay, TX Sarasota Bay, FL Laguna Madre, TX
2	Variable	1. Salinity controlled by multiple factors. 2. Riverflow component important, tidal flow dominates 3. Medium to high variability at day-week time scales. 4. Low variability at day-week time scales. 5. Low to medium salinity variability at yearly time scales	San Antonio Bay, TX Terrebonne/Timbalier, LA Aransas Bay, TX Barataria Bay, LA Apalachee Bay, FL
3	Variable	1. Salinity controlled by multiple factors. 2. Riverflow and tidal flow are equal. 3. Medium variability at day-week time scales. 4. High variability at day-week time scales. 5. Medium salinity variability at yearly time scales.	Suwanne River, FL Perdido Bay, FL Pensacola Bay, FL Apalachicola Bay, FL Mermantau River, LA
4	Variable	1. Salinity controlled by multiple factors. 2. Tidal flow component important, river flow dominates 3. Low variability at day-week time scales 4. Medium variability at day-week time scales. 5. Low to Medium salinity variability at yearly time scales	Sabine Lake, LA-TX Mobile Bay, LA Breton Sound, LA Galveston Bay, TX Calcasieu Lake, LA
5	Stable	1. Salinity controlled by one factor. 2. Lack of dominant saltwater source. 3. Salinity values always quite low except for extreme 4. Low salinity variability at all times scales	Atchafalaya Bay, LA Lakes Pontchartrain, LA Clealeleur Sound, LA Mississippi Sound, LA

ents the changes in surface salinity (from normal) for high and low freshwater input years. The data show a general trend of salinity decreases of 2 to 5 ppt for high freshwater input years and increases of 5 to 7 ppt for low freshwater input years. There are a few exceptions to the overall pattern which is to be expected since this is a very limited data set. In general, however, these changes are the types of changes that might be expected.

9.4 Discussion

9.4.1 Impacts of Predicted Salinity Changes in Barataria Bay, Louisiana

In general, the predicted salinity changes are fairly small (3 ppt or less). Boesch et. al., (2000) state that major changes in salinity would be required before shifts in the saline marsh communities would occur. In the brackish-intermediate sections of the Barataria system however, these predicted changes, although small, could result in some minor species shifts along the vegetative community boundaries. Sasser, et. al., (2001) documented increases in polyhaline and mesohaline vegetation and decreases in oligohaline and fresh vegetation types in the Barataria Bay system as a result of the recent (1999-200) high salinity event in that system.

9.4.2 Implications for Other Gulf of Mexico Estuaries

The two climate models (Hadley and Canadian) used for the basis for this study give conflicting estimates of the potential changes in the hydrologic cycle (Boesch et. al. 2000). In general, there is low confidence in the predicted precipitation changes on a regional level (Adams, D. B. and P. H. Gleick, 2000). This makes it difficult to assess the impacts around the Gulf of Mexico without detailed data from each estuarine system as was utilized in the Barataria assessment. However, some general statements regarding possible impacts can be made. The stable systems such as Lagiuna Madre, Texas, or Atchafalaya Bay, Louisiana should not be affected by changes in the forcing functions that may result from global climate change, provided the changes are on the order of those predicted for the Barataria Bay, Louisiana estuary (1 – 3 ppt). These systems will only be effected by extremely large changes in the environmental forcing functions. The Types 2, 3, and 4 systems are the systems that would exhibit the greatest response to climate change due to their dynamic nature. In these systems, however, a negative change in one forcing function may be offset by a positive change in another forcing function. For example, in the Barataria System, a decrease in the local precipitation would lead to an increase in estuarine salinity, however, an increase in Mississippi River discharge occurring at the same time could offset this salinity increase.

9.5 Conclusions

This case study has yielded some insight on the potential changes in estuarine salinity that may occur as a result of global climate change. This was accomplished through the development of statistical models to explain the observed salinity signal, in relation to forcing functions, at one (Barataria Bay, Louisiana) of the many estuaries around the northern Gulf of Mexico. In order to more adequately address the issue around the Gulf, this type of detailed analysis should be conducted on several representative estuaries in order to cover the wide range of salinity variability observed in the Gulf of Mexico estuaries. The major findings of this case study are summarized below:

- Estuaries in the northern Gulf of Mexico are influenced by (1) exchange between the estuarine waters and the waters in the coastal zone; and (2) local forcing (river discharge, precipitation) occurring within the estuary proper.

- The Mississippi-Atchafalaya discharge dominates the input in the central portion of the Gulf, while the western (Texas) and eastern (Mississippi to Florida) portions of the Gulf are more heavily influence by local river flow.

- The northern gulf of Mexico precipitation-evaporation exhibits a general characterized by a decrease in precipitation from east (Florida) to west (Texas), while surface evaporation rates generally increase from east to west across the Gulf. This results in an overall pattern in which there is a precipitation deficit in the western part of the Gulf (and southern Florida) and a precipitation surplus in the central portion of the Gulf.

- Isohaline data from the Barataria estuary in Louisiana indicated that a change from low rainfall to high rainfall shifts the 5 ppt isohaline ~15 km south, and the 15 ppt isohaline ~8 km south, and a change from low Mississippi River discharge to high Mississippi River discharge shifts the 5 ppt isohaline 20 km south, and the 15 ppt isohaline ~10 km south.

- The Mississippi River discharge exhibits a seasonal pattern in which the maximum discharge of ~22,000 m^3sec^{-1} occurs in April, and the minimum discharge of ~6,000 m^3sec^{-1} occurs in September.

- The mean monthly coastal water levels (at Grand Isle, Louisiana) show a pattern in which there are two peaks. One is in May-June and the second (and larger) is in September-October. The water level at Grand Isle also exhibits a statistically significant trend (which is also a major portion of the signal) of ~1.17 cm yr^{-1} over the time period from 1955 through 2000.

- The time period from the fall of 1999 through the end of 2000 was characterized by an extended and severe drought, low Mississippi River discharge, and low coastal water levels. This time period was also characterized by the highest salinities on record.

- Regression models (SAS, 1988) were used to look at the importance of Mississippi River discharge, the Palmer Drought Severity Index, rainfall, and coastal water levels on salinity in the Barataria estuary, Louisiana.

- Climate model predictions are for increases in precipitation on the order of 10% for all of the Gulf states, except Florida. The predicted changes for streamflow are, in most cases, still uncertain. The effect of climate change on Mississippi River discharge is the most important consideration for the Louisiana estuaries. Boesch et. al., (2000) present data indicating that the Hadley model predicts an increase of ~5%, and the Canadian Model predicts a decrease of ~35% for the Mississippi River discharge over the time period from 2025 through 2034. They further state that the Hadley model predicts an increase of ~50%, and the Canadian Model predicts a decrease of ~30% for the Mississippi River discharge over the time period from 2090 through 2099, and sea level is predicted to increase on the order of 30 centimeters by 2100.

☼ The most successful models were those that contained an autoregressive term. The model for station 315 (coastal station at Grand Terre) explained a total of 72 percent of the observed signal, with the linear portion of the model explaining 48 percent, using Mississippi River discharge, precipitation, Grand Isle water levels, and the previous months salinity. The model for station 317 (mid-estuary station at St. Marys' Point) explained a total of 74 percent of the observed signal, with the linear portion of the model explaining 41 percent, using Mississippi River discharge, precipitation, Grand Isle water levels, and the previous months salinity. The model for station 326 (upper-estuary station in Little Lake) explained a total of 63 percent of the observed signal, with the linear portion of the model explaining 16 percent, using Mississippi River discharge, precipitation, and the previous 3 month's salinity.

☼ The yearly salinity patterns were calculated for the following scenarios, and compared to baseline conditions, using the models developed for the prediction of salinity from the forcing functions: (1). An increase (or decrease) of 30 % in Mississippi River discharge; (2) An increase (or decrease) of 10 % in local precipitation; (3) An increase (or decrease) of 10% in local precipitation; (4) An increase of 30 cm in water levels; (5) Combinations of (1) through (4).

☼ The results were similar at all three stations, with changes in Mississippi River discharge resulting in the majority of the salinity changes. Taking the worst case scenario (30 percent change in the Mississippi occurring with a 10 percent change in precipitation), the analysis predicts changes of ~3 ppt.

☼ Literature data for Gulf of Mexico estuaries (Orlando et. al., 1993) show salinity decreases of 2 to 5 ppt for high freshwater input years and increases of 5 to 7 ppt for low freshwater input years. These are the magnitude of the salinty changes that might be expected with global climate changes.

☼ The predicted salinity changes for the Barataria estuary would likely have little impact in the salt marsh. In the intermediate sections of the system, these predicted changes, could result in minor species shifts along the vegetative community boundaries.

☼ For estuaries around the Gulf, assuming the impacts to be on the order of the Barataria system (~ 3ppt), large scale negative impacts would not be expected. A majority of these systems are influenced by multiple forcing functions, thus a negative change in one forcing function may be offset by a positive change in another forcing function.

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Chapter 10

Assessing and Modeling Flood Event and Climate Change in the Gulf Coast Region

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Summary

A wide variety of regional assessments of the potential water-related impacts from climate changes have been conducted over the past two decades using different methods, approaches, climate models, and assumptions. Several studies have suggested that projected changes in temperature and precipitation along with anthropogenic activities could have significant influences upon the impacts of extreme flooding events. A promising modeling approach has been developed linking the General Circulation Models (GCMs) to hydrologic models and results from this linked modeling system have been applied for flood control planning and management. A good understanding of the current conditions and future trends is critical to conducting any climate change impact assessment. The purpose of this case study is to contribute to the Gulf Coast regional assessment through credible evaluation of the potential consequences of climate change with a focus on extreme flood events. Establishment of regional hydrologic and climatic baseline conditions, climate forcing scenarios, an hydrologic simulations and analysis were conducted in this case study.

In this case study, the Canadian General Coupled Model (CGCM2, hence referred to as the Canadian model) was integrated with the Soil and Water Assessment Tool (the SWAT model) to assess the vulnerability of flood events in the Gulf Coast region to its projected changes in climate. The predictions were dependent upon the specific assumptions employed regarding future changes in climate (the Intergovernmental Panel for Climate Change, IPCC, 2000; the National Assessment Synthesis Team, NAST, 2000), as well as the particular methods and models applied in this analysis (Khairy, 2000). All other hydrologic characteristics remained constant during the study period (1938-2100). Therefore, the results extracted from this study can be considered direct impacts of the applied projected climate scenarios. To interpret these projections, it is important to bear in mind that, uncertainties regarding the character, magnitude and rate of future climate change remain. These uncertainties impose limitations on the ability of scientists to project impacts of climate change, particularly at sub-regional scale.

The hydrologic and anthropogenic activities baseline conditions, which are the actual existing conditions based on the period (1983-2000), were established for the Tangipahoa watershed in southeastern Louisiana (518,600 acres). The geographic location of Tangipahoa watershed is in the center of the Gulf Coast region. The hydrologic and topographic conditions of Tangipahoa watershed are the average (typical) among the Gulf Coast region basins. Therefore, Tangipahoa watershed was considered a good prototype for the entire Gulf Coast region. The existing hydrologic baseline conditions were established and the performance of the SWAT model was evaluated and verified. This study considered detailed time series of projected climate forcing parameters as well as hydrologic processes for the period (1938-2100).

The Canadian model projected future trends of precipitation, temperature, solar radiation, and humidity in the Gulf Coast region over the next 100 years. The Canadian model projects that the mean annual surface temperature of the Gulf Coast region will increase by 5 – 8 ^{o}C, annual precipitation will increase by 7 – 10 %, and there will be increased variability in precipitation and temperature patterns by year 2100.

Projected change in annual stream flow of the Tangipahoa River using the SWAT model and based on the Canadian model projected climate forcing scenarios indicated potential projected increases as well as decreases. Seasonal changes in surface runoff also could be substantial. The climate change scenarios suggested increased winter precipitation, which could result in increased surface runoff in the Tangipahoa River flow in winter and spring. On the other hand, the projected climate scenarios showed reductions in summer precipitation and as a result lower summer soil moisture levels could occur, which could result in significant declines in summer and autumn surface runoff. Due to the differences in scale (spatial and temporal resolutions) between the regional Canadian model and the local SWAT model, uncertainty levels in predicting stream flow and extreme flood events using the current coupled climate and hydrologic models could be introduced. This scaling problem was treated in this study by applying a disaggregation technique and introducing correction factors for the projected climate parameters before being used by the SWAT model.

The annual average stream flow trend that was estimated within this study for the period 1938 – 2100 using the SWAT model indicated significant increase in the Tangipahoa River projected discharges over the next 100 years. Using the SWAT model, the Tangipahoa River annual average discharge recorded 892 cfs, 1,319 cfs, and 1,286 cfs during the periods 1938 – 1999, 2000 – 2049, and

2050 – 2100, respectively. This trend suggests that stream flow of the Tangipahoa River could be decreased during the second half of this century, but still the flood hazard will remain since the average annual discharge is expected to exceed the current records by about 44%. Based on the Tangipahoa watershed assumption as a good prototype for the Gulf Coast region, flood hazard possibility in the Gulf Coast region during the next 100 years is suggested to be high, because the projected increase in annual average stream flows are suggested at 48% and 44% during the periods 2000 – 2049 and 2050 – 2100, respectively. The projected peak flow during the next 100 years is suggested almost double the current records. These results, which suggest a high possibility of stream flow rise and increased flood risk over the Gulf Coast region in the next 100 years, strongly agree with previous reported findings about expected increase in temperature, precipitation, and stream flow in the Gulf Coast region (NAST report, 2000; Watson et al., 1997; IPCC report, 2000).

Should the Canadian projections of temperature rise of 5 – 8 ^oC and precipitation increase of 7 – 10% in the Gulf Coast region in the next 100 years occur then they could have a major influence on the economics of the region. Human settlements and infrastructure are especially vulnerable to extreme flood events, and the socioeconomic impacts could be significant if the frequency and intensity of extreme flood events were to increase over the next 100 years. The human and economic impacts from significantly large floods are difficult to measure. In addition, any extreme flood events have the potential to impact recreational activities, wetlands productivity, the fish and poultry industries, and agriculture especially in Louisiana, Mississippi, and Alabama, where these activities are centered.

10.1 Introduction

Over the past few hundred years, evidence clearly indicates that human activities have started to change the balance. Originally, plant respiration and decomposition of organic matter released more than 10 times the CO_2 released by human activities; but these releases have generally been in balance during the centuries leading up to the industrial revolution. That situation caused the rapidly usage of fossil fuels in industry. The fossil fuels were formed many millions of years ago from the fossil remains of plants and animals in the geological formation of the earth. They produce carbon dioxide, which can be absorbed by terrestrial vegetation and the oceans, and added to the atmospheric carbon levels. Since the beginning of the industrial revolution, atmospheric concentrations of carbon dioxide have increased nearly 30%, methane concentrations have more than doubled, and nitrous oxide concentrations have risen by about 15%. Deforestation and the spread of intensive agriculture initiated a growth in emissions of CO_2, in the mid-18th century (Houghton, 1995). Starting in the 19th century and accelerating in the 20th century, combustion of coal, oil, and natural gas has led to additional emissions (Andres et al., 2000). These increases have enhanced the heat-trapping capability of the earth's atmosphere. Combustion of fossil fuels is currently a significant source of emissions to the atmosphere (IPCC, 2000).

The earth's climate is predicted to change because human activities are altering the chemical composition of the atmosphere through the buildup of greenhouse gases (primarily carbon dioxide, methane, and nitrous oxide). Carbon dioxide alters the radiative balance and tends to warm the atmosphere. The heat-trapping property of these gases is still undisputed clearly. Although uncertainty exists about exactly how earth's climate responds to these gases, global temperatures are rising. Estimating future emissions is difficult, because it depends on demographic, economic, technological, policy, and institutional developments. Several emissions scenarios have been developed based on differing projections of these underlying factors. For example, by 2100, in the absence of emissions control policies, carbon dioxide concentrations are projected to be 30-150% higher than today's levels (Ning and Abdollahi, 1999; Harvey, 2000; Mitchell et al., 2000). Sulfate aerosols, a common air pollutant, cool the atmosphere by reflecting light back into space; however, sulfates are short-lived in the atmosphere and vary regionally. Aerosols, which have an opposite effect on the atmosphere's radiative balance tends to cool the atmosphere. Aerosols can have important conse-quences for continental-scale patterns of climate change (Watson et al, 1997).

There has been an increase in the global atmospheric content of carbon dioxide by about 9% since the mid-1970 (Weber et al., 1993). Carbon dioxide allows incoming short-wavelength energy to reach the earth from the sun, but impedes the return radiation from the earth as longer wavelengths. This has led to a temperature increase of 1^oC and the heating of the ocean as well as the melting of land-based glaciers have led to an increase in sea level of 10 cm over the last century (Nakicenovic et al, 2000). It is predicted that there will be a further rise of 1.5 to 4.5°C and sea level is predicted to rise 50 cm by 2050, and 1m by 2100 (Moore III, 1999). Global mean surface temperatures have increased 0.2 – 0.6°C since the late 19th century. The 20th century's 10 warmest years all occurred in the last 15 years of the century. Of these, 1998 was the warmest year on record. The snow cover in the Northern Hemisphere and floating ice in the Arctic Ocean had decreased. Globally, the sea level has risen 4 – 10 inches over the past century (Leatherman et al., 2000).

Worldwide precipitation over land has increased by about 1%. The frequency of extreme rainfall events has increased throughout much of the United States. Over the US, precipitation has increased by 5-10% on average (Watson et al, 1997). Evaporation will increase as the climate warms, which will increase average global precipitation. Soil moisture is likely to decline in many regions, and intense rainstorms are likely to become more frequent. Calculations of climate change for specific areas are much less reliable than global ones, and it is unclear whether regional climate will become more variable. Global climate change could also change the frequency and severity of inland flooding, particularly along rivers.

General Circulation Models (GCMs) suggest that some regions of the United States may have more rainfall in the future during the wet season, which could increase river and lake levels. One of these areas the Gulf Coast region (The National Assessment Synthesis Team report, 2000). The most flood-prone communities of the United States are at least partly protected by levees and reservoir flood-storage capacity. Large sections of the upper Mississippi/Missouri River basins experienced major flooding during the summer of 1993. The Mississippi/Missouri River floods of 1993 illustrated that the protection systems are designed to prevent the relatively frequent, moderately destructive floods (up to 100-yr occurrence floods), those with at least a 1% chance of occurring in any given year. However, these systems are overwhelmed and almost completely ineffective against the rare flood that is more devastating than the flood the system was designed to handle (e.g., 500-yr floods).

10.2 Methods of Study

The approach followed in this study consists of five stages: 1) establishing the hydrologic conditions and verifying the model used for estimated flood events; 2) projecting the climate change in the period (2000 – 2100); 3) estimating the expected flood events based on the projected climate change and the already established hydrologic model; 4) assessing the implications of climate change and anthropogenic activities; and then 5) discussing the control of floods.

10.2.1 The Study Area Description

This study was limited to the Tangipahoa River watershed within the Gulf Coast region. The geographic location of Tangipahoa watershed is in the central part of the Gulf Coast region. The hydrologic and topographic conditions of Tangipahoa watershed can be considered the average (typical) among the Gulf Coast region basins. Therefore, Tangipahoa watershed can be considered a fairly good prototype for the whole region. Assumption of generalizing the findings of this case study to be relevant for the entire Gulf Coast region was specified in this study. This assumption might not be accurate enough in the coastal areas near to the Gulf Coast where significant climate variability may occur in some months during the year. Chapter 9 of this book "Assessing the Potential Climate Change Impacts on Salinity in Northern Gulf of Mexico" stated that there are large differences in the various estuaries of the Gulf Coast region with various amounts of freshwater inputs. Even so, this study can give overall indication about the impact of climate change on extreme flood events in the entire Gulf Coast region.

The Tangipahoa River Watershed

Tangipahoa River watershed, in southeastern Louisiana (LA) has a total area of 518,600 acres (about 1,900 km^2). The northern portion of Tangipahoa watershed extends into Pike County in Mississippi (MS). Tangipahoa Parish, which includes the majority of Tangipahoa watershed, is 536,148 acres, of which 22,228 acres are lakes, bayous, and rivers (USDA and SCS, 1990). Tangipahoa Parish is bordered on the north by Amite and Pike Counties; on the south by Lake Pontchartrain, Lake Maurepas, and St. John the Baptist Parish; on the east by St. Tammany and Washington Parishes; and on the west by Livingston and St. Helena Parishes as shown in Figures 1 and 3. According to the 1980 census, Tangipahoa Parish population was 80,698. About 65% of the Parish population is in rural areas.

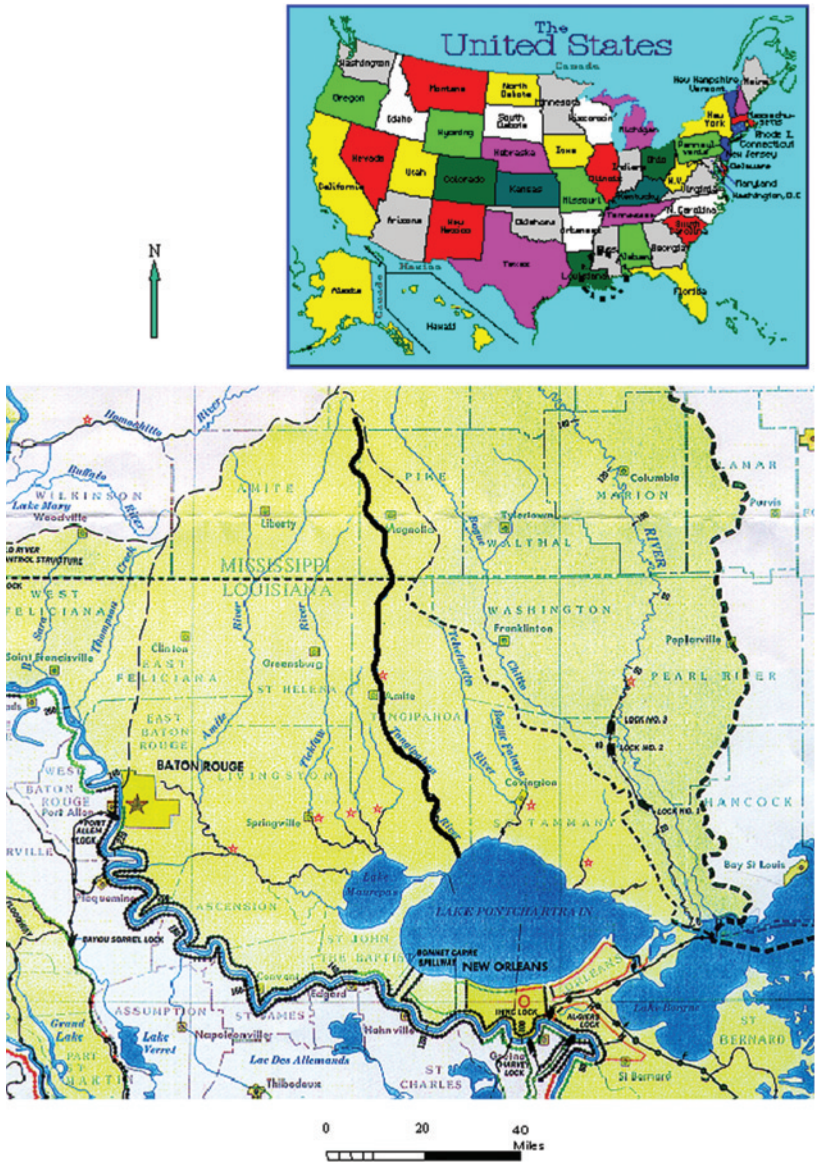

Figure 1. Lake Pontchartrain Basin, Louisiana State, USA

The Tangipahoa River is a popular recreational resource for MS and LA. In MS, the Tangipahoa River is classified as a fish and wildlife preserve; however, in the last decade the primary contact recreation activities were prohibited during the summer months due to recorded high pollution loads. In LA, the River is listed as a wild and scenic stream by the Louisiana Scenic Streams Program and is used for recreational contact. Both states have designated the Tangipahoa River as a targeted watershed in their non-point source management program reports. By this designation, the River has been identified as being potentially impaired by agricultural non-point pollution sources.

History

The name Tangipahoa is derived from the Indian village, which was located north of Lake Pontchartrain. The "Tangibao," corncob people or corn gatherers, were mentioned in accounts of French explorers dating back to 1683 (Nicholes, 1979). The Indian heritage of Tangipahoa Parish is most evident in the place names of Indian origin. Because of an increase in population and the resulting municipal needs, Tangipahoa Parish was created in 1869 from the western parts of St. Tammany and Washington Parishes and the eastern parts of Livingston and St. Helena Parishes (Lanier, 1969).

Historic Floods

Over half of the nation's costliest weather-related disasters of the past 20 years have occurred in the Southeast (where the Gulf Coast region is located), costing the region over $85 billion in damages, mostly associated with flood and hurricanes (NAST Overview Report, 2000). The Mississippi basin, the largest river basin in the United States, forms a wedge of 1,243,000 square miles (3,220,000 sq. km.) in the center of the continent. As the Mississippi River system drains toward the Gulf of Mexico, the basin narrows, centering on the state of Louisiana. Although the basin stretches into the alpine pastures of the Rocky Mountains and the wooded valleys of the Appalachians, it covers mainly the rich grain belts of the Midwest and the Great Plains. Thirty-one states and two Canadian provinces contribute water to the Mississippi system. Figure 2, which is a false color image taken over St. Louis, Missouri on July 29, 1993 using a special NASA airborne scanner, shows the study area of St. Charles and the Missouri River. It also shows a portion of St. Louis and the Mississippi and Illinois rivers at flood stage (Baumann, 1996).

The Mississippi River system in the Gulf Coast region has experienced several major floods within the 20th century. Until the 1993 flood, the 1927 flood was considered the greatest inundation of the river. Over 700,000 people were forced to leave their homes; 246 people and 165,000 head of livestock drowned; and property damage exceeded $364 million. In 1937, heavy rains drenched the lower Mississippi, creating a lake nearly the size of Lake Superior in area. Several smaller floods in the 1940s and 1950s plagued the basin and extreme floods hit the upper basin in 1965 and 1973. Unusually high precipitation combined with soil saturation from earlier precipitation significantly contributed to the 1993 Mississippi River flood (Kunkel et al., 1994). The 1993 flood was concentrated in the upper Mississippi basin (Iowa state) and the middle and lower sections of the Missouri basin (Missouri and Ohio states). The Ohio basin, which generally accounts for about 70 percent of the total volume within the system, was not experiencing any major flooding. The discharge from the Ohio basin was being controlled during the flood period by holding water back in the numerous reservoirs on the river and its tributaries. The much larger channel and floodplain of the lower Mississippi River reduced greatly any flooding in the lower Mississippi valley. The 1993 Mississippi River flood caused wide dispersal of microorganisms and chemicals from agricultural lands and industrial sites.

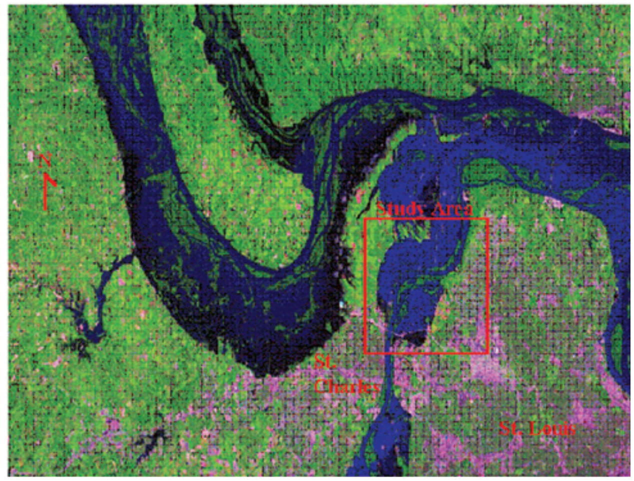

Figure 2. The Affected areas in Iowa, Missouri, and Ohio states by the 1993 Mississippi River Flood (source: Baumann Flood Analyses Report, 1996).

Within the flooded area, the 1993 flood reached record levels. On the upper Mississippi at Keokuk, Iowa, peak discharges exceeded significantly the previous record discharges in 1973 and 1851 and went well above the 100-year flood mark. At Boonville, Missouri, the 1993 peak discharge on the Missouri matched the 1844 flood and exceeded the 1951 and 1903 floods, all three of which were identified as 100-year or greater floods. The discharge could have been higher than the estimated 1844 peak discharge if it was not for a number of reservoirs within the upper and middle Missouri basin holding water back. The upper Mississippi basin does not have as large reservoirs as the Missouri. At St. Louis, where the Missouri and upper Mississippi merge, the 1993 peak discharge was above the 100-year flood mark, but below the 1844 level. Again, flood control through dams held the 1993 flood discharge level down; these dams and their large reservoirs did not exist in 1844.

The 1999 North Carolina flood, resulting from Hurricane Floyd, offers a recent example of the massive dislocations and multi-billion dollar costs that often accompany such events. Dams and levees have also saved billions of dollars of investment, but these facilities, together with insurance programs, encourage development in floodplains, thereby indirectly contributing to damages (Frederick and Schwarz, 1999b). In addition, structural flood control features have high environmental costs. Climate change may affect flood frequency and amplitude, with numerous implications for maintenance and construction of infrastructure and for emergency management. Erosion and deposition rates in rivers and streams are likely to change under different precipitation regimes. The reduction in reservoir construction

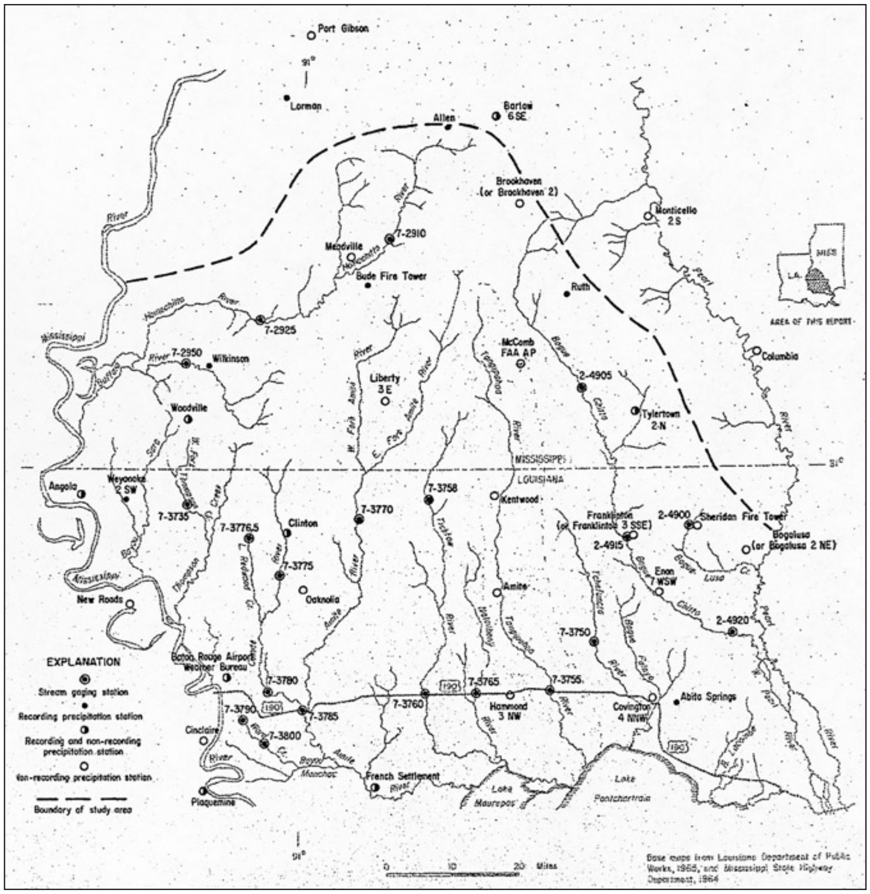

Figure 3. The Main Cities and Weather Stations in Lake Pontchartrain Basin

along with the buildup of sediment in reservoirs will affect the resilience of water supply systems and their ability to handle flood flows.

In the United States, flash floods — enormous land inundation due to extensive rainfall or hurricane events that much more above the stream system capacity, currently are the leading cause of weather-related mortality. The Gulf Coast region is subject to such extreme flood events especially during the hurricane season (late summer and fall of each year). In addition to causing deaths by drowning, flooding can lead to widespread destruction of food supplies and outbreaks of disease as a result of breakdowns in sanitation services. Flooding also may result in the release of dangerous chemicals from storage sites and waste disposal sites into floodwaters. Increased runoff from agricultural lands during periods of heavy precipitation also can threaten water supplies (Karl and Knight, 1998; Knutson and Tuleya, 1999, Meehl et al., 2000).

Geology of the Regional Aquifer System

The Gulf of Mexico Coastal Plain is a gently rolling to flat region of about 670,000 km^2 extending from the southern tip of Illinois to the Laguna de Te'rminos near the southwestern terminus of the Yucata'n peninsula (Grubb and Carrillo, 1988). It is underlain by a Gulfward-thickening wedge of unconsolidated to semi-consolidated sedimentary rocks of Cenozoic age (Hanshaw and Bredehoeft, 1968).

Groundwater is present in a complex series of alternating beds of sand and clay. The beds dip gently southward (on the order of 25 ft/mi) as a result of down warping on the southern flank of the Southern MS uplift. The dip increases progressively toward the coast as a result of subsidence caused by the sediment out-land migration and deposition in the Gulf of Mexico. The Southern MS uplift structural trough, a downwarp that parallels the present Mississippi River valley, is the geologic structure that affects the regional groundwater flow patterns (Grubb, 1984). The alternation of sand forms aquifers and the beds of clay form confining units between the aquifers. The LA southeastern aquifer system is defined as the succession of beds of sand and clay from the land surface to the base of the "1,200-foot" aquifer. The surficial deposits in the aquifer outcrop area consist of clay and interbedded thin beds of sand.

Climate

In winter the average temperature is 11^{O}C, and the average daily minimum temperature is 4^{O}C. The lowest temperature on record, which recorded at Amite weather station (as shown in Figure 3) on January 12, 1962, was –13^{O}C. In summer the average temperature is 27^{O}C, and the average daily maximum temperature is 33^{O}C. The highest temperature recorded was on July 1, 1954 as 40^{O}C. The monthly heat unit accumulation is used to schedule single or successive plantings of a crop between the last freeze in spring and the first freeze in fall. The daily maximum and minimum temperature records and the air temperature seasonal variability in Tangipahoa watershed are shown in Appendix I.

The average total annual precipitation is 34 inches. Of this, 19 inches, or 55%, usually falls between April and September. The growing season for most crops also falls within this period. In two years out of ten, the rainfall from April through September is more than 27 inches. The heaviest 1-day rainfall during the period of record was 8.55 inches at Amite on September 6, 1977. Thunderstorms occur on about 70 days each year, mostly in the summer. Snowfall is rare in the Tangipahoa watershed. In 90% of the winters, there is no measurable snowfall. In 10% of the winters, the snowfall is usually of short duration but more than 2 inches in depth. The average relative humidity in mid-afternoon is about 60%. Humidity is higher at night, and the average at dawn is about 90%. The sun shines 70% of the time in summer and 50% in winter. The prevailing wind is from the southeast. The maximum wind speed is at the average of 10 miles per hour in spring (USDA, et al., 1991). The daily rainfall depths are measured at Hammond, Amite, Kentwood, and McComb rain-gauge stations on regular basis. Rainfall historical records at those stations are illustrated in Appendix I.

Land Use

The Tangipahoa area consists primarily of forests and agricultural land. According to the 1982 annual report of the Louisiana Cooperative Extension Service, there were 1,267 farms in the Tangipahoa area. The average size of a farm in 1978 was about 133 acres, and by 1983 it had decreased to about 122 acres. In 1982, 3% of the total population was employed by agriculture industries. In 1983, there were 349 dairies in the area; 92,512 acres were cropland; and 48,989 acres were pastureland. The wetlands in the Tangipahoa watershed are located downstream of the Robert Bridge (which is located at the intersection of Highway 190 with the Tangipahoa River as shown in Figure 3). It constitutes about 2% of the total Tangipahoa basin. Those wetlands are covered with weeds and aquatic plants most of the year. The dominant land use/land cover (LULC) in the Tangipahoa watershed were estimated based on the U.S. Department of Agriculture (USDA) Census of Agriculture data during the period (1980-1996) and are shown in Table 1. LULC spatial distribution that was used for simulating the baseline hydrologic condition of the Tangipahoa watershed is discussed under 3.3.2.

Table 1 Dominant Land Uses in the Tangipahoa Watershed (average values for the period 1980-1996).

Land-Use	Acres	Percentage (%)
Crop Land	25,930	5
Pasture Land	155,580	30
Forest Land	305,974	59
Urban Land	15,558	3
Other Land*	15,558	3
Total	518,600	100

* Other land includes swamps, wetland, water, barren, farmsteads, and rural roads.

Water Resources

Surface water:: the Tangipahoa River and its tributaries are the major conveyers of surface water in the Tangipahoa watershed. The average annual runoff of the Tangipahoa watershed at the Robert bridge location (the simulated watershed outfall point as shown in Appendix II) is about 835,496 acre-feet per year (Carlos et al., 1983). The daily and seasonal variability streamflow record plots at the Tangipahoa River outfall (Robert location) are shown in Appendix I. Also, the peak flow at Robert location and other upstream locations are shown in Appendix I. The Tangipahoa River drains its water and pollution loads into Lake Pontchartrain at its outfall as shown in Figure 1.

Groundwater: the aquifers in the Tangipahoa watershed constitute one of the largest sources of fresh groundwater in Louisiana. They yield good quality water at rates of 1,000 to 3,000 gallons per minute (Nyman and Larry, 1978). The groundwater is a sodium bicarbonate type. In most aquifers, concentrations of iron and manganese are less than 0.5 mg/l. Hardness is less than 30 mg/l, and content of dissolved solids is less than 350 mg/l. Locally, water may contain objectionable amounts of hydrogen sulfide and silica.

Soil Classification

The Tangipahoa watershed is made up of two major land resource areas: the central and northern parts, mainly in woodland, pastureland, and truck crops; and the southern part, used mainly as habitat for wetland wildlife and for recreation. Soils of the central and northern parts are loamy and predominantly moderately well drained to well drained. Soils of the southern part are loamy, predominantly poorly drained, mainly ponded, and frequently flooded. These muddy and clayey soils are in swamps and marshes. Elevation ranges from 340 ft above mean

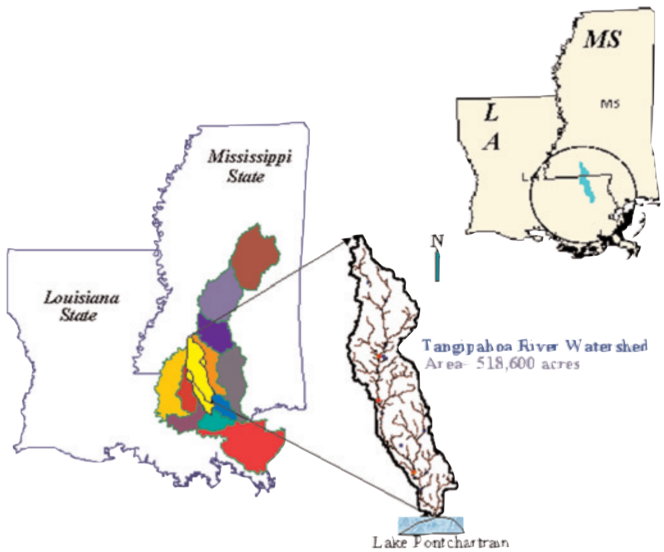

Figure 4. Location of the Tangipahoa Watershed in Lake Pontchartrain Basin.

sea level in uplands of the northern part to about 5 ft on stream or marine terraces of the southern part.

The Lake Pontchartrain Ecosystem

The headwaters of the Tangipahoa River originate in the southern portion of Lincoln County, Mississippi, approximately 30 miles north of the Mississippi-Louisiana state boundary as indicated in Figure 1. The water flows southward, entering Pike County approximately 5 miles west of Interstate Highway 55. The river continues in a southerly direction in the upper regions of Pike County. Then, it crosses into Amite County for a very short distance before re-entering Pike County and flowing directly into Lake Tangipahoa, located within Percy Quinn State Park, approximately 5 miles southwest of McComb, MS.

Lake Tangipahoa water spills from the southern area of the lake and flows, as the Tangipahoa River, in a southeasterly direction through the remaining portion of Pike County, MS, and into Tangipahoa Parish, LA. The waters continue on a south-south-easterly course across Tangipahoa Parish, flow into a wetland area and ultimately discharge directly into Lake Pontchartrain in southeast Louisiana (USDA et al., 1991). For the purpose of this research, the Robert bridge location (at the intersection of Highway 190 with the Tangipahoa River, at Lat. 30^{o} 30' 23" and Long. 90^{o} 21' 42") is hypothetically considered the outfall of Tangipahoa River, about 15 miles upstream of the Tangipahoa River mouth at Lake Pontchartrain (Figure 3). The downstream area of Robert bridge location is mainly wetlands.

The Lake Pontchartrain system in LA is a large impoundment in a complex estuary system (Figure 4). The unique mixture of biota in this ecosystem is composed of freshwater and marine species supported by physiochemical and hydrologic processes involving river inflows, exchanges with interconnected high salinity coastal waters, and interactions with surrounding watersheds, which have experienced major urban developments over the last five decades.

In 1988, Lake Pontchartrain experienced a phase of declining water quality accompanied by decreased productivity and limitations on its use for recreational activities (Ismail et al., 1998). These factors influence economic development and quality of life in this history-rich urban center of the state. Because of its proximity to New Orleans, Lake Pontchartrain has traditionally been important for such recreational activities as swimming, boating, and sport fishing. The lake produced commercial quantities of finfish and shellfish in the past, and presently supports an important commercial blue crab fishery.

10.2.2 Climate and Stream Flow Measurement Data

The purpose of this case study is to contribute to the assessment of the potential consequences of climate variability and climate change in the Gulf Coast region. The focus is the potential and the consequences of extreme flood events.

The current climate baseline conditions were established and the projected climate forcing scenarios/future trends were projected using the Canadian General Coupled Model. The climate data used for establishing the baseline and projected conditions for the Gulf Coast region were obtained from the Canadian Centre for Climate Modelling and Analyses. The established climate baseline conditions provided information needed for projecting of the climate forcing scenarios. The baseline hydrological conditions included regional historical and current data such as temperature, precipitation, stream flow, soil moisture, soil properties, crop development, and land-use practices for the period of 1938 – 2000. Data obtained from the baseline condition and projected climate forcing scenarios were used to assess and model extreme flood events over the next 100 years using the Soil and Water Assessment Tool (SWAT) model.

The Climate Data

Simulating the hydrological conditions of the study area requires historical spatial data records about daily temperature and precipitation (Neitsch et al., 1999). SWAT has a weather generator engine to predict the precipitation within an ungauged watershed based on stochastic and probabilistic methods (Richardson, 1981), however, it is more realistic to use actual rainfall measurement, especially for research purposes. The real rain data for the Tangipahoa watershed were collected using the US Geological Survey (USGS) database. Four weather stations were located inside or around the Tangipahoa watershed at Amite, Kentwood, Hammond, and McComb cities as shown in Figure 3. The Thiessen graphical method was used to allocate the daily real rain depth for each subbasin. The available rainfall and temperature data used in this study are shown in Appendix I.

The weather generator engine of the SWAT model selected the closest weather station to the center of each subbasin (Neitsch et al., 1999). The predicted daily rainfall or temperature by the SWAT model weather generator engine was used in the Tangipahoa watershed simulation only when the measured data were missing for a specific period of time during the simulation period. Also, the SWAT model weather generator engine was used to predict the solar radiation, wind speed, and relative humidity trends to be used in the hydrologic processes simulation.

The Stream Flow Measurement Data

Historical stream flow daily data of 1938 – 2000 were used to establish a powerful modeling baseline for the study area. The initial conditions for the SWAT model were created based on year 1938. The period of 1980 – 1989 was used to calibrate the model results. Finally, the period of 1990 – 1995 was used to validate the model performance.

The SWAT model hydrologic component of the stream flow (on a daily, monthly, and annual basis) was calibrated at its outlet to Lake Pontchartrain (Robert bridge location). The Robert location was considered the simulated outfall of the Tangipahoa River, since the remaining downstream portion of the watershed is wetlands (constitutes less than 3% of the whole watershed area), which was excluded from this study. The measured stream flow data of the Water Data Storage and Retrieval database (WATSTORE) of the USGS were used to calibrate the hydrologic component of the SWAT model. Long-term flow trend plots as well as peak flow comparisons were implemented at some other locations (graphs are available in Appendix I).

10.2.3 The SWAT Model Application

Recently, there has been considerable effort devoted to utilizing a Geographic Information System (GIS) to extract the SWAT model inputs data from various geographic layers (topography, soils, land-use/cover, and groundwater). This approach saves time that would be devoted to constructing the tremendous amount of input data files required, especially for large watersheds. The final effort was the development of an interface for the SWAT model (Srinivasan and Arnold, 1994) using the Graphical Resources Analyses Support System (GRASS) by the U.S. Army, 1988.

The Tangipahoa Watershed Delineation

The SWAT-GRASS interface is an interactive program used to create the necessary environment variables that are needed by the SWAT-GRASS interface project manager. Based on the aforementioned GIS map layers of resolution 5 km x 5 km, the SWAT-GRASS interface has automatically subdivided the Tangipahoa watershed into 76 subbasins, of approximately 7,000 acres each (about 25 km^2) as shown in Figure 5. Then the spatial data were extracted from the 1:100,000 scale map layers in association with the relational databases. Finally, the spatial data, e.g., soil characteristics, topography, channel geometry and schematization, land-use, weather, crop and land management have been aggregated and written to the appropriate model input data files.

Hydrologic Data Extraction

Land-use data were extracted by the SWAT-GRASS interface using a knowledge-based approach, where a set of rules along with model-supported crop database are incorporated in the programs that automate inputs required by the model using a GIS land-use map layer (Neitsch et al., 1999) as shown in Appendix II.

The SWAT-GRASS interface supports relational soil databases such as STATSGO (USDA, 1992), where each soil polygon identifier has more than 10 attribute tables. Accuracy of the soil data is limited to the accuracy and resolution of the land-use raster map used in addition to the reliability of the aggregation method used by the SWAT-GRASS interface. The topographic features, which are required for the entire basin and for each subbasin, were gathered using the GIS raster elevation map as shown in

Appendix II. The stream lengths, stream slopes, and stream dimensions were estimated (Srinivasan and Arnold, 1994) using the appropriate aggregation methods. The drainage area of each subbasin was computed along with the drainage sequence of which subbasin flows into which subbasin. Those data have been used to automate the routing structures of the Tangipahoa watershed by the SWAT-GRASS interface. Overland slope and slope length were estimated and aggregated by the mode method (Srinivasan and Arnold, 1994). Some groundwater parameters have been created for each subbasin using the groundwater *"alpha"* map (Neitsch et al., 1999). *"Alpha"* parameter is required to lag the groundwater flow as it leaves the shallow aquifer to return to the stream (Arnold et al., 1993). An *"alpha"* map has been identified in the SWAT-GRASS interface.

The Weather Data Prediction Capability

If a daily (or a period of time) record of measured weather data is not available, the SWAT model predicts it by its weather generator engine. It estimates that weather parameter based on statistical and probability approach from approximately 1130 weather stations to estimate that daily record, such as precipitation, maximum and minimum temperatures, solar radiation, wind speed, and relative humidity. The selected weather stations are based on their proximity to the study area. The SWAT also estimates the daily weather parameters for each subbasin (Khairy, 2000).

10.2.4 Data Consistency Check and SWAT Hydrologic Verification

The consistency check between the input data files of the SWAT model was implemented. It was essential to do that check since the mechanism of extraction of the data from the GIS map layers depends mainly on the resolution and accuracy of the raster maps used. The discrepancy among the input data could lead to unrealistic estimation and doubtful results.

The Stream Flow Calibration

The hydrologic calibration was conducted for the Tangipahoa watershed during the period of 1980 – 1989 then, the calibrated parameters were used for the model validity check during the period of 1990 – 1995. To setup/initialize the different parameter values for the SWAT simulation, the model has run for 10 years under the conditions of year 1979. For evaluating the stream flows predicted by the model during the calibration and validation periods, graphical comparisons and linear regression methods were used. Also, by using one of the most important statistical criteria for evaluation of hydrologic goodness-of-fit, the Nash-Suttcliffe coefficient, R^2, (Khairy, 2000; ASCE, 1993, and Suttcliffe and Nash, 1970).

Figure 5. The Tangipahoa Watershed Delineation into 76 Subbasins by the SWAT Model (based on a GIS map resolution of 5 km x 5 km).

To obtain better and more realistic simulation results, numerous changes were made to the input parameters used in the original simulation of the SWAT model on the Tangipahoa watershed (Khairy, 2000). A comparison between the simulated and observed annual average stream flow at the Tangipahoa watershed outfall (Robert location) during the calibration period is shown in Figure 6.

The SWAT model is intended as a long-term yield model and is not capable of accurate details, e.g., single-event flooding. SWAT over-estimates the storm peak flow values unless it is calibrated with high consideration for the interactive effects of a group of hydrologic input parameters at the same time using the objective function approach (Arnold and Allen, 1996). One of the major causes of the over-estimation problem of peak flow using the SWAT model is that the SWAT-GRASS interface ignores the spatial distribution of rainfall over large watersheds. Also, the storm intensity and duration are not considered in the simulation, since the SWAT model uses the SCS-CN method in calculating surface runoff. Those two causes are considered the major weak points in the SWAT model simulation.

The monthly and daily comparisons between the simulated and observed stream flow at the Tangipahoa watershed outfall (Robert location) are shown in Appendix III. The coefficient of determination (R^2) for the linear regression between the monthly observed and simulated stream flow was 0.977. The slope of the regression line was 1.306 and was marginally different from 1.0 at 95% confidence level. The average Nash-Suttcliffe coefficient during the calibration period was 0.867. The average Root Square Error and Standard Error were 0.777 and 344.783 respectively; also the average deviation (D_v) was 2.004%. Therefore, the SWAT model performance considering daily average flow rates over the entire simulation period achieved considerable success.

The modified recursive digital filter technique that was developed by Nathan and McMahon in 1990, and recommended by Arnold and Allen in 1999 was used for the base-flow calibration in the Tangipahoa watershed during the period (1984 – 1995). For more details, please see Khairy, 2000.

The Stream Flow Verification

Flow validation was conducted using the observed stream flow data at Robert location for the period 1990 to 1995. A comparison between the measured and simulated average annual stream flow at Robert location is shown in Figure 7. The time series plots of monthly observed and simulated stream flow comparison at Robert location are given in Appendix III. The figures show acceptable correspondence of simulated stream flows with the observed values. In the analyses of the scatter-plot of the observed vs. the simulated monthly stream flow values, the observed values had a strong linear relationship with the predicted results. R^2 between observed and simulated stream flow ranged from 0.864 to 0.809. The average Nash-Suttcliffe coefficient during the validation period was 0.769. The average RSE and SE were 0.759 and 371.138 respectively; also the average D_v was –1.608%. Based on that analyses, the SWAT model predicted the annual, monthly, and daily stream flow at the Tangipahoa watershed outlet satisfactorily.

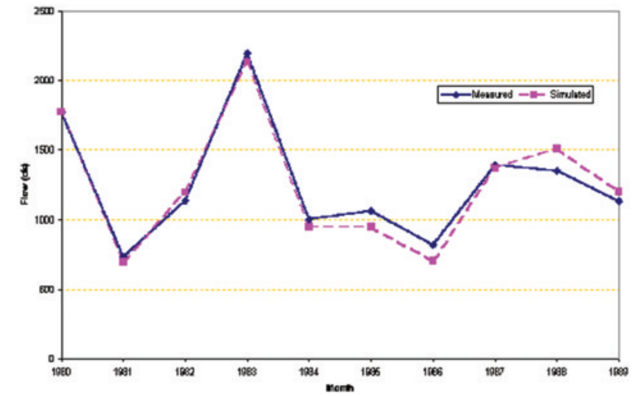

Figure 6. Simulated Against Observed Annual Average Stream Flow at the Tangipahoa Watershed Outlet (Robert location) During 1980 – 1989.

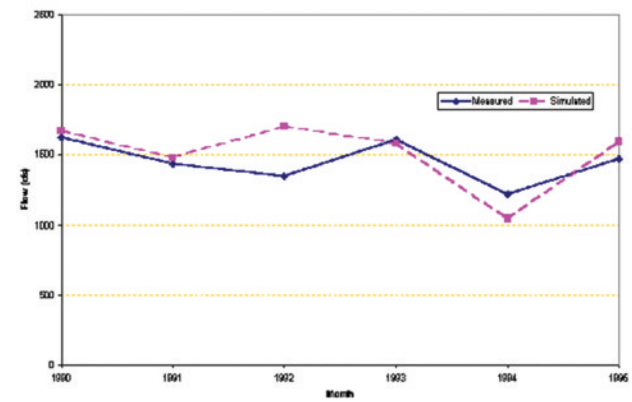

Figure 7. Simulated Against Observed Annual Average Stream Flow at the Tangipahoa Watershed Outlet (Robert location) During the Period 1990 – 1995.

10.2.5 The Climate Change Forcing and Prediction

The earth's climate is predicted to change because human activities are altering the chemical composition of the atmosphere through the buildup of greenhouse gases (primarily water vapor, carbon dioxide, methane, ozone, and nitrous oxide). The heat-trapping property of these gases is still undisputed clearly. Uncertainty exists about exactly how the earth's climate responds to these gases. Worldwide concern about possible climate changes resulting from increasing concentrations of greenhouse gases has led governments to consider international action to address this issue, particularly, through the development of the United Nations Framework Convention on Climate Change (UNFCCC). The extent and urgency of action required to mitigate the sources of the problem, namely the emission of greenhouse gases by human activities, depend on the level of human and natural resources vulnerability. This level can be defined as the degree to which human conditions and natural environment are vulnerable to the potential effects of climate change. The fundamental policy needed to tackle climate change consequences depends not only on information regarding greenhouse gas emissions and climate system changes but also on the likely impacts on human activities and the environment, e.g., extreme flood hazard, which is the primary concern of this case study.

The General Circulation Model

A key advantage of climate models is that they are quantitative and grounded in scientific measurements. They are based on fundamental laws of physics and chemistry, and incorporate human and biological interactions. They allow examination of a range of possible futures that cannot be examined experimentally. The General Circulation Model (GCM) based scenarios are the most credible and frequently used projections of climate change. Other types of climate projections include synthetic and analogue scenarios. They vary in their approaches and limitations. In addition, most climate change experiments have not accounted for human-induced landscape changes and only recently has the effect of aerosols been investigated. Both of these factors can further affect projections of climate change particularly on a smaller than global – regional scale. From the hydrologic point of view, GCMs can predict future regional climate parameters, for example, precipitation and (to a lesser extent) temperature. The use of GCM-produced scenarios with the hydrologic models adds a further degree of uncertainty in studying the hydrologic events impact assessments.

Confidence in the accuracy of climate models is growing. The best models have been carefully evaluated by the Intergovernmental Panel on Climate Change (IPCC) and have the ability to replicate most aspects of past and present climate. Two of these models have been used to develop climate projection scenarios for the U.S. climate impact assessment studies (e.g., the National Assessment Synthesis Team, Climate Change Impacts on the United States: the Potential Consequences of Climate Variability and Change, NAST, USGCRP, 2000). Projections of changes in climate from the Hadley Center in the United Kingdom and the Canadian Center for Climate Modeling and Analysis served as the primary resources for the assessment studies. While the physical principles driving these two models are similar, the models differ in how they represent the effects of some important processes. Therefore, the two primary models paint different views of 21st century climate. On average over the US, the Hadley model projects a much wetter climate than does the Canadian model, while the Canadian model projects a greater increase in temperature than does the Hadley model. Extreme flood events are more associated with wet weather conditions more than greater temperature conditions. The Canadian model might be more reasonable for this case study to avoid excessive flood predictions if the Hadley model is being used, especially because the Gulf Coast region is located close to the Equator where GCM generally over-predict worming and wetting conditions. Also, selected results of the Canadian model simulations were contributed to the IPCC Data Distribution Center to facilitate its use for climate impact studies (Boer et al., 2000 a, b). Based on this justifications, the Canadian model was selected for this case study for studying extreme flood events in the Gulf Coast region.

The Canadian model integrates the Atmospheric General Coupled Model (AGCM2) with a specially adapted version of the Modular Ocean Model (MOM) and a thermodynamic sea-ice model (Flato and Boer, 2000). The ocean mixing parameterization is included in the Canadian model through the isopycnal/eddy stirring parameterization of Gent and McWilliams, 1990. Also, sea-ice dynamics is included recently. In addition, some technical modifications were made in the ocean spinup and flux adjustment procedure. A description of the Canadian model can be found in Flato and Boer, 2000. An overview of the Canadian model is available at http://www.cccma.bc.ec.gc.ca/models/cgcm2.shtml.

Historical Climate

The time series of anomalies in mean annual temperature for the entire North American continent reveals temperatures increasing through the 1920s and 1930s, peaking around 1940, and then gradually decreasing through the early 1970s. From this point through the late 1980s, temperatures increased to levels similar to the 1940 era; they have remained mainly above normal, with the exception of 1996. The more recent warmth has been accompanied by relatively high amounts of precipitation, unlike the dry and warm 1930s.

The precipitation amounts over the Gulf Coast region are probably the largest in United States. Precipitation is centered mainly along the central Gulf

Coast states during winter, spring, and autumn and over Florida in the summer (Higgins et al., 1997). The mean annual precipitation amounts along the central Gulf Coast exceed 150 cm. By reviewing the analyses of U.S. Historical Climatology Network data by Karl and Riebsame in 1998 over North America, the following findings can be extracted. Annual precipitation amounts from 1901 to 1995 showed evidence of a gradual increase since the 1920s, reaching their highest levels in the past few decades. The Gulf Coast region has experienced the largest increase in annual precipitations, which was estimated at 10 – 20%.

Current trends in regional variations of precipitation and temperature are important parts of the hydrologic baseline conditions against which the potential effects of climate change should be assessed. The Gulf Coast region of the United States possesses a multitude of diverse climates as a consequence of its topography and being adjacent to a large body of water with widely varying thermal characteristics. The regional atmospheric circulation is dominated by disturbances (waves) in the upper-level westerly winds. In summer and autumn, tropical storms of the Atlantic, Caribbean, or Gulf of Mexico origin occasionally impact the coastal areas of the Gulf of Mexico. For the purpose of this case study, historical baseline precipitation and temperature are collected for the Tangipahoa watershed during the period of 1960 – 2000. These data will be used to evaluate the Canadian model predictability. Daily maximum and minimum temperature, and precipitation intensity records in the Tangipahoa watershed during the period of 1960 – 2000 are shown in Appendix I.

Projected Climate Forcing Scenarios

The wide range of projected changes in temperature and precipitation suggest that caution is required in treating future climate scenarios developed using the GCMs. Such scenarios should be regarded as internally consistent patterns of plausible future climates, not as predictions. The climate scenarios were projected using future climate trends based on assumptions of one percent per year increase in greenhouse gas concentration, and stabilization of greenhouse gas concentration occur. Some other important assumptions in projecting climate scenarios are that by year 2100: 1) population will nearly double; 2) the economic growth rate will continue at an average rate similar to the existing one; and 3) total energy production from non-fossil sources will continue to increase to more than ten times the current amounts (IPCC, 2000).

Projected climate data from an ensemble of four 50-year simulations using the IPCC "IS92a" forcing scenario in which the change in greenhouse gases (GHG) forcing corresponds to that observed from 1900 to 1996 and an increases in CO_2 at a rate of 1% per year thereafter until year 2100 were used to project the climate forcing parameters in the next 100 year. The direct effect of sulphate aerosols (A) was also included. All Canadian model runs were performed with the same greenhouse gas and aerosol forcing. The only difference was that the runs were initiated from different initial conditions. The reason for doing an ensemble of integrations is to reduce the natural climate variability by taking the ensemble average over the four runs. Therefore, differences between the individual integrations were entirely due to natural variability and not due to the differences in the model computation or forcing. The data were provided on one Gaussian grid (approximately 3.75^{o} lat x 3.75^{o} long or 1000 to 1500 km in mid-latitudes). The Canadian Model Gaussian grid showing the Gulf Coast region is included in Appendix IV.

These Gaussian grids were linearly interpolated to Northern and Southern Hemisphere polar stereographic grids. There is only one Gaussian grid box roughly covers the whole Gulf Coast region. The Canadian model attempts to represent the full climate system from first principles on a large scale probably greater than the Gulf Coast region. In this case study — Tangipahoa watershed is only about 518,600 acres however the Gaussian grid box used by the Canadian model probably exceeds 800 times the Tangipahoa watershed area. Therefore, projected climate parameters adaptation process was needed before comparing climate model output with observations or analyses on spatial scales smaller than the Gaussian grid size, or when using model output to study the hydrological impacts of climate variability and change. The Canadian model climate trends were integrated in a total of two sets of monthly projection data for the period of 1900 – 2100 for the Gulf Coast region. The first record was for year 1900 month 1 and the last one was for year 1999 month 12. The second record was for year 2000 month 1 and the last one was for year 2100 month 12. The projected climate trends included monthly temperature (maximum and minimum), precipitation, evaporation, solar radiation, specific humidity, and soil moisture. The whole set of the Canadian model climate parameters trends are presented in Appendix IV.

The Canadian model results, particularly monthly precipitation and temperature (maximum and minimum), were disaggregated to estimate the daily values using basic statistics in addition to the known measured trends in precipitation and temperature as described earlier under 3.2.1 and as shown in Appendix I. Ignoring the spatial and temporal variability and uncertainty of the projected precipitation over a local or relatively small area (Tangipahoa watershed) are among the major weaknesses of the existing regional GCMs generally. Therefore, to reduce this inherent uncertainty associated with the regional GCMs, part of the first set of Canadian model precipitation trends of 1960 – 1999 was compared to the actual measurements in the Tangipahoa watershed. The projected daily time series precipitation plot was generally flat passing by the average annual precipitation value and did not show the storm peak events. It was obvious that the Canadian model ignored the temporal variability of precipitation; furthermore, it averaged the projected precipitation over the study period of time. This situation reveals that, regional GCMs mainly are incapable of determining wet periods of the individual storm events on a sub-regional area, so that, the amount of rain was distributed over the storm duration period. This situation underestimated the amount of surface runoff and as a result the stream flow. Consequently, this situation significantly underestimated the extreme flood events since the storm peaks were not clearly defined.

A simple daily correction factor was determined based on the actual seasonal rainfall variability and the available historic daily rainfall observations of 1960 – 1999 in the Tangipahoa watershed. The adapted (corrected) daily precipitation projection values were estimated by multiplying the Canadian model daily precipitation values of 1960 – 1999 by the correction factor in order to enhance the daily precipitation prediction of the Canadian model. This calibration process was repeated several times until the adapted daily precipitation values showed satisfactory matching trends and agreement with the actual daily precipitation observations during the period of 1960 – 1999. The final correction factor was used to adapt the projected precipitation during the period of 2000 – 2100. Daily plots of the Canadian model adapted precipitation results during the period of 2000 – 2100 versus the actual measurements during the period of 1960 – 1999 are available in Appendix V.

The Canadian model projection to the year 2100 determined that annual precipitation will increase by 7–10%, and changes in spatial and tem-poral precipitation patterns would occur with higher variability (Figure 8). The Canadian model showed also that the mean annual surface temperature will increase by 5 – 8^{O}C, which agreed with the general finding of global warming in the United States, (Figures 9). In the meantime, the temperature variability in the next 100 years recorded a significant increase if compared with its trend in the period of 1960 – 1999 as shown in Figure 9 and the yearly moving-average graph shown in Appendix V. Daily presentation of the Canadian model temperature results during the period of 2000 – 2100 versus the actual measurements during the period of 1960 – 1999 are available in Appendix V.

The Canadian model predicted the continuous increase in annual average precipitation amounts from 56 inches to 60 inches, and to 62 inches during the periods of 1960 – 1999, 2000 – 2049, and 2050 – 2100, respectively. The percentage of precipitation increase over the period of 1960 – 2100 was estimated to be about 7 – 10%. This finding agreed with the analyses of U.S. Historical Climatology Network data described under 3.5.2 and with Lettenmaier and Sheer (1991). Figure 8 shows the increase in annual average precipitation during the same periods of 1960 – 1999, 2000 – 2049 and 2050 – 2100 as 4.15, 4.20, and 4.30 mm/day, respectively. In addition, annual variability of the precipitation increased during the period of 2000 – 2100 if compared with its trend during the period of 1960 – 1999. The same finding can be extracted from the precipitation yearly moving-average as shown in Appendix V. Based on the Canadian model adapted daily precipitation (Appendix V), it was obvious that, stronger storms with higher peak intensities are more likely to occur during the next 100 years. Instead of getting storm with peaks of about 250 mm/day during 1960 – 1999, it is expected to get storms of peaks up to 450 – 500 mm/day during the next 100 years. Furthermore, intervals between consequent storms are getting shorter, which increases the possibility of flood hazard. Based on this discussion, the Canadian model projected and adapted climate data for the period 2000 – 2100 can be used by the hydrological model with a significant degree of confidence to estimate the future extreme flood events in the Tangipahoa watershed. Therefore, the daily data of adapted precipitation, maximum and minimum temperatures; monthly data of solar radiation, specific humidity; and annual increase in greenhouse gases rate +1% were used by the SWAT model in order to estimate the extreme flood events in the next 100 years to the year 2100 in the Tangipahoa watershed.

10.3 Typical Hydrologic Results of the Projected Climate Forcing (2000-2100)

The annual average stream flow of the Tangipahoa River at its outfall during the period of 1938 – 2100 is presented in Figure 10. The monthly estimated stream flow at the Tangipahoa River outlet during the period of 1938 – 2100 is shown in Figure 11. The seasonal variation in precipitation versus stream flow at the Tangipahoa River outfall is illustrated in Figure 12. In addition, typical monthly SWAT model stream flow results based on the Canadian model projected climate data at the Tangipahoa River outfall during the periods of 2000 – 2049 and 2050 – 2100 as well as the SWAT estimation based on the actual climate data during the period of 1938 – 1999 are available in Appendix VI.

10.3.1 Impacts of Climate Forcing, Anthropogenic Activities, and the Greenhouse Effect on Extreme Flooding

Other studies concerning recent trends in precipitation and streamflow have shown generally increasing values throughout much of the United States. Total precipitation trends indicate an increase and monthly streamflow analyses show varying seasonal changes. Lettenmaier et al., (1994) analyzed the precipitation data over the period of 1948 – 1988 and found generally increasing trends during the months of September to December and increasing trends in streamflow during the months of November to April, particularly in the central and north-central portions of the United States. Similarly, Hurd et al., (1999a; b) reported that streamflow has increased throughout much of the conterminous United States since the early 1940s, with the increases occurring primarily in autumn and winter. Groisman, et al., (2001) explained the changes in the intensity of precipitation and streamflow during the period of 1939 – 99 based on over 150 unregulated streams across the US with nearby precipitation measurements. It was found that, the largest changes have been the significant increases in the heaviest precipitation events and the highest streamflows. It was found that changes in streamflow follow changes in precipitation, but are amplified by about a factor of 3. In the Gulf Coast region, precipitation and surface runoff have increased significantly over the past 100 years (Keim et al., 1995).

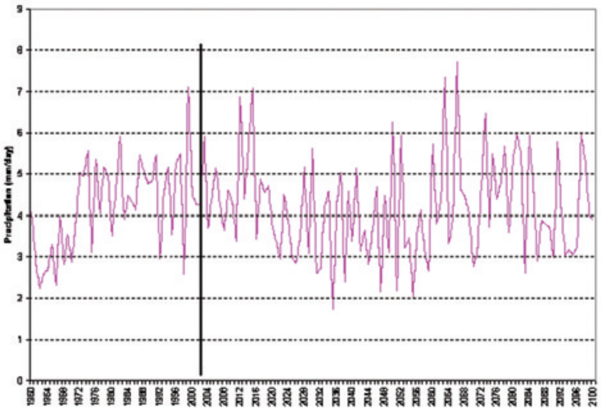

Figure 8. Annual Average Precipitation at the Tangipahoa Watershed (1960-2100).

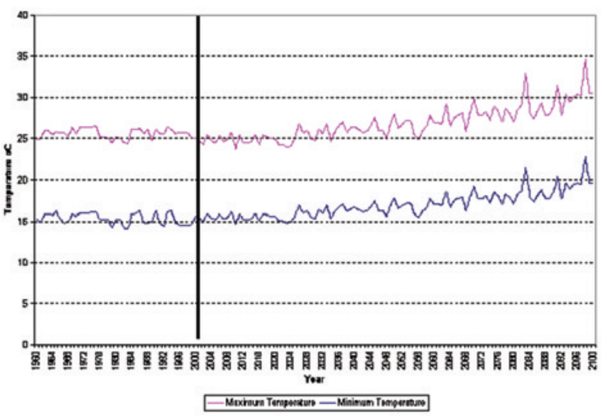

Figure 9. Annual Average Maximum and Minimum Temperature at the Tangipahoa Watershed (1960-2100).

The annual average stream flow trend during the period of 1938 – 2100, as shown in Figure 10, indicated a significant increase in the Tangipahoa River projected discharges in the next 100 years. These results strongly confirmed the reported findings of Lins and Michaels (1994); and Keim et al., (1995). However, the Tangipahoa River annual average discharge recorded 892 cfs, 1,319 cfs, and 1,286 cfs during the periods of 1938 – 1999, 2000 – 2049, and 2050 – 2100, respectively. These results suggest that, the projected climate forcing could decrease the stream flow of the Tangipahoa River in the second half of this century, but still the flood hazard will remain since the average annual discharge is expected to exceed the existing average records by about 44%. During the early period (1938 – 1962), the Tangipahoa watershed was virtually undeveloped.

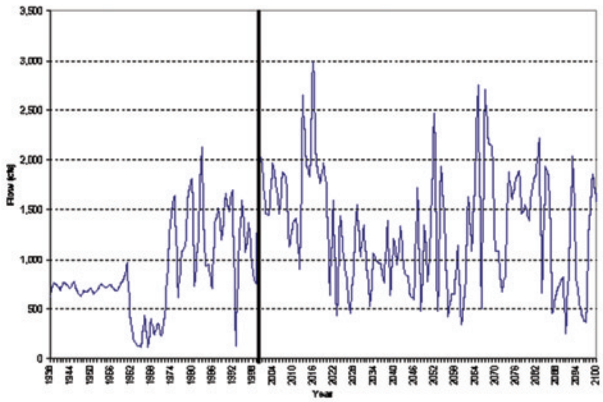

Figure 10. Annual Average Stream Flow at the Tangipahoa River Outfall (1938-2100).

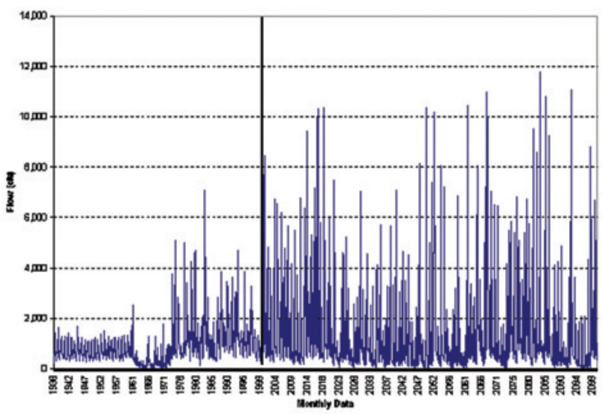

Figure 11. Monthly Estimated Stream Flow at the Tangipahoa River Outlet (1938-2100).

Introduction of development, urbanization, and other human activities to the area seemed to result in the river flow increasing. The projected climate data, in association with the SWAT model monthly stream flow prediction (Figure 11), indicated that the Tangipahoa River flow increase will continue with a rising trend of the mean value and could cross the safe threshold band causing severe flood events during the next 100 years. These results supported and strengthened the previous studies findings and analyses, and indicate a high possibility of stream flow rise and increased flood risk in the Tangipahoa watershed and probably the Gulf Coast region as well based on the study assumption which considered Tangipahoa watershed as a good prototype of the Gulf Coast region.

Although the Canadian model projects an increase in precipitation over the Tangipahoa watershed, the rates of evaporation and perhaps transpiration also are likely to increase with increasing temperatures (Appendix IV). Therefore, in locations where the changes in precipitation do not offset the increasing rates of evaporation and transpiration they may experience declines in surface runoff and consequently show a decline in Tangipahoa River flow trends. Such offsets could explain the seasonal projected stream flow for the Tangipahoa River in the period of 2050 – 2100, as shown in Figure 12. The increase in temperature and evaporation trends would also result in a lower soil moisture trend especially in the summer seasons during the next 100 years as indicated in Appendix IV. Alternatively, the substantial increases in precipitation are likely to have associated substantial increases in surface runoff and Tangipahoa River flow trends as indicated in Figures 10–12. On the other hand, the soil radiation trend did not show significant change, however, the specific humidity trend scored significant increase of about 25% (Appendix IV).

Projected change of the Tangipahoa River annual stream flow using the Canadian model climate change scenarios indicate potential increases as well as declining trends. Seasonal changes in stream flow also could be substantial. The climate change scenarios suggest increased winter precipitation, which could result in increased stream flow of the Tangipahoa River in winter and spring. On the other hand, the climate change scenarios show declines in summer precipitation and as a result declines in summer soil moisture levels could occur, which could result in significant declines in summer and autumn stream flows. However, climate change scenarios would likely show summer decline in precipitation or soil moisture trends generally if simulations were done using doubled CO_2 forcing alone; but since aerosol forcing was included, summer precipitation and soil moisture levels increased only slightly. This pattern highlighted the large uncertainty in climate change projections of stream flow and as a result the flood event analyses.

10.3.2 Variation in Climate and Flooding Mechanisms

Global climate models are not capable of predicting extreme flood events because they lack regional and local spatial and temporal resolution. While, there is no clear evidence that sustained changes in extreme flood events have occurred in the past few decades in the Gulf Coast region, such events can be serious. They can cause loss of life and endanger human health or property. Extreme flood events can results in the spread of infectious diseases, incidence of stress-related disorders, and other adverse health effects associated with social and environmental disruptions (e.g., flooding of sewage systems).

During the period of 1938 – 1974, as long as the Tangipahoa River flowed close to the average or expected level (892 cfs), there was no significant flood hazard and the discharge was perceived as a resource, as shown in Figure 11. Smith and Ward, 1998 stated, that when the river flow exceeds some predetermined threshold of local significance and extends outside the band of tolerance, it ceased to be beneficial and was perceived as a flood hazard. In this case study, the Tangipahoa River showed an increased tendency to be a flood hazard during the period of 1974 – present. It is expected that the flood risk will rise dramatically during the next 100 years due to the projected sharp rise in stream flow and increase in the flow variability as shown in Figure 10. However, determination of the safe band of tolerance is uncertain because it depends on the overall ecosystem integrated with the anthropogenic activities and socioeconomic systems in place as well. Also, the impact of the hazard is, in part, determined by the magnitude of the flooding event (expressed by the peak deviation beyond the damage threshold on the vertical scale) and the duration of the event (expressed by the length of time of which the threshold value is exceeded on the horizontal scale). The true significance of any flood disaster will depend primarily on the vulnerability of the local community. The Tangipahoa River often overflows its banks in some areas along its length, without creating a significant hazard and such hydrologically defined "flood flows" may create little economic damage and produce no response from the emergency services.

10.4 Implications of Projected Climate Forcing and Anthropogenic Activities

Four points must be kept in mind when considering the extent to which adaptive strategies should be relied upon. First, adaptation is not without cost. Sometimes, they are not expensive but may also bring unexpected benefits. Natural and financial resources must be diverted away from some activities into adaptive practices. Second, the economic and social costs of adaptation will increase the more rapidly climate change occurs. Third, although many opportunities exist for technological and behavioral adaptation, uncertainties exist about potential barriers and limitations to their implementation. Fourth, uncertainties exist about the efficacy and possible

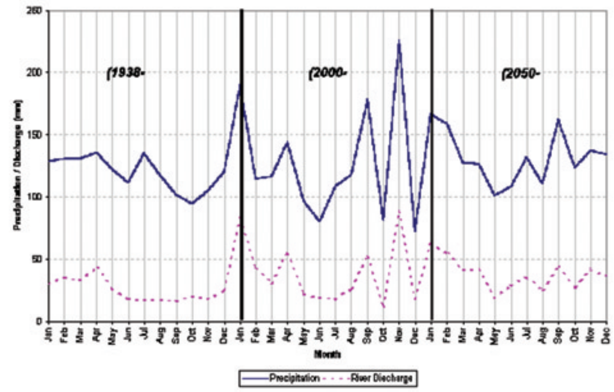

Figure 12. Seasonal Precipitation vs. River Discharge in Tangipahoa Watershed (1983-2100).

secondary effects of particular adaptive strategies. Climate change creates long-term components for decision makers and policy makers that influence natural and human systems and pose significant challenges (environmental, social, and economic issues). For example, climate change assessment of the potential impacts and variability on extreme flood events must account for the qualities of water in the storage, supply, and distribution systems that are being used for various anthropogenic activities.

10.4.1 Socioeconomic Impacts of Projected Ecological Change

Changes in the climate system such as extreme flood events can affect natural and human systems in a chain of consequences. Some of these consequences are results of direct effects of climate change and variability on physical, biological, and socioeconomic systems. Some impacts are the result of indirect links between climate-sensitive systems and related social and economic activities. And some impacts result from feedbacks between human activities that affect the climate system that in turn can lead to further impacts on human health, the environment, and socioeconomic systems.

Wetlands in the Gulf Coast region traditionally have been viewed as wasted land available for conversion to more productive uses. Alteration of the original wetland functions leads to significant ecological impacts such as extinction of various plants, animals, and birds species, loss of hydrological and cultural wetlands functions, and overall disturbance in the natural chemical, physical, and biological balance. The projected extreme flood events in the next 100 years have the potential to impact those wetlands to an extent equivalent to these expected ecological changes described above. These two forces would contribute to the loss of millions of wetland hectares. In general, the United States lost approximately 53% of the original wetland area in the lower 48 states (Maltby, 1986; Mitsch and Gosselink, 1986). In 1997, the FEMA estimated damage caused by weather-related natural disasters (wildfires, hurricanes, extreme floods, ice, tornadoes, and other extreme weather events) during the years 1992–96 in the United States by about $39 billion per year.

Socioeconomically, for example, wetlands surrounding Lake Pontchartrain, LA (Figure 1), provide direct benefits through the harvesting of timber, wild rice, cranberries, and horticultural peat as well as through recreational activities such as hunting, fishing, and bird watching. The cultures and spiritual values of many First Nation peoples are linked to the health of such wetlands. However, vulnerability of the Pontchartrain ecosystems and the related socioeconomic sectors may be affected by changes in climate system. For example, the projected extreme flood events in the Tangipahoa watershed in the next 100 year will directly affect the quality of life, alter patterns of settlement and human activities, and subject humans to risks regarding their health, safety, and property in the Pontchartrain ecosystem.

The projected extreme flood events could include secondary impacts on market activities. For example, extreme flood events directly affect crop yields and hence agricultural production and prices. These effects, in turn, influence the prices of goods and services that use agricultural commodities in their production, which feed back to the agricultural sector and agricultural prices. Shifts in agricultural production could have a large impact on freight transport patterns and may require adjustments in the transportation network with marine, road, rail, and air links potentially needing expansion into areas not currently serviced. In severe flood events, water transport could be affected by changes in river navigability. During the 1993 flood in the upper Mississippi valley, it disrupted the barge transportation system. Also during the 1997 hurricane George, increased siltation associated with floods prevented ships from reaching the port of New Orleans, LA for several days. Furthermore, offshore oil and gas exploration and production in the Gulf of Mexico could be influenced by the projected extreme flood events in the next 100 years. Generally, extreme flood events have direct impacts on: economic activity in the industry, energy, and transportation sectors, markets for goods and services, offshore oil and gas production, manufacturing dependent on water, tourism and recreation, and natural resources in the Gulf Coast region.

10.4.2 Human Health Aspects

Extreme flood events in the Gulf Coast region are likely to have wide-ranging and mostly adverse impacts on human health. These impacts could arise by direct pathways (e.g., contaminated drinking water by chemical and/or biological leakage) and indirect pathways (e.g., potential increase in: transmission of vector-borne and waterborne diseases; mold spores; malnutrition; and general public health infra-structural damage). Extreme flood events could also jeopardize access to traditional foods garnered from land and water (such as game, wild birds, fish, and berries), leading to diet-related problems such as obesity, cardiovascular disorders, and diabetes of indigenous peoples as they make new food choices (Government of Canada, 1996; IPCC, 2000).

Warming may at first appear beneficial. Plants may be fertilized by warmth, moisture, more CO_2, and nitrogen. But warming and increased CO_2 can also stimulate microbes and their carriers, and added heat can destabilize weather patterns. In the Gulf Coast region, the frequency of very hot days in temperate climate is expected to approximately double in the summer. Heat waves cause excess deaths (Kilbourne, 1992), many of which are caused by increased demand on the cardiovascular system required for physiological cooling. Aging can be expected to be accompanied by multiple, chronic illnesses that may result in increased vulnerability to infectious disease or external/environmental stresses such as extreme heat (Hobbs and Damon, 1998). Warmer temperatures can accelerate production and increase concentrations of photochemical oxidants in urban and rural areas and thus exacerbate respiratory disorders. Consequences of warming on human illness and health of livestock and fisheries may be significant (Santer et al., 1996). The resurgence of infectious diseases thus poses threats to food and biological security, and to economic development. Probable water-borne pathogens due to extreme flood events in the Pontchartrain ecosystem, LA include viruses, bacteria, and protozoa. Examples include Vibriovulnificus, a naturally occurring estuarine bacterium responsible for a high percentage of the deaths associated with shellfish consumption (Shapiro et al., 1998); Cryptosporidium parvum and Giardia lamblia, protozoa associated with gastrointestinal illnesses (Craun, 1998); and biologic toxins associated with harmful algal blooms (Baden et al., 1996).

In the United States, 145 natural disasters resulted in 14,536 deaths from 1945 to 1989. Of these events, 136 were weather disasters; these extreme weather events caused 95% of all disaster-related deaths. According to the National Weather Service, severe storms caused 600 deaths and 3,799 reported injuries in 1997 (NWS, 1999). Floods are the most frequent natural disaster and the leading cause of death from natural disasters in the US; the average annual loss of life is estimated to be as high as 146 deaths per year (NWS, 1992).

The probable risk of water-borne diseases in the next 100 years as a result of extreme flood events depends mainly on policy responses and level of maintenance or improvement of infrastructure. Current adaptations for assessing and preventing water-borne diseases include legal and administrative measures such as water safety criteria, monitoring requirements, and health outcome surveillance, as mandated under the Safe Drinking Water Act, with amendments in 1996 (USEPA, 1997b). Recent legislative and regulatory attention has focused on improved treatment of surface water to address microbial contaminants and on ground water and watershed protection (ASM, 1998; USEPA, 1998b).

10.5 The Control of Flood (Coping Strategy)

Strategies for technological and behavioral adaptation offer an opportunity to reduce the vulnerability of sensitive systems to the effects of climate change and variability. The purpose of flood control is to modify the hydrodynamic characteristics of river flows in order to reduce the flood risk. Flood control in the Gulf Coast region can be achieved by two ways. First, traditional flood protection methods, e.g., channel modifications, using artificial materials for constructing levees and dams. In coastal areas, sea walls are highly recommended to resist the energy of incoming waves and tides. Second, by flood abatement methods, e.g., using essential natural materials, whether of geological or biological origin, and the existing environmental processes to control flooding and land erosion. In coastal areas, salt marshes are important to protect the banks of estuaries and beaches. Vegetation cover management is one of the most effective methods of flood control. A complete vegetation cover helps to reduce soil erosion and flooding through the detention of rainfall by interception, increased infiltration, and reduced runoff through enhanced evaporation and evapotranspiration. Also, local flood abatement can be achieved in urban areas by encouraging the maximum infiltration rates in parks and water detention basins.

10.6 Information and Research Needed in the Future

Most future climate impact studies have assessed how natural systems will respond to climate change resulting from projected climate forcing scenarios. These scenarios are subjected to regional-scale analyses to the extent that they inadequately correspond to the local scale studies, e.g., the Tangipahoa watershed. They also lack the resolution to permit an examination of the effects of climate variability on physical, biological, and socioeconomic systems.

Understanding historic changes, or projecting future changes in streamflow conditions will require more evaluation of the complex role of changing precipitation and temperature patterns as well as the role of land-use change on streamflow. These unresolved issues further reinforce the importance of maintaining adequate nationwide networks of precipitation and streamflow gages to help describe and predict changes in average streamflow and, more importantly, streamflow variability. Projecting future changes in streamflow conditions will require more evaluation of the complex role of changing precipitation and temperature patterns as well as the role of land-use change on streamflow. There is a need to continue to refine existing GCMs, and improve model validation and comparison. Hydrologic and climate modeling tools integration could be improved if scaling problems between the models are better understood. Output should be tailored to users needs. Key areas for model development include better physically based parameterizations for groundwater/surface water interactions, atmospheric feedbacks, variability of precipitation, and land surface characteristics at a watershed scale.

Wetlands restoration in managed watersheds can reduce the impact of storm water runoff to waterways by slowing down or absorbing excess water. Providing wetland protection including buffer areas beyond the wetland boundary is a viable method of avoiding flood damage or the cost of flood protection.

There have been relatively few studies addressing the change in risk directly because of the lack of credible climate change scenarios at the level of detail necessary to predict, for example, extreme flood events. There is a lack of accurate information on: 1). Links between land use and water quality, through better assessment at the watershed level of the food-borne transport and fate of microbial pollutants associated with rain and snowmelt; 2) Methods to improve surveillance and prevention of water-borne disease outbreaks; 3) Epidemiologic studies; 4) Molecular tracing of water-borne pathogens; 5) Links between drinking water, recreational exposure, and food-borne disease monitoring; 6) Links between marine ecology and toxic algae; and 7) Vulnerability assessment to improve water and waste water treatment systems. We are living in a period of accelerated social, ecological, and climatic change. But will our global society react to the symptoms of environmental dysfunction in time to take corrective measures?

10.7 Findings and Conclusions

Multiple activities induced in the Earth's atmosphere (e.g., carbon buildup and gasses accumulation) are changing the chemistry of the air and in the process altering the heat budget of the world. These also constitute a destabilizing array of forcing factors. Together they have already begun to alter natural climatic modes. These modifications have begun to affect biological systems and human health. The purpose of this case study is to contribute to the long-term sustainability of the Gulf Coast region through credible evaluation of the consequences of climate change with a focus on the extreme flood events. Establishment of the regional baseline and scenarios is the first step of this assessment. Without a good understanding of the current conditions and future trends, one could not conduct any climate change impact assessment. The current climate baseline was established and the climate forcing scenarios/future trends were also projected. The established current condition provided information needed for the projection of the future scenarios. Results obtained from this case study can be helpful in assessing the impacts of future climate change on the natural environment, human, society, and economy of the Gulf Coast region through parallel research case studies.

Using the Canadian climate model that incorporates projected changes in greenhouse gases and aerosols into scenarios resulted in likely, projected trends of precipitation, tempera-ture, solar radiation, and humidity in the Gulf Coast during the next 100 years. The Canadian model projection to the year 2100 determined that the mean annual surface temperature will likely increase by 5 – 8^{o}C, annual precipitation will likely increase by 7–10%, and that changes in the spatial and tem-poral patterns of precipitation would occur. The increase in heavy rainfall events could increase the potential for flooding of human settlements in the Gulf Coast region. The expected severe storms (double the magnitude of the existing storms) could have widespread impacts on roads, railways, and other transportation links. As long as rainfall will become more intense, impacts on urban areas are likely to be significant. In the next 100 years, extreme flooding (+44%) could be one of the significant impacts of climate change because of the large amount of property and human life potentially at risk in the Gulf Coast region. The expected more frequent and stronger flood events could cause considerable disruption of transportation and water supply systems.

In this study, a 5 – 8^{o}C rise in temperature and a 7–10% increase in annual precipitation were projected for the next 100 years. This situation could create opportunities and limitations for outdoor recreation. Human activities and infrastructure are especially vulnerable to extreme flood events. Hence, there could be severe impacts if the frequency or intensity of extreme floods increases as predicted. The specific human and economic impacts from significantly large floods are difficult to measure. The ability to predict changes in the frequency or intensity of extreme flood events using global and regional models has been limited by their lack of small-scale spatial and temporal resolution and uncertainties about representation of some processes. The historical changes in frequencies of extreme flood events also provide some insights on possible changes. Several questions arise at this stage, among them, 1) If the current climate forcing trends continue, what are the environmental impacts that would result? 2) What if the slope of already observed trends gets steeper? 3) What has the cost already been just from the observed trends? 4) What if it continues? And 5) What if it gets steeper?

The projected extreme flood events in the next 100 years could impact the wetlands (e.g., Lake Pontchartrain ecosystem, LA) to an equivalent extent as that expected from ecological changes, such as extinction of various plants, animals, and birds species, as well as loss of hydrological and cultural wetlands functions, and overall disturbance in the natural chemical, physical, and biological balance. Extreme flood events are likely to have wide-ranging and mostly adverse impacts on anthropogenic activities and human health. These impacts would arise by direct pathways (e.g., contaminated drinking water by chemical and/or biological leakage) and indirect pathways (e.g., potential increase in: transmission of vector-borne and waterborne diseases; mold spores; malnutrition; and general public health infra-structural damage).

Scientific studies show that human health, ecological systems, and socioeconomic sectors (e.g., hydrology and water resources, food and fiber production, coastal systems and human settlements), all of which are vital to sustainable devel-opment, are sensitive to extreme flood events (including both the magnitude and duration of the flood). During the last 100 years, the Gulf Coast region was likely to experience several severe climate events and they brought both adverse and beneficial impacts. Climate change represents an important additional stress on those systems already affected by increasing resource demands, unsustainable management practices and pollution, which in many cases may be equal to or greater than those of climate change. Additional research is needed to better understand the sensitivity and vulnerabilities of human settlements and infrastructure to extreme flood events in the Gulf Coast region, including factors beyond climate that are changing those vulnerabilities.

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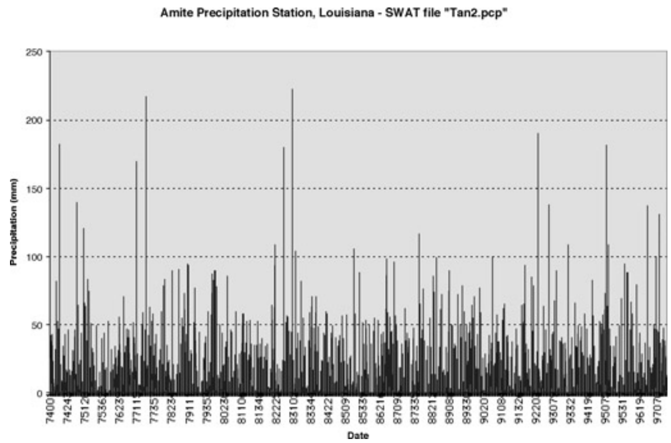
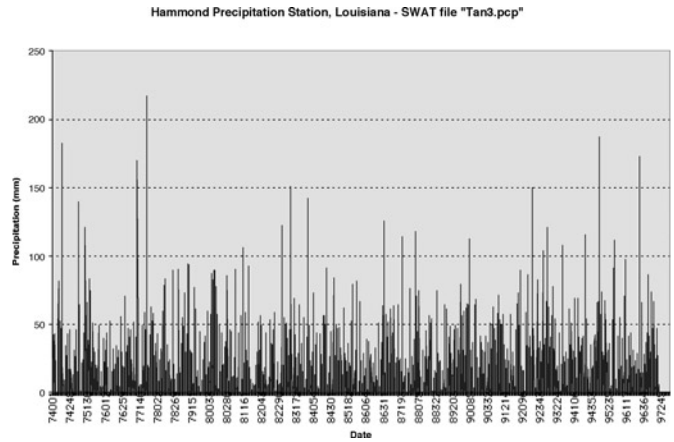
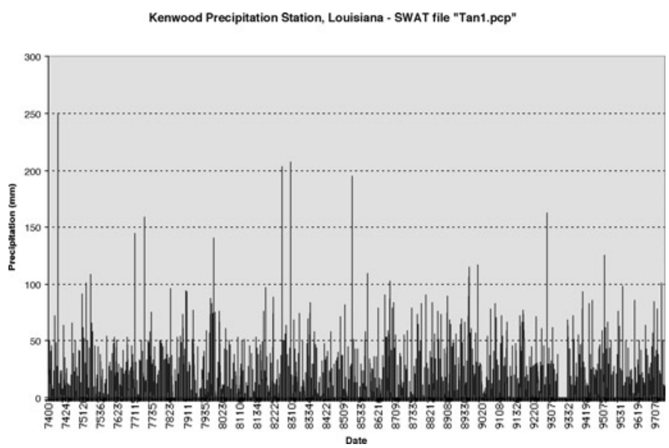
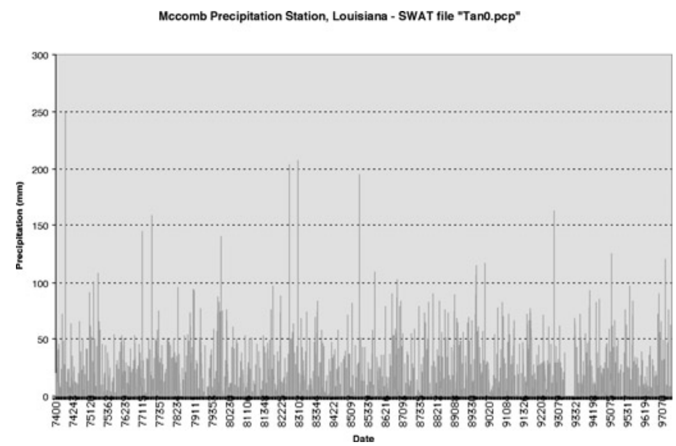
APPENDIX I

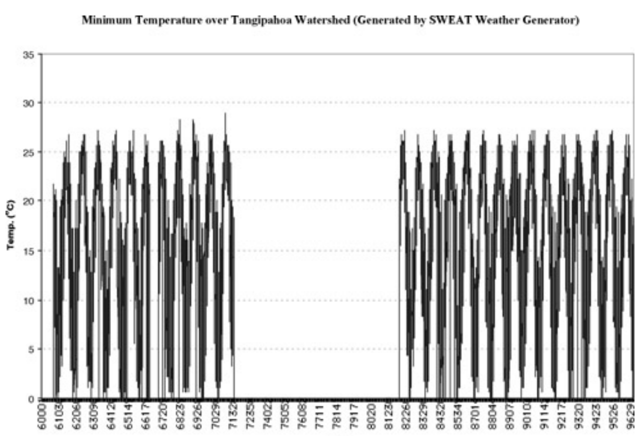
- Daily rain records measured at Hammond, Amite, Kentwood, and McComb rain gauge stations (1960 – 2000)
- Daily maximum and minimum temperature records and the air temperature seasonal variability in Tangipahoa watershed (1960 – 2000)
- Daily and seasonal variability stream flow records plots at the Tangipahoa River outfall (Robert location) – period (1938 – 2000)
- Peak flow at Robert location and other upstream locations

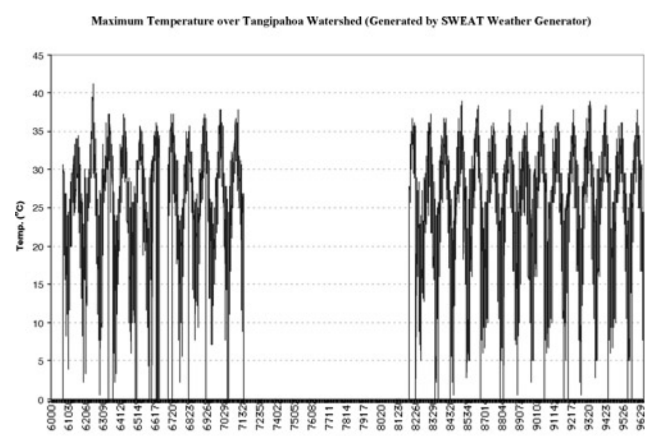

Amite Precipitation Station, Louisiana - SWAT file "Tan2.pcp"
Precipitation (mm)
Date

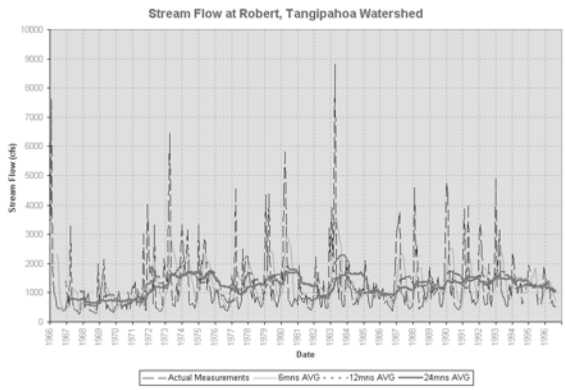

Hammond Precipitation Station, Louisiana - SWAT file "Tan3.pcp"
Precipitation (mm)
Date

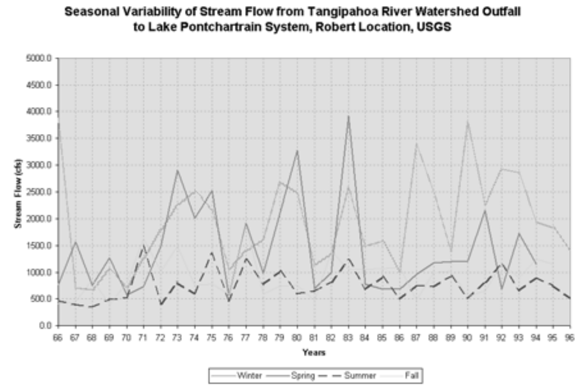

Kenwood Precipitation Station, Louisiana - SWAT file "Tan1.pcp"
Precipitation (mm)
Date

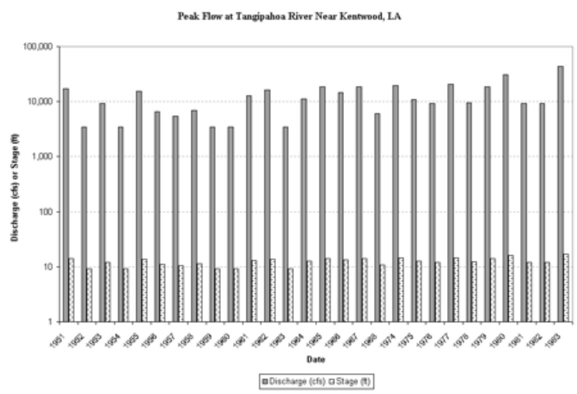

Mccomb Precipitation Station, Louisiana - SWAT file "Tan0.pcp"
Precipitation (mm)
Date

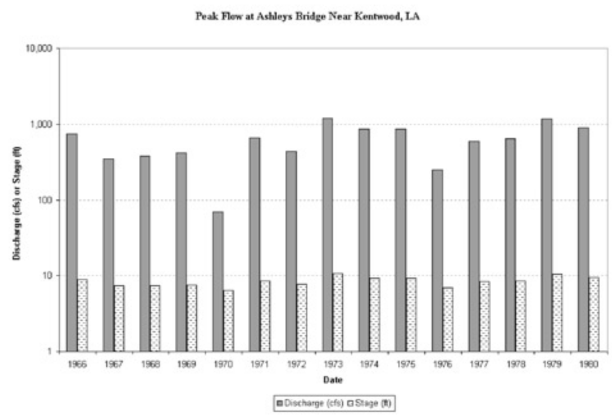

Minimum Temperature over Tangipahoa Watershed (Generated by SWEAT Weather Generator)
Temp. (°C)
Date

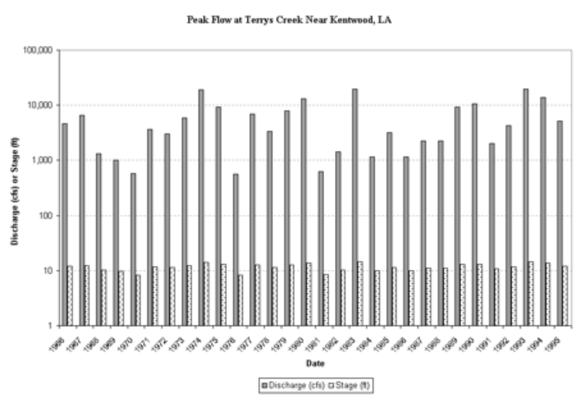

Maximum Temperature over Tangipahoa Watershed (Generated by SWEAT Weather Generator)
Temp. (°C)
Date

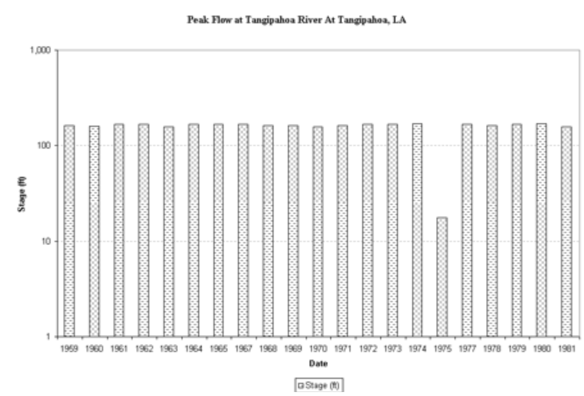

Stream Flow at Robert, Tangipahoa Watershed
Stream Flow (cfs)
Date
Actual Measurements
6mns AVG
12mns AVG
24mns AVG

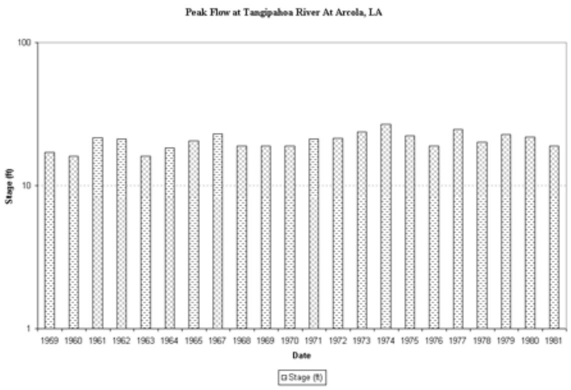

Seasonal Variability of Stream Flow from Tangipahoa River Watershed Outfall to Lake Pontchartrain System, Robert Location, USGS
Stream Flow (cfs)
Years
Winter
Spring
Summer
Fall

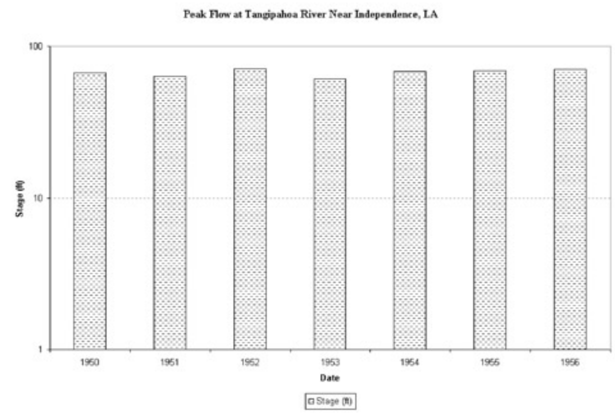

Peak Flow at Tangipahoa River Near Kentwood, LA
Discharge (cfs) or Stage (ft)
Date
Discharge (cfs)
Stage (ft)

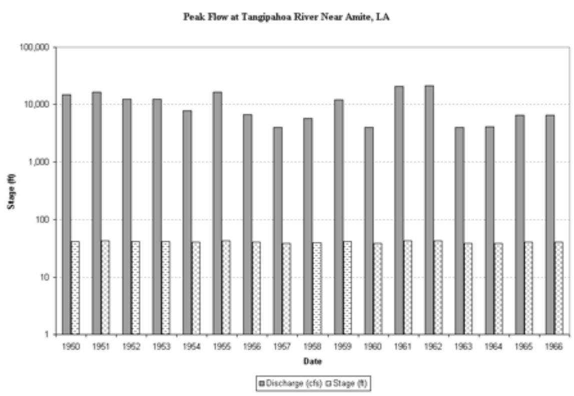

Peak Flow at Ashleys Bridge Near Kentwood, LA
Discharge (cfs) or Stage (ft)
Date
Discharge (cfs)
Stage (ft)

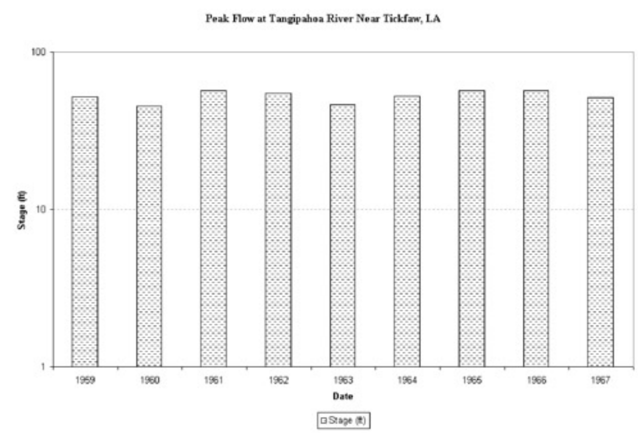

Peak Flow at Terrys Creek Near Kentwood, LA
Discharge (cfs) or Stage (ft)
Date
Discharge (cfs)
Stage (ft)


Peak Flow at Tangipahoa River At Tangipahoa, LA
Stage (ft)
Date
Stage (ft)


Peak Flow at Tangipahoa River At Arcola, LA
100
10
1
Stage (ft)
1959 1960 1961 1962 1963 1964 1965 1967 1968 1969 1970 1971 1972 1973 1974 1975 1976 1977 1978 1979 1980 1981
Date
Stage (ft)


Peak Flow at Tangipahoa River Near Independence, LA
100
10
1
Stage (ft)
1950 1951 1952 1953 1954 1955 1956
Date
Stage (ft)


Peak Flow at Tangipahoa River Near Amite, LA
100,000
10,000
1,000
100
10
1
Stage (ft)
1950 1951 1952 1953 1954 1955 1956 1957 1958 1959 1960 1961 1962 1963 1964 1965 1966
Date
Discharge (cfs) Stage (ft)

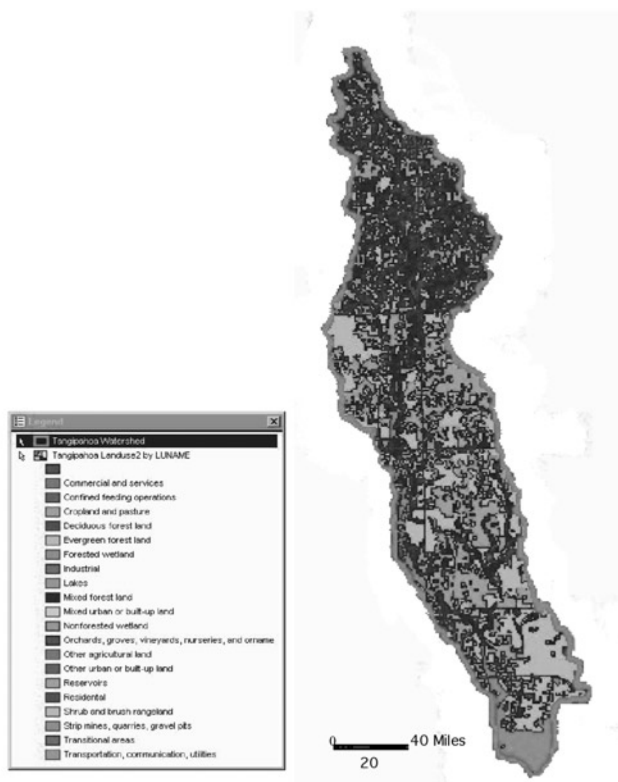

Peak Flow at Tangipahoa River Near Tickfaw, LA
100
10
1
Stage (ft)
1959 1960 1961 1962 1963 1964 1965 1966 1967
Date
Stage (ft)

APPENDIX II

- Main Cities and Measurement Locations in The Tangipahoa Watershed
- The Tangipahoa watershed GIS land-use map layer
- The Tangipahoa watershed topographic GIS elevation map layer


N
McComb
Kentwoo
Amit
Hammond
Robert
0
5
10 Miles
Legend
DEQ sampling stations in Tangipahoa
Perrenial streams in Tangipahoa
Tangipahoa watershed
USGS gages in Tangipahoa

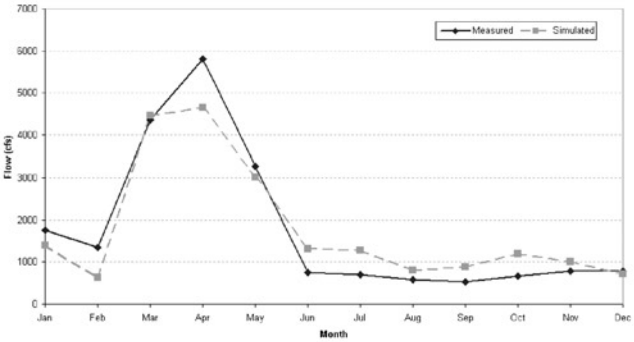

0
40 Miles
20


Tangipahoa Watershed
Tangipahoa Landuse2 by LUNAME
Commercial and services
Confined feeding operations
Cropland and pasture
Deciduous forest land
Evergreen forest land
Forested wetland
Industrial
Lakes
Mixed forest land
Mixed urban or built-up land
Nonforested wetland
Orchards, groves, vineyards, nurseries, and orname
Other agricultural land
Other urban or built-up land
Reservoirs
Residential
Shrub and brush rangeland
Strip mines, quarries, gravel pits
Transitional areas
Transportation, communication, utilities
0
40 Miles
20

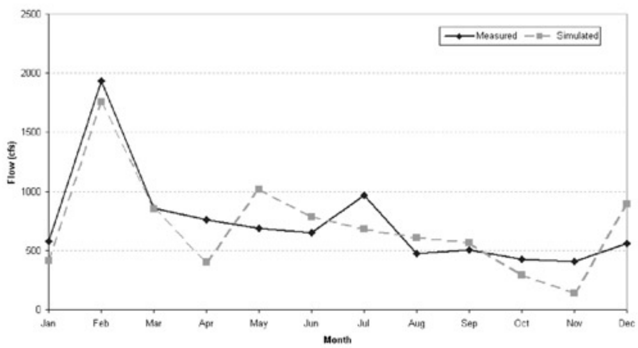
APPENDIX III

- Monthly comparisons between the simulated and observed stream flow at the Tangipahoa watershed outfall (Robert location)
- Daily time series plots observed and simulated stream flow comparison at the Tangipahoa watershed outfall (Robert location)

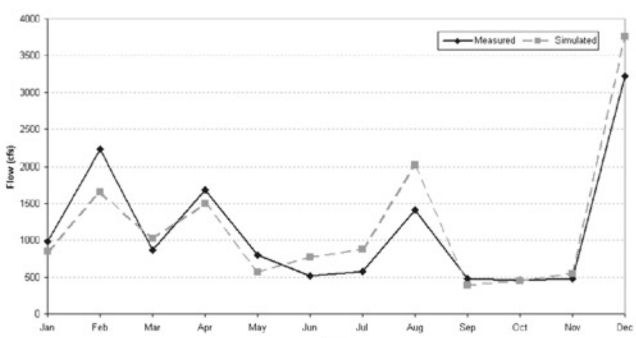
Comparison Between Measured and Simulated Stream Flow at Tangipahoa Watershed Outfall (Robert Location), Year 1980



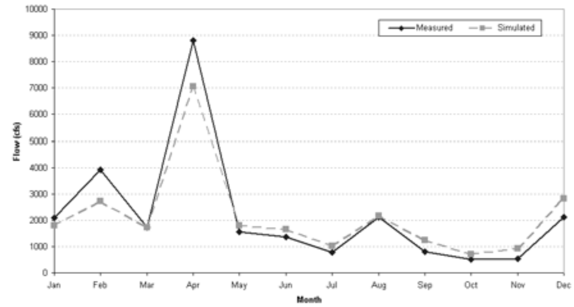
Comparison Between Measured and Simulated Stream Flow at Tangipahoa Watershed Outfall (Robert Location), Year 1981



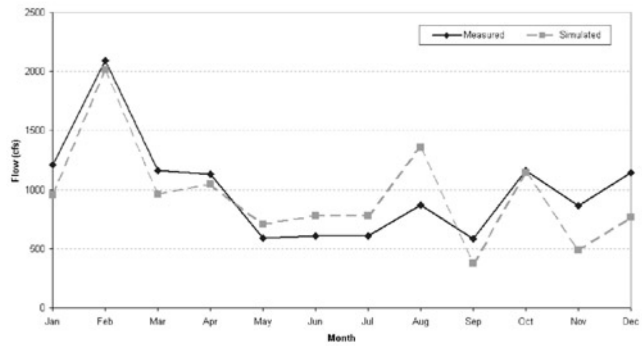
Comparison Between Measured and Simulated Stream Flow at Tangipahoa Watershed Outfall (Robert Location), Year 1982



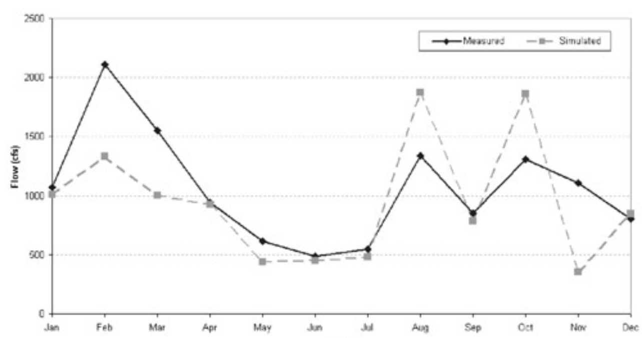
Comparison Between Measured and Simulated Stream Flow at Tangipahoa Watershed Outfall (Robert Location), Year 1983



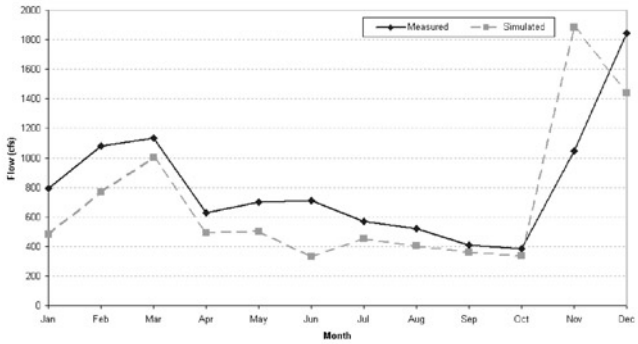
Comparison Between Measured and Simulated Stream Flow at Tangipahoa Watershed Outfall (Robert Location), Year 1984



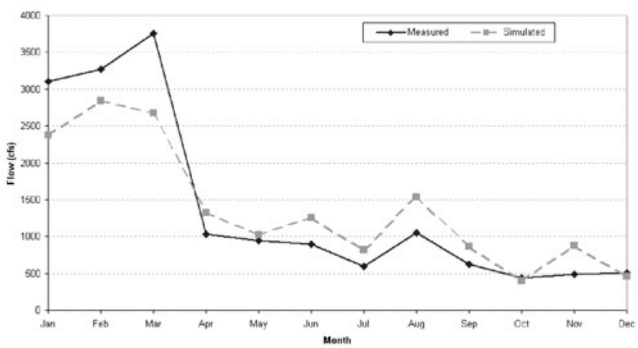
Comparison Between Measured and Simulated Stream Flow at Tangipahoa Watershed Outfall (Robert Location), Year 1985



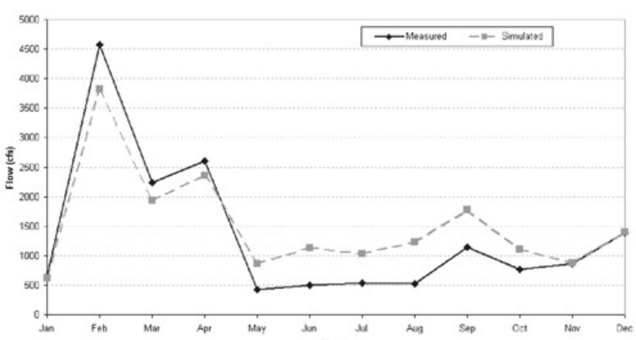
Comparison Between Measured and Simulated Stream Flow at Tangipahoa Watershed Outfall (Robert Location), Year 1986



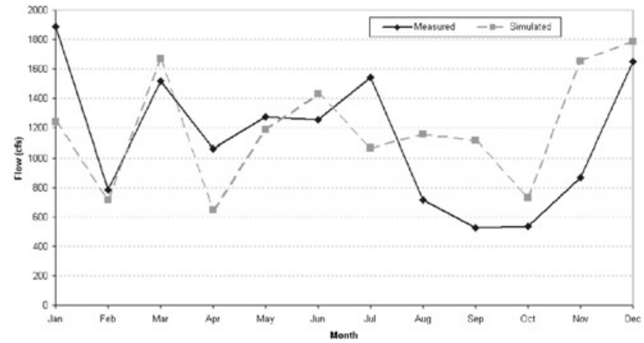
Comparison Between Measured and Simulated Stream Flow at Tangipahoa Watershed Outfall (Robert Location), Year 1987



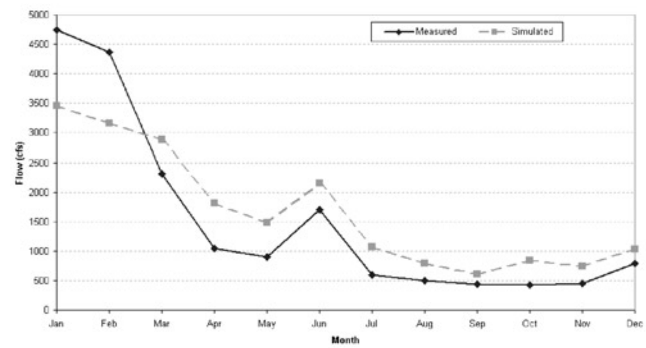
Comparison Between Measured and Simulated Stream Flow at Tangipahoa Watershed Outfall (Robert Location), Year 1988



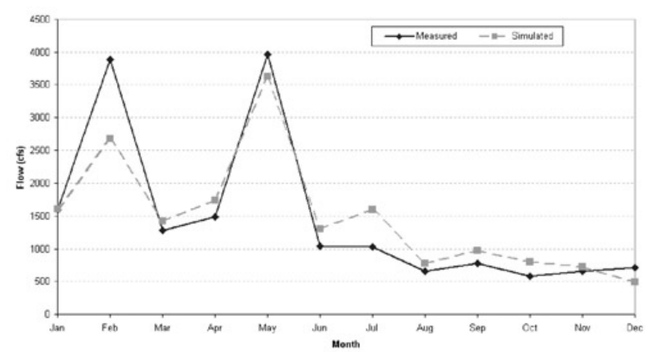
Comparison Between Measured and Simulated Stream Flow at Tangipahoa Watershed Outfall (Robert Location), Year 1989



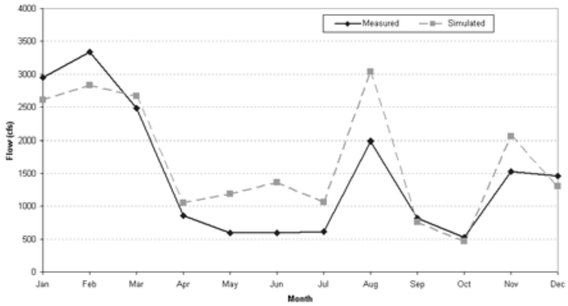
Comparison Between Measured and Simulated Stream Flow at Tangipahoa Watershed Outfall (Robert Location), Year 1990



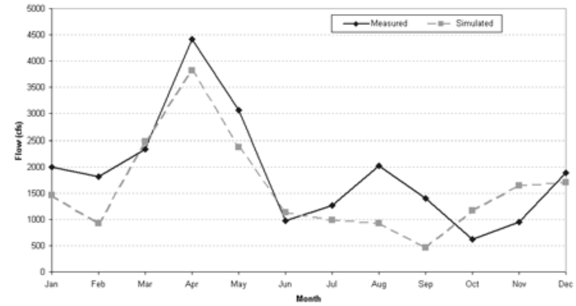
Comparison Between Measured and Simulated Stream Flow at Tangipahoa Watershed Outfall (Robert Location), Year 1991



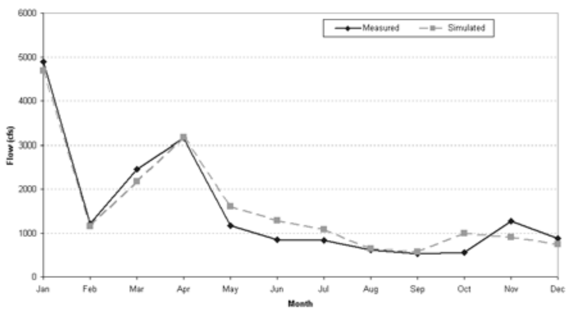
Comparison Between Measured and Simulated Stream Flow at Tangipahoa Watershed Outfall (Robert Location), Year 1992



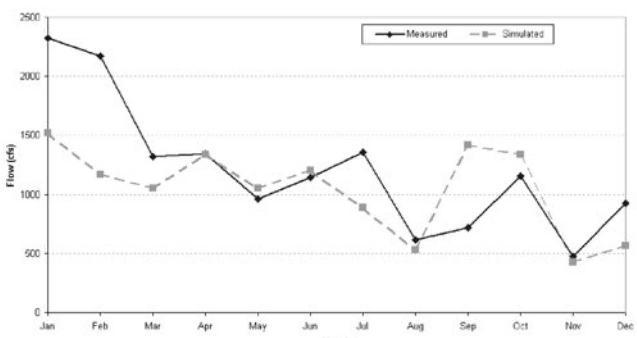
Comparison Between Measured and Simulated Stream Flow at Tangipahoa Watershed Outfall (Robert Location), Year 1995

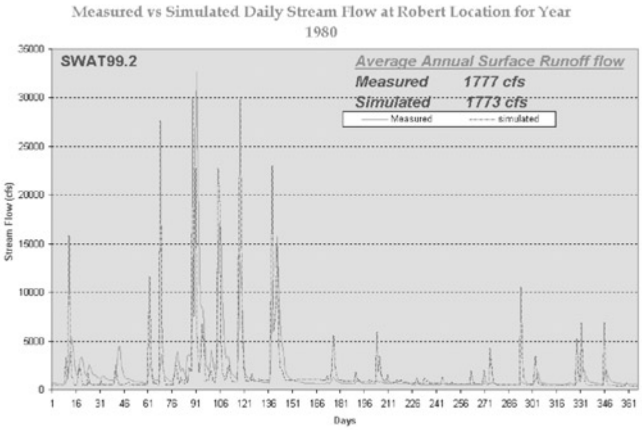


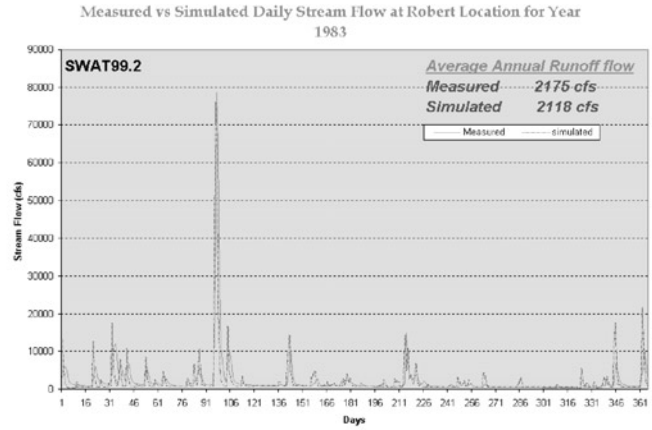
Comparison Between Measured and Simulated Stream Flow at Tangipahoa Watershed Outfall (Robert Location), Year 1993

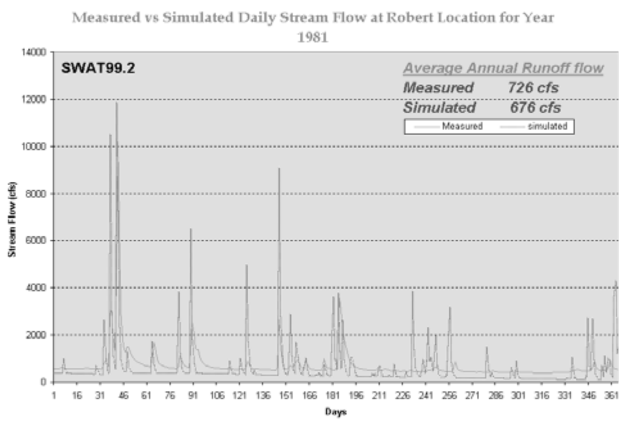


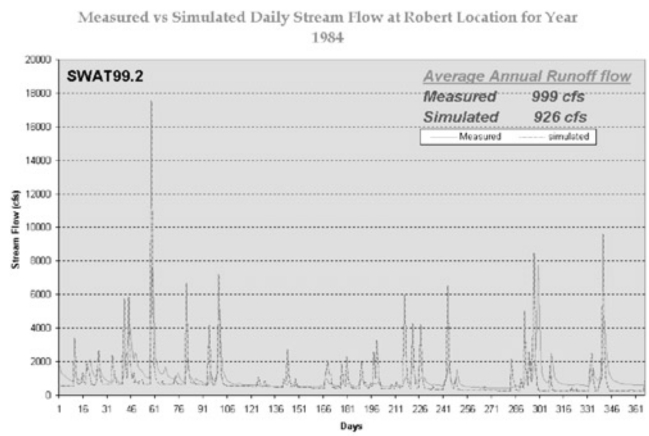
Comparison Between Measured and Simulated Stream Flow at Tangipahoa Watershed Outfall (Robert Location), Year 1994

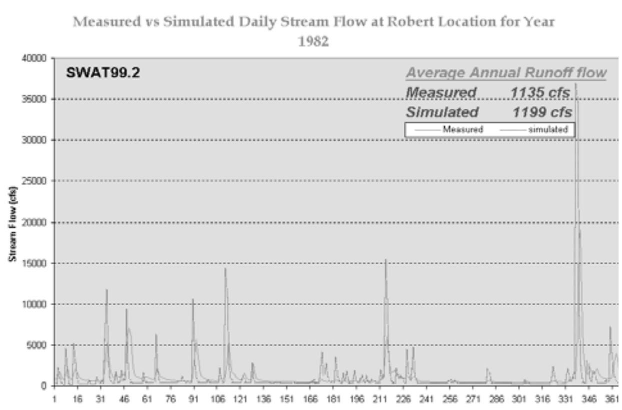


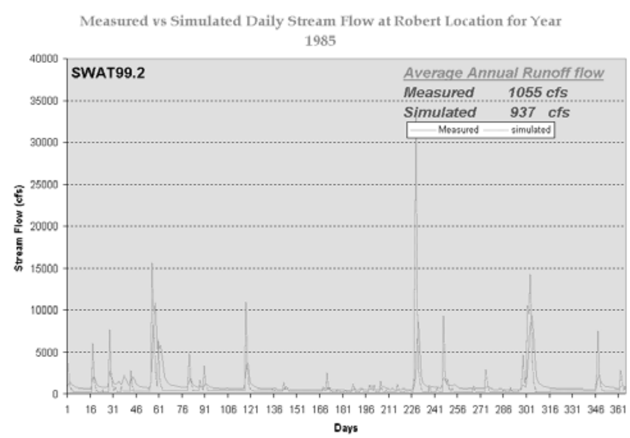

Measured vs Simulated Daily Stream Flow at Robert Location for Year 1980
SWAT99.2
Average Annual Surface Runoff flow
Measured 1777 cfs
Simulated 1773 cfs
Measured
simulated
Stream Flow (cfs)
Days

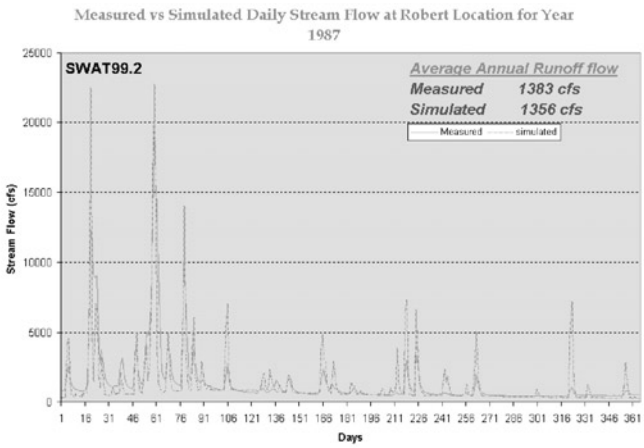

Measured vs Simulated Daily Stream Flow at Robert Location for Year 1983
SWAT99.2
Average Annual Runoff flow
Measured 2175 cfs
Simulated 2118 cfs
Measured
simulated
Stream Flow (cfs)
Days

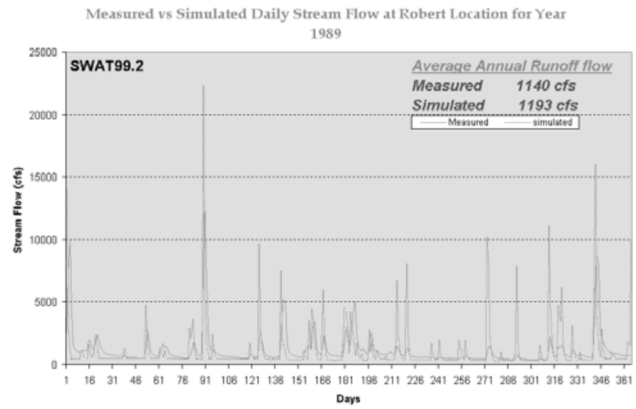

Measured vs Simulated Daily Stream Flow at Robert Location for Year 1981
SWAT99.2
Average Annual Runoff flow
Measured 726 cfs
Simulated 676 cfs
Measured
simulated
Stream Flow (cfs)
Days

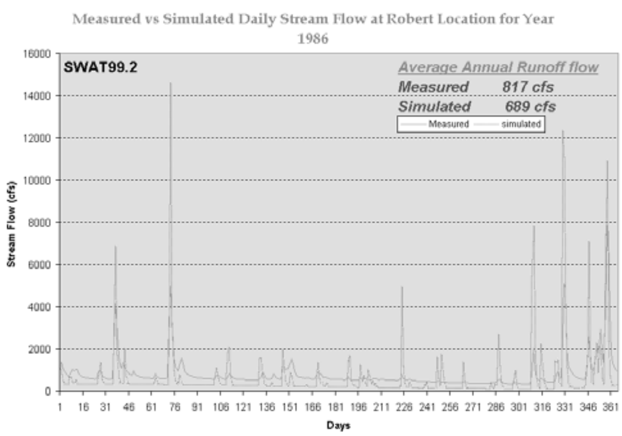

Measured vs Simulated Daily Stream Flow at Robert Location for Year 1984
SWAT99.2
Average Annual Runoff flow
Measured 999 cfs
Simulated 926 cfs
Measured
simulated
Stream Flow (cfs)
Days

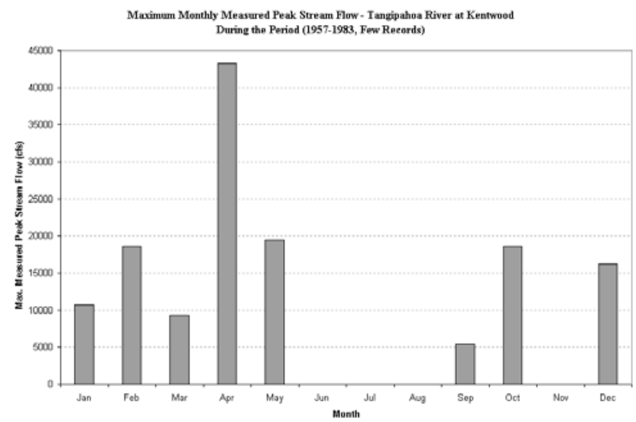

Measured vs Simulated Daily Stream Flow at Robert Location for Year 1982
SWAT99.2
Average Annual Runoff flow
Measured 1135 cfs
Simulated 1199 cfs
Measured
simulated
Stream Flow (cfs)
Days

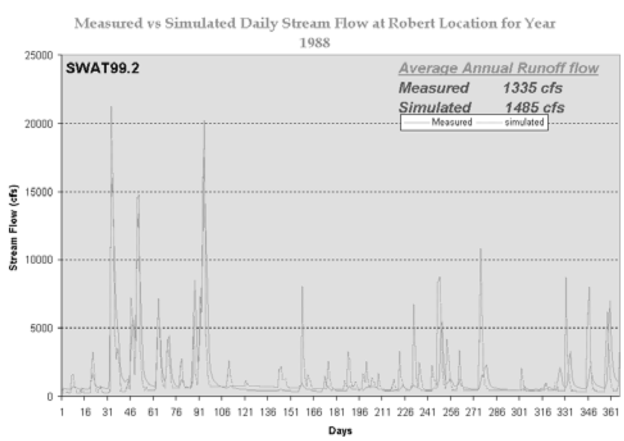

Measured vs Simulated Daily Stream Flow at Robert Location for Year 1985
SWAT99.2
Average Annual Runoff flow
Measured 1055 cfs
Simulated 937 cfs
Measured
simulated
Stream Flow (cfs)
Days

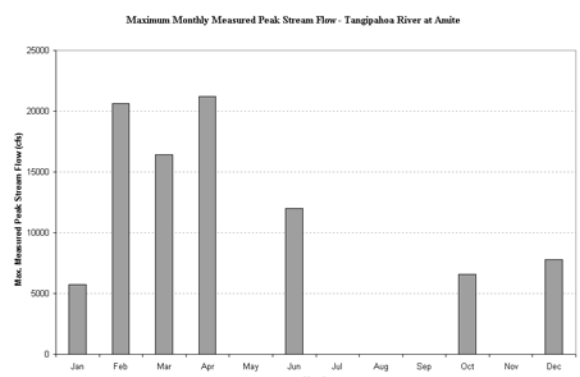

Measured vs Simulated Daily Stream Flow at Robert Location for Year 1987
SWAT99.2
Average Annual Runoff flow
Measured 1383 cfs
Simulated 1356 cfs
Measured
simulated
Stream Flow (cfs)
Days


Measured vs Simulated Daily Stream Flow at Robert Location for Year 1989
SWAT99.2
Average Annual Runoff flow
Measured 1140 cfs
Simulated 1193 cfs
Measured
simulated
Stream Flow (cfs)
Days


Measured vs Simulated Daily Stream Flow at Robert Location for Year 1986
SWAT99.2
Average Annual Runoff flow
Measured 817 cfs
Simulated 689 cfs
Measured
simulated
Stream Flow (cfs)
Days


Maximum Monthly Measured Peak Stream Flow - Tangipahoa River at Kentwood
During the Period (1957-1983, Few Records)
Max. Measured Peak Stream Flow (cfs)
Month


Measured vs Simulated Daily Stream Flow at Robert Location for Year 1988
SWAT99.2
Average Annual Runoff flow
Measured 1335 cfs
Simulated 1485 cfs
Measured
simulated
Stream Flow (cfs)
Days


Maximum Monthly Measured Peak Stream Flow - Tangipahoa River at Amite
Max. Measured Peak Stream Flow (cfs)
Month

APPENDIX IV

- The whole set of original Canadian model results including climate trends (precipitation, temperature, evaporation, solar radiation, specific humidity, and soil moisture)

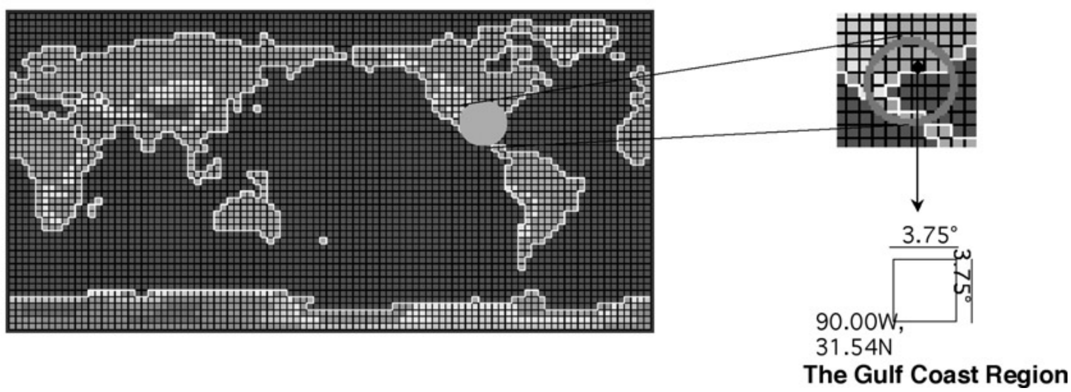
The Canadian Model (CGCM 2) Gaussian Grid
Future Forcing Climate Scenarios

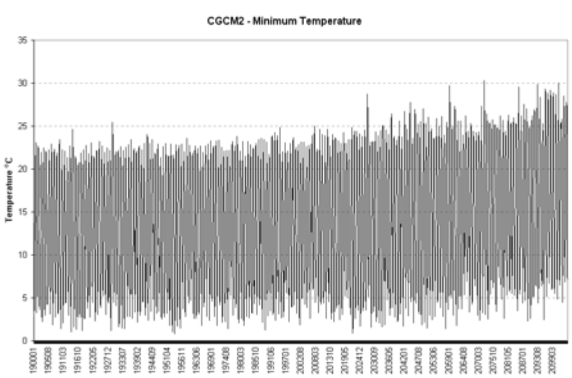
GHG+A IPCC Scenario 'IS92a' with the Canadian Model

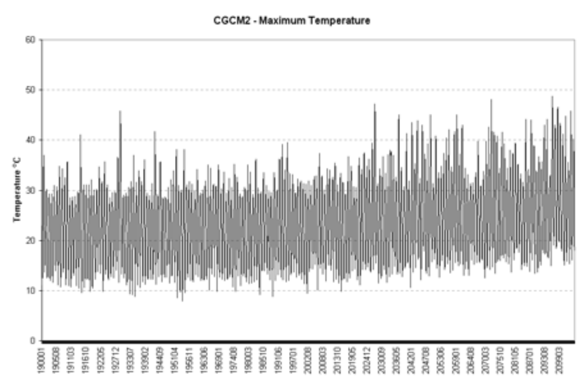
Grid Box Used

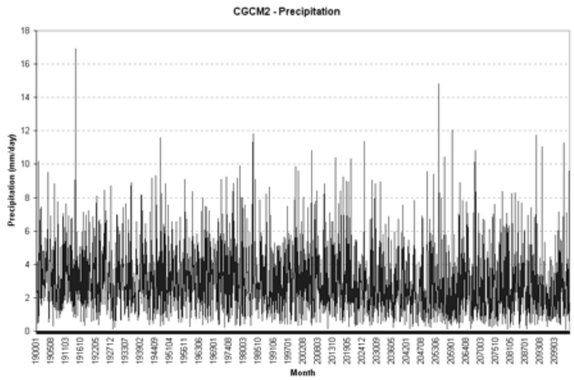
(approximately 1000 to 1500 km in mid-latitudes)

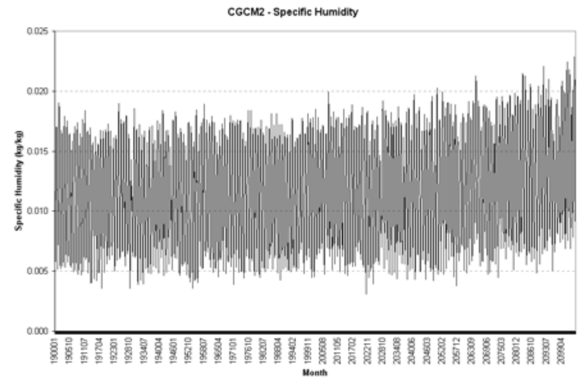
800 times the Study Area

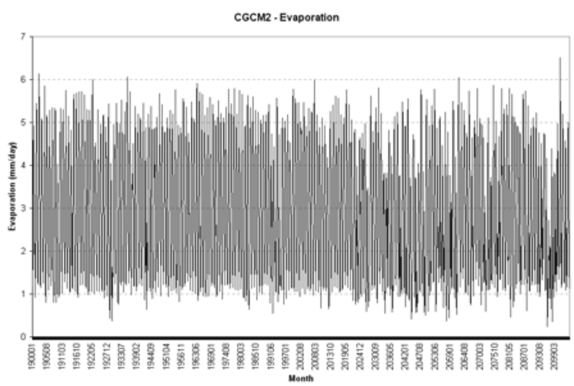


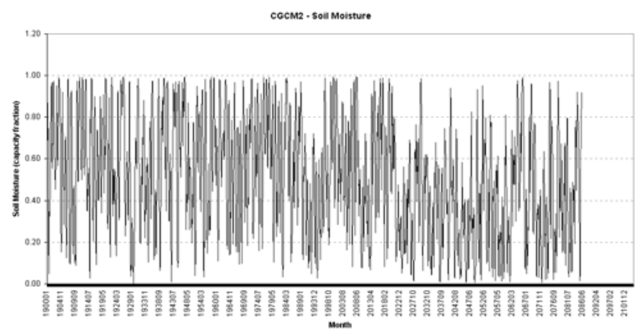


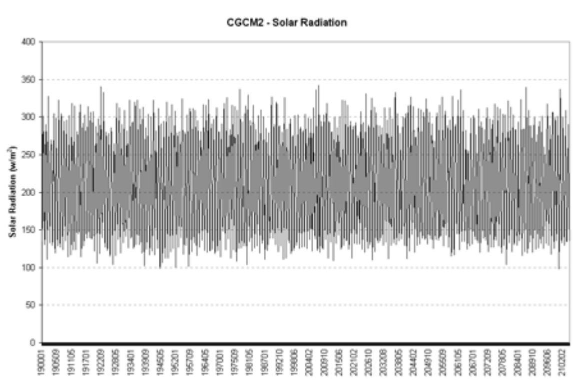



CGCM2 - Precipitation
Precipitation (mm/day)
Month


CGCM2 - Specific Humidity
Specific Humidity (kg/kg)
Month

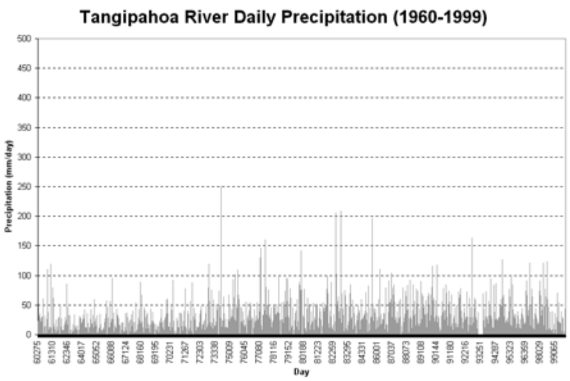

CGCM2 - Evaporation
Evaporation (mm/day)
Month

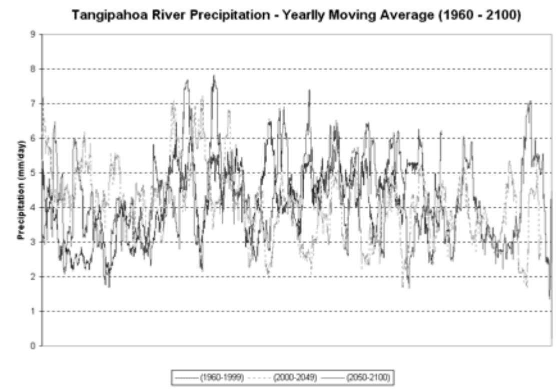

CGCM2 - Soil Moisture
Soil Moisture (capacity fraction)
Month

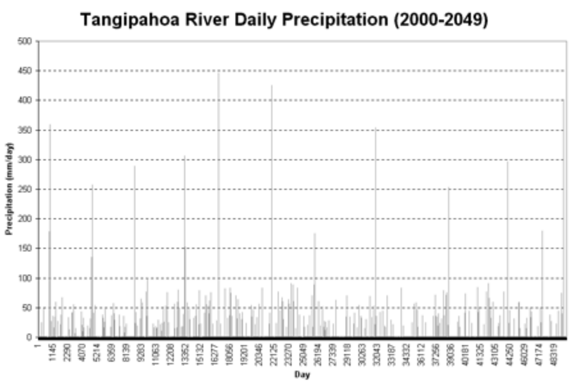

CGCM2 - Solar Radiation
Solar Radiation (w/m²)
Month

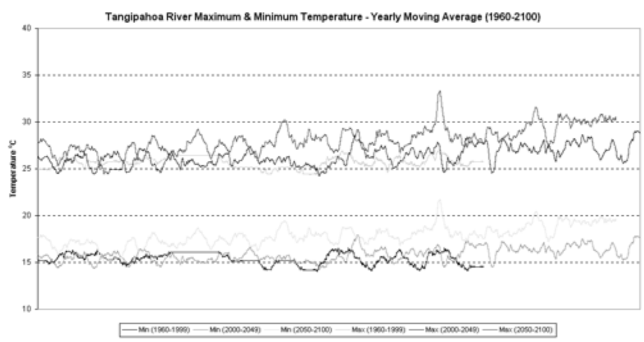
APPENDIX V

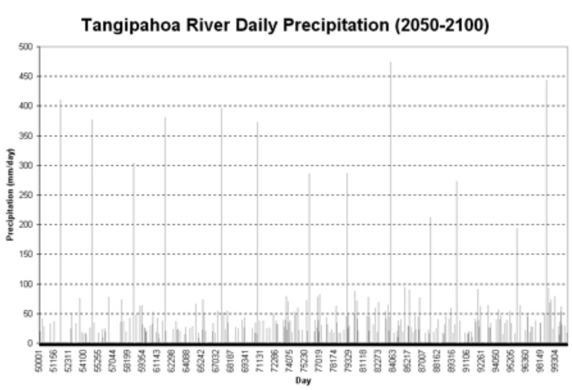
- Daily plots of the Canadian model adopted precipitation results during the period of 2000 – 2100 and the actual measurements during the period of 1960 – 1999
- Daily temperature results during the period of 2000 – 2100 using the Canadian model vs. the actual measurements during the period of 1960 – 1999
- Projected yearly-moving average precipitation
- Projected yearly moving average temperature

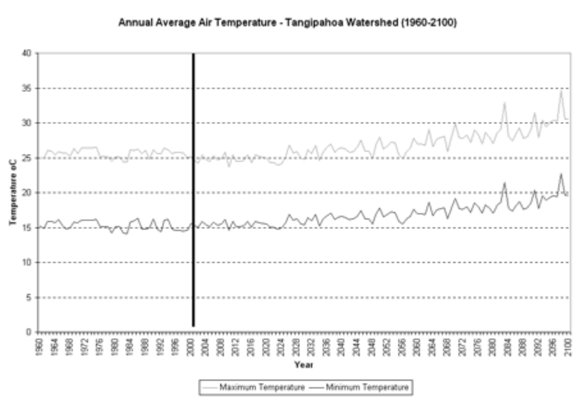

Tangipahoa River Daily Precipitation (1960-1999)
Precipitation (mm/day)
Day

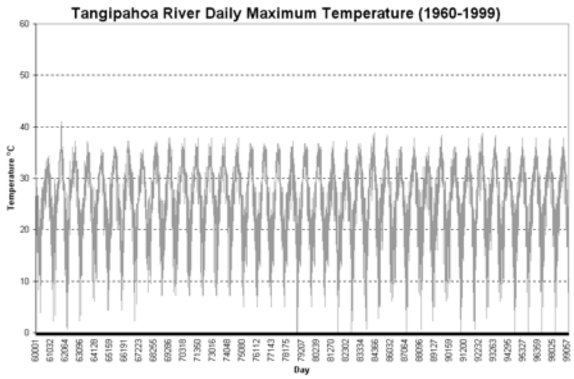

Tangipahoa River Precipitation - Yearlly Moving Average (1960 - 2100)
Precipitation (mm/day)
(1960-1999)
(2000-2049)
(2050-2100)

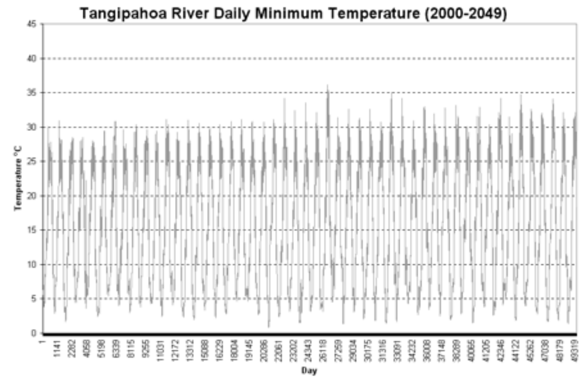

Tangipahoa River Daily Precipitation (2000-2049)
Precipitation (mm/day)
Day

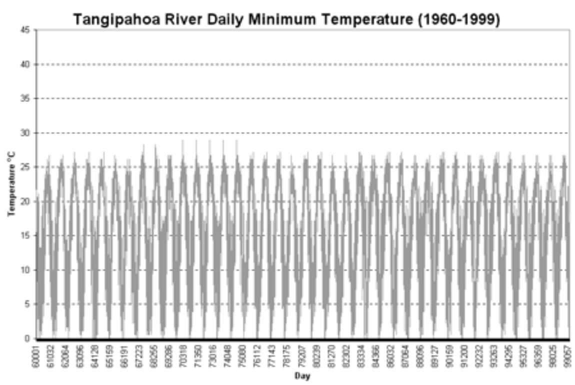

Tangipahoa River Maximum & Minimum Temperature - Yearly Moving Average (1960-2100)
Temperature °C
Min (1960-1999)
Min (2000-2049)
Min (2050-2100)
Max (1960-1999)
Max (2000-2049)
Max (2050-2100)

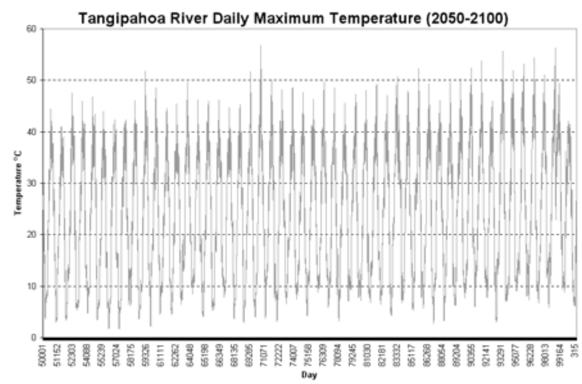

Tangipahoa River Daily Precipitation (2050-2100)
Precipitation (mm/day)
Day

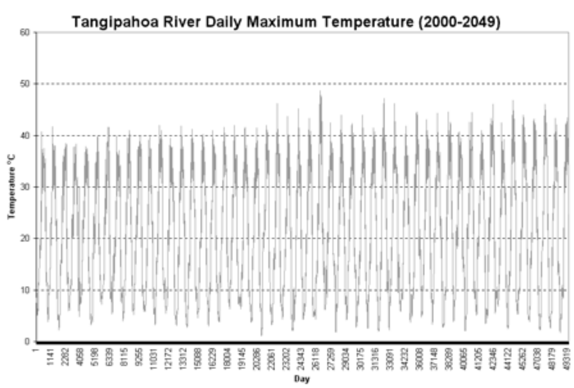

Annual Average Air Temperature - Tangipahoa Watershed (1960-2100)
Temperature oC
Year
Maximum Temperature
Minimum Temperature

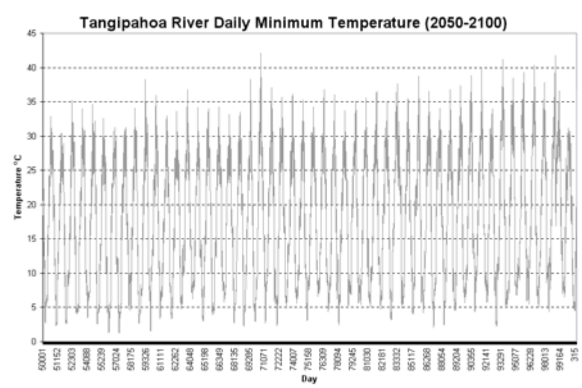

Tangipahoa River Daily Maximum Temperature (1960-1999)
Temperature °C
Day


Tangipahoa River Daily Minimum Temperature (2000-2049)
Temperature °C
Day


Tangipahoa River Daily Minimum Temperature (1960-1999)
Temperature °C
Day


Tangipahoa River Daily Maximum Temperature (2050-2100)
Temperature °C
Day

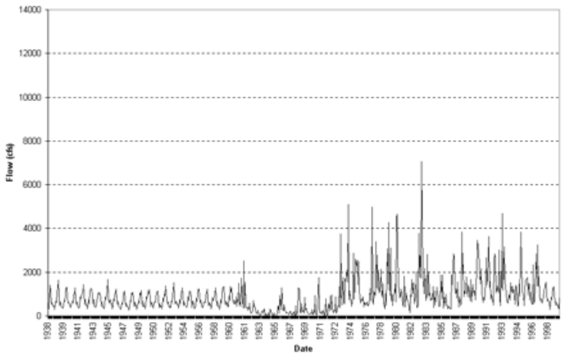

Tangipahoa River Daily Maximum Temperature (2000-2049)
Temperature °C
Day


Tangipahoa River Daily Minimum Temperature (2050-2100)
Temperature °C
Day

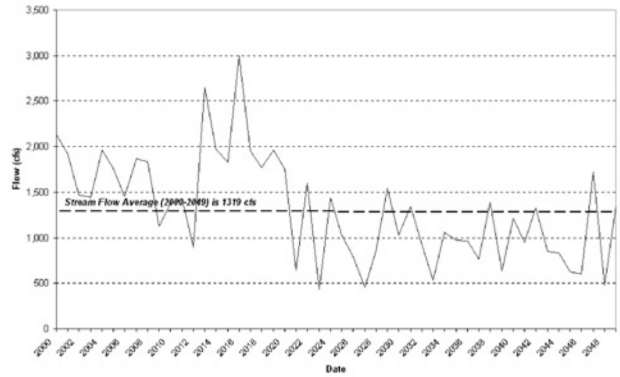
APPENDIX VI

- Typical monthly SWAT model stream flow results based on the Canadian model projected climate data at the Tangipahoa River outfall during the periods of 2000 – 2049 and 2050 – 2100 as well as the SWAT estimation based on the actual climate data during the period of 1938 – 1999

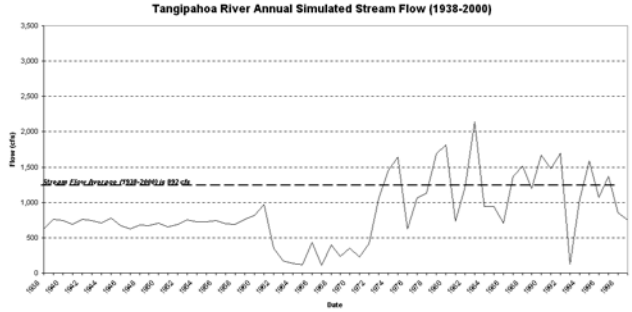
Tangipahoa River Monthly Simulated Stream Flow (1938-2000)



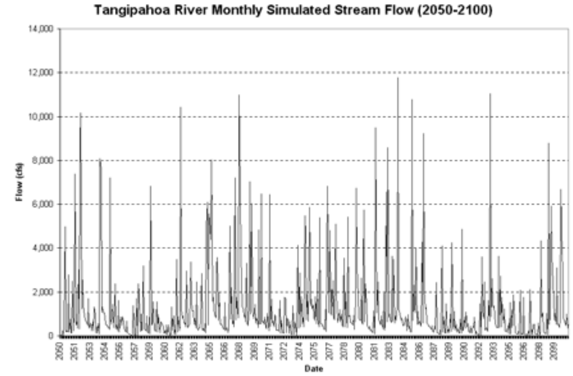
Tangipahoa River Annual Simulated Stream Flow (2000-2049)



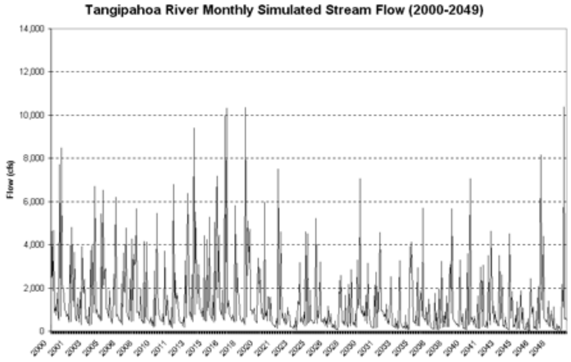
Tangipahoa River Annual Simulated Stream Flow (1938-2000)



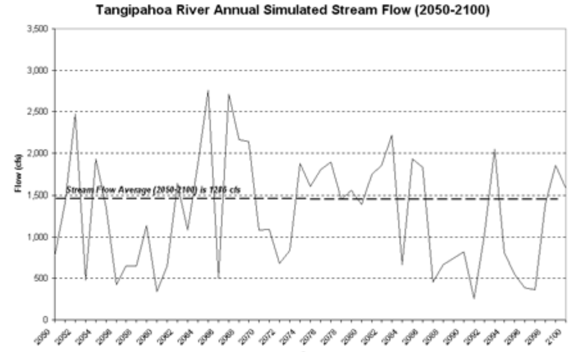
Tangipahoa River Monthly Simulated Stream Flow (2050-2100)



Tangipahoa River Monthly Simulated Stream Flow (2000-2049)



Tangipahoa River Annual Simulated Stream Flow (2050-2100)



Part III

Maritime Forests and Climate Change

Chapter 11

Predicting Coastal Retreat in the Florida Big Bend Region of the Gulf Coast under Climate Change Induced Sea-Level Rise

Thomas W. Doyle, Richard H. Day, and **Janelda M. Biagas** U.S. Geological Survey, National Wetlands Research Center, Lafayette, LA

Summary

Many wildlife preserves and refuges in coastal areas of our nation are slowly being inundated by rising sea-level. Land elevation and tidal flooding are key factors controlling the extent and zonation of coastal habitats. Warming of our global environment threatens to speed the rate of sea-level rise and perhaps further amplify the detrimental effects of tropical storms, droughts, and lightning fires. A field and modeling study was conducted to determine the current status of emergent vegetation and surficial hydrology and to predict marsh transgression under rising sea-level. Field surveys were conducted to relate vegetation cover and ecotones to surface elevation and tidal inundation. A regional site application of a GIS-based simulation model, WETLANDS, was developed to predict ecosystem response to changing sea-level conditions on a coastal reach of the Big Bend region in northwest Florida. The WETLANDS model contains functional probabilities of community tolerance to flooding conditions that dictate the rate and process of ecological succession and coastal retreat. Map information of hypsography and bathymetry of the study area were digitized and interpolated to construct a digital elevation model. Classified thematic mapper imagery of aquatic and terrestrial habitat at a community level was used to initialize model simulation by vegetative type. Model simulations were generated to predict a likelihood index of habitat change and conversion under different scenarios of sea-level rise. The WETLANDS model was applied to track the process and pattern of coastal inundation over space and time for low, mid, and high sea-level rise projections of 15, 50, and 95 cm over the next century. Model results indicated that major portions of this coastal zone will be permanently inundated by 2100, bringing about a combined migration of marsh habitat and displacement of forest habitat. Results show that lowland pine forests will undergo retreat on the order of thousands of hectares over the 21st century. Coastal marsh extent may actually increase slightly as a function of the low lying topography. Socioeconomic implications may be nominal for this area given its remote and fairly undeveloped and protected coast-

line. The model offers a technological tool for research and policy purposes that allows for effective land and water management, risk assessment, and cumulative impact analysis of wetland systems and landscapes.

11.1 Current Status and Stresses

Coastal communities worldwide are threatened by rising global sea-level in part contributed by human-induced causes related to fossil fuel consumption and increasing carbon dioxide concentrations in the atmosphere known as the "greenhouse effect." Many believe that these greenhouse gases may be contributing to warming of surface air and sea temperatures sufficient to accelerate sea-level rise, increase tropical storm intensity (Emanuel 1987), and alter regional climate patterns (Giorgi et al. 1994) commonly referred to as "climate change." Coastal margins are most vulnerable to all these potential impacts and interactions of climate variability and change (Boesch et al. 2000).

Sea-level has reportedly been rising since the last ice age (15,000 B.P.) and over the last century by as much as 1 – 2 mm/year (Gornitz, 1995). The latest Intergovernmental Panel on Climate Change (IPCC 1996) has projected a 50 cm rise in average global eustatic sea-level by year 2100 within a probable range of 15 – 95 cm given some uncertainties (Watson et al. 1996). Other conservative estimates by the U.S. Environmental Protection Agency indicate that global warming will likely raise sea-level by at least 42cm by 2100 (4.2 mm/yr, Titus and Narayanan, 1995).

These sea-level projections, however, do not consider increases in relative sea-level by region which will be affected by local factors other than warming sea temperatures (e.g., land subsidence). Gulf of Mexico coastal wetlands, in particular, have shown high rates of land subsidence attributed to soil decomposition and compaction, deep fluid extraction, and the lack of allochthonous sediment deposition. Relative sea-level is the effective change in the land/water datum relationship at a given site that includes both the eustatic sea-level change condition and changes in surficial elevation and accretion (Stevenson et al., 1986; Cahoon et al., 1998). For example, because of rapid subsidence, the Mississippi River delta region demonstrates relative sea-level rise rates of 10 mm/yr, tenfold greater than current eustatic sea-level rise (Penland and Ramsey, 1990, Turner, 1991; Gornitz, 1995).

As sea-level rises, flooding and salinity intrusion increase with slope at the coastal interface. Tidal marshes demarcate the boundary of tidal exchange though local conditions may dictate the actual height relative to tidal range. Coastal salt marshes, in general, exhibit fairly distinct zonation patterns grossly determined by the range and frequency of tidal inundation (Johnson and York, 1915; Jackson, 1952; Kurz and Wagner, 1957; Adams, 1963). The fate of persisting marshes depends on their ability to keep pace with relative sea-level rise through accretion by a combination of root production and organic and/or inorganic deposition and to tolerate any changes in soil salinity. Freshwater forest communities abutting marsh zones must likewise tolerate the increase in tidal influence or succumb to marsh migration upslope. The ability to predict coastal transgression from sea-level rise depends on the slope and height of the coastal landform and belowground processes and rates of elevation change. Because of the low relief of most gulf coast tidal marshes, rather small increases in sea-level could affect large expanses of the coastal zone.

Predicting the fate of our shorelines and coastal ecosystems is confounded by the diverse set of environmental forces and gradients that differ for each physical and biological setting. Areas along the gulf coast, for example, share the Gulf of Mexico but have different tidal regimes, energies and amplitudes, as well as different ecosystems, tropical and temperate. The frequency, periodicity, and intensity of tropical storm landfalls likewise varies across the Gulf basin. The degrees of coastal development and protection that have been applied by state and county as dictated by population, port facilities, or other priorities also differ. Detailed case studies of representative settings are needed to elucidate the specific effects and implications of climate change on our coastal resources. We reviewed the impact of probable rates of sea-level rise on the coastal wetlands of the Big Bend region of northwest Florida including St. Marks National Wildlife Refuge based on field surveys and simulation models. We considered socioeconomic implications and coping strategies that may reasonably minimize societal costs and consequences.

11.2 Regional Site Application, Big Bend Region, Florida

Tidal marshes of the Big Bend region of northwest Florida cover a 250 km stretch of coastline from

Panacea to Tarpon Springs encompassing an area estimated at 65,000 ha (Raabe et al, 1996). This coastal reach is characterized by low wave energy, semi-diurnal tides, microtidal range, low relief, and sharp vegetation zones and ecotones. A typical marsh is prominently dominated by black needlerush, *Juncus roemerianus*, interspersed with barren sand flats, and bounded by cordgrass, *Spartina alterniflora,* on tidal creeks and flats at low elevations and a diverse high marsh community at upper elevations along a forest ecotone (Figure 1). Marsh extent is usually no more than several kilometers wide, exhibiting a rather subtle elevation change of less than a meter rise from shore to coastal forest edge. Figure 2 depicts the distribution of wetland and upland habitats across the study area taken from thematic mapper imagery at 30 m pixel resolution.

Figure 1. Aerial view of typical saltmarsh and coastal pine/palmetto zones of St. Marks National Wildlife Refuge, Florida.

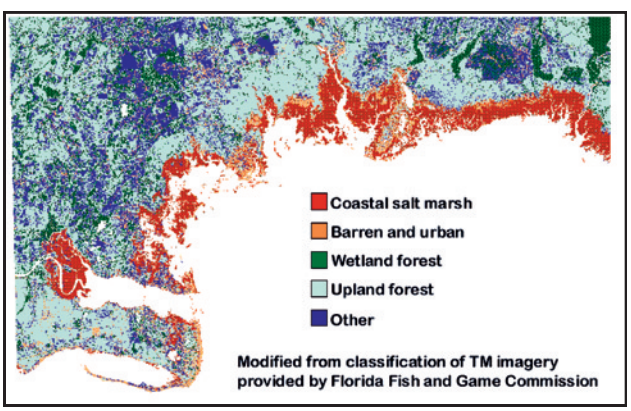


Figure 2. Habitat map of Big Bend coastal region including the boundary area of St. Marks National Wildlife Refuge south of Tallahassee, Florida.

Wave energy is classified as "zero" from St. Marks River east along the central Florida coastline to Cedar Key, Florida, and moderate from St. Marks River west to Apalachicola, Florida (Tanner, 1960). This coastal reach displays a low-relief topography of less than 1% (Coultas and Gross, 1975) that allows direct exchange of tidal ebb and flow. Tidal range is little more than 1 m between mean lower low water (MLLW) and mean higher high water (MHHW) at the mouth of the St. Marks River.

Field surveys and model applications were conducted on aquatic and terrestrial habitats of St. Marks National Wildlife Refuge in the Big Bend region of northwest Florida. The refuge is situated approximately 20 miles south of Tallahassee and covers parts of Wakulla, Jefferson, and Taylor counties. The total area of federally owned land encompasses 64,599 acres. Of the total acreage, 31,500 acres are open water in Apalachee Bay and 32,082 acres are forest and marsh. The refuge is bordered by Apalachee Bay on the south, Ochlockonee Bay on the west, and the Aucilla River on the east. The reserve was purchased in 1929 and is one of the oldest refuges in the entire refuge system of the U.S. Fish and Wildlife Service.

The refuge landscape is characterized by a relatively low elevation gradient that is intersected by several rivers and a number of freshwater springs and intertidal creeks. Upland pine sandhills drain into wet pine flatwoods and hardwood swamps within the freshwater zone and into tidal salt marsh and mudflats at bay's edge. Seagrass beds are abundant throughout Apalachee Bay, a shallow low-energy system open to the Gulf of Mexico. Elevations of these major habitat types ranges from below sea-level for seagrass, 0 – 2 ft mean sea-level (msl) for salt and fresh marsh, 2 – 4 ft msl for coastal pine, palm, and hardwood hammocks, 4 – 6 ft msl for bottomland hardwood and pine flatwoods, and above 6 ft msl for pine sandhill and oak associations in the higher elevations approaching 40 ft msl. The absence of relief contributes to the largely wetland composite of vegetation types.

11.3 Zonation of Coastal Marsh and Forest Ecotones

Zonation of low marsh habitat at St. Marks NWR is readily apparent with a narrow band of S*partina alterniflora* along tidal creeks, and then a broad expanse dominated by *Juncus roemerianus* that gives way to sand flats sparsely vegetated with succulent species, *Salicornia virginica* and *Batis maritima*. High marsh zonation above the sand flats is generally a diverse assemblage of brackish tolerant graminoids in a fairly narrow band at the ecotone of lowland pine-palmetto forest. Plant height and biomass (*Juncus roemerianus* and *Spartina alterniflora*) varies with inundation and salinity exposure, tallest near tidal creeks and lowest on higher sand flats (Kruczynski et al. 1978). Coultas and Gross (1975) described the soil types and particle size relations in this marsh which vary with elevation and vegetation from coarse-loamy Sulfaquents within low marsh grading to sandy Psammaquents and Haplaquods within high marsh habitats. Interspersed within the salt marsh zones are disjunct pine/palmetto islands from the coastal forest fringe. Island vegetation is a mix of stunted slash pine, *Pinus elliotti,* sabal palmetto, *Sabal palmetto,* saw palmetto, *Serenoa repens,* and associate shrub species. Remnant stumps of pine species and standing dead palmetto trunks are evident in high marsh zones and on small islands within the salt marsh zone (Figure 3).

Jackson (1952) and Kurz and Wagner (1957) noted the threat of coastal erosion and sea-level rise on these same coastal wetlands of the northern Florida gulf coast as evidenced from scoured beaches and remnant pine stumps in salt marsh and tidal flats. Their investigations focused on this coastal reach long before "climate change" was coined to describe the human-induced factors of fossil fuel consumption and rising CO2 that may accelerate or exacerbate global warming trends and sea-level rise. Several zonation and elevation studies have been conducted in this marsh setting denoting the close association of tidal dynamics on vegetation distribution, soils, and growth forms (Jackson 1952; Kurz and Wagner, 1957, Coultas and Gross, 1975, Kruczynski et al., 1978, Raabe et al., 1996, Cahoon et al. 1998, Doyle 1998; Williams et al., 1999). Ramsey et al., (1998) used satellite and aircraft remote sensing tools to dynamically monitor the coastal flooding extent for specific tidal events to validate and relate surface topography to vegetation zonation. A review has been conducted on coastal marshes of the northern gulf coast by Stout (1984) that illustrates the strong correlation of marsh species zonation with tidal dynamics (Eleuterius, 1976; Eleuterius and Eleuterius, 1979; Hackney and De La Cruz, 1982; Eleuterius, 1984).

Figure 3. Photograph of marsh/forest ecotone showing dead cabbage palms trunks in Juncus and high marsh settings of St. Marks National Wildlife Refuge, Florida.

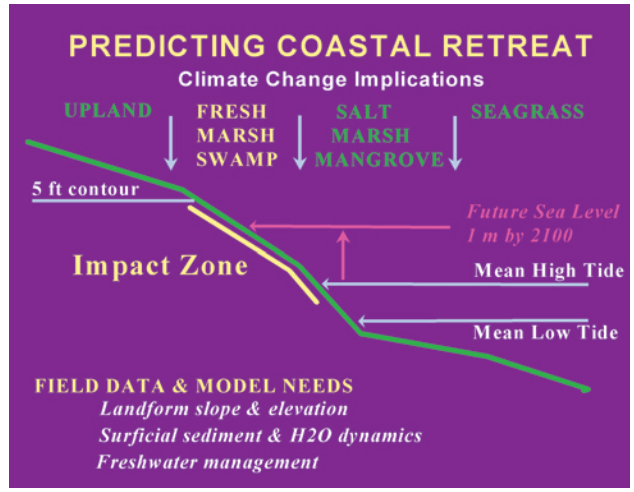


Figure 4. Conceptual model of coastal slope and process of habitat zonation and potential migration and displacement in relation to tidal range and rising sea-level. This graph illustrates the importance of characterizing the landward slope and the lack of readily available data between the 5 ft contour on USGS quadrangle maps and bathymetric data below mean high tide.

The goal of this case study was to develop a spatial simulation model to predict the effects of changing sea-level based on IPCC (1996) climate change scenarios on coastal wetlands of the gulf coast region. A field study was conducted to elucidate vegetation relations with elevation for constructing and validating a digital elevation model of the land surface. A high resolution model of surface topography was needed to predict the rate and fate of coastal inundation from sea-level rise over the next century. Figure 4 illustrates the purpose and process of characterizing the slope of the coastal landform and habitat relations linked with the tidal prism and future sea-level rise. Land elevation and tidal inundation are key factors controlling habitat type and distribution in this coastal environment. Elevation surveys were conducted across the forest/marsh ecotone in various watersheds to test the vegetation-elevation relations under different freshwater and tidal forcing.

11.4 Elevation Surveys of Landform Slope and Vegetation

The ability to predict landward transgression of coastal marsh caused by sea-level rise depends on knowledge of vegetation distribution linked to land elevation. First order benchmarks were used to open and/or close multiple transect surveys using a laser level with millimeter accuracy. Figure 5 shows a surveying crew laying out transects intersecting a typical ground view of the marsh/forest ecotone. Global positioning system dataloggers were used to record real-time differential coordinates at each transect station. Station locations were established every 30-m along a given transect from which land elevation, surface water elevation, vegetation cover and stature were recorded. Horizontal stations were increased to less than 1-m intervals to capture sharp transition zones near tidal creeks, pine-palmetto islands, and at the terrace escarpment delineating the transition between high marsh and forest cover. Field data were verified by constructing histograms of vegetation distribution with surface elevation. Most surveys closed to within 3-mm.

Figure 5. Photograph of surveying crew laying out transects intersecting a typical ground view of the marsh/forest ecotone. Note the stressed canopy condition and dead snags of cabbage palm, hardwoods, and pines along the marsh/forest transition zone.

Field survey results were used to produce proxy elevation contours within the tidal marsh landscape by identifying transition zones of vegetation types on aerial photography and even satellite imagery. Figure 6 illustrates the ranges of species occurrence with elevation and observed tidal datums. Exposed sand flats occupied by *Batis* and *Salicornia* are highly visible on remote imagery and coincidentally occurred at the upper elevations at mean high water (30 – 45 cm, low and high side, NAVD88) based on field results and observed tide tables for the area (See Figure 6). Also highly visible on aerial imagery was the distinct marsh-forest boundary which measured near the elevation of mean higher high water (MHHW, 55 – 60 cm, NAVD88) (See Figure 6). Continuous forest cover was surveyed above 1.1-m NAVD88 that was coincident with height of maximum observed normal tides. The surveyed height of the forest/marsh ecotone and exposed sand flat demarcation were used to create proxy elevation contours to construct a digital elevation model (DEM) of the study area.

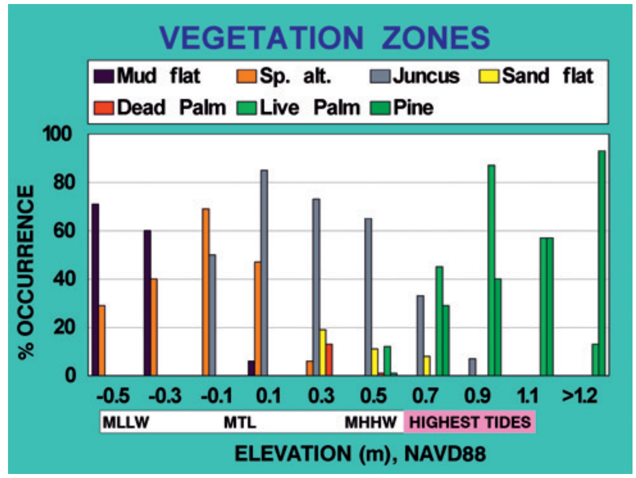


Figure 6. Elevation ranges of vegetative cover and bare substrate in relation to normal tides for St. Marks river expressed in NAVD88. Percent occurrence is based on the frequency of presence in decimeter classes for all transect points surveyed for elevation within St. Marks National Wildlife Refuge, Florida. Tidal range bar depicts height of upper (MHHW, mean higher high water), mean (MTL), lower (MLLW, mean lower low water) and highest observed tide limits recorded for the St. Marks river tide station.

11.5 Development of Landscape Digital Elevation Model (DEM)

A DEM of the study area was constructed to track the process and pattern of coastal inundation over space and time for various projections of sea-level rise. Hypsography and bathymetry of the study area were digitized from a series of coastal map products obtained from USGS 7.5' quadrangle maps (1:24,000 scale) and National Oceanic and Atmospheric Administration (NOAA) hydrographic charts (1:20,000 scale). Contour intervals on standard USGS topographic maps begin at the 5-ft or 1.5-m contour which is well above the marsh system in this locale. Proxy elevation contours based on vegetative features distinguishable on aerial photography and satellite imagery products were digitized to provide intermediate slope contours of the salt marsh system. A DEM was spatially interpolated from the collective contour lines and point data of surface elevations (NAVD88).

A complex TOPOGRID algorithm within the ARC-INFO geographic information system program was used to construct a high resolution, 30-m, DEM of the coastal reach (Figure 7). Classified thematic mapper imagery at 30-m pixel resolution of aquatic and terrestrial habitat at a community level was obtained from the Florida Freshwater Game and Fish Commission in conjunction with the Florida Department of Transportation to provide a habitat layer. Likelihood indices were derived for marsh species and forest cover in relation to land elevation to predict changes in habitat cover with increasing tidal inundation across the simulated landscape.

Model simulations were initialized with present day habitat and tidal conditions (1995). Simulated forecasts of the tidal regime were based on mean annual sea-level for Key West (assumed tectonically stable for gulf coast gages) redundantly repeated to the year 2100. Simulated sea-level rise was incremented to the observed tidal record based on IPCC

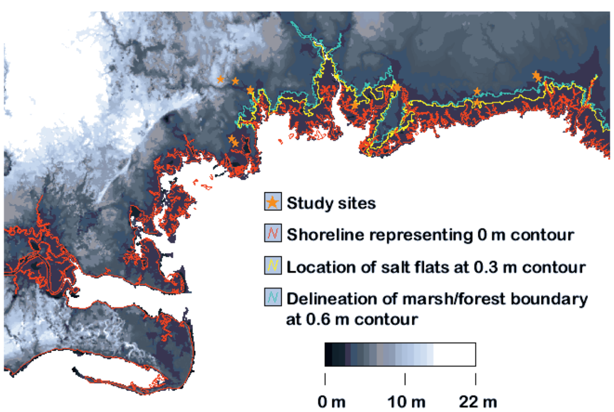


Figure 7. Digital elevation model for Big Bend coastal region encompassing St. Marks National Wildlife Refuge, Florida. Contours denote proxy elevations calibrated for given ecotones based on field survey transects (stars).

(1996) eustatic sea-level rise projections at 15 (low), 50 (mid), and 95 (high) cm. Figure 8 illustrates the modeled low-case, mid-case, and high-case sea-level projections as described for model simulation. The model maintained a register of land elevation, mean tide elevation, and current habitat type for each 30-m land unit (pixel cell) in the landscape template of the study area. This approach is similar to the USEPA Sea Level Affecting Marsh Model (SLAMM) by Lee et al. (1992) and Park et al. (1993) except for the much higher resolution DEM and empirically based habitat tolerance model that dictates habitat succession. The model is updated annually for predicted tide height which is then contrasted with the land elevation of each land unit (i.e., 30-m pixel) to determine flood height or deficit. Flood height is then used to predict favored habitat condition based on probability functions of species and community tolerance to coastal inundation and elevation calibrated from field surveys. In years where flood height exceeds tolerance for the prevailing habitat condition and favors a different habitat type, the model updates the habitat array to reflect a change in ecological succession. Model output consists of pixel counts and hectares of converted habitat, loss and gain, by calendar year.

11.6 Coastal Wetland Habitat Loss and Migration

Sea-level rise was simulated based on a series of case projections, low, mid and high, adopted from the IPCC (1996) for 2000 to 2100 (See Figure 8). At these levels, major portions of the coastal zone in this region will be permanently inundated over the next century, bringing about a migration and loss in the total area and proportion of some habitats. The model incrementally increases the flooding height on an annual basis according to the predicted change in sea-level by year for each sea-level scenario. It determines whether or not habitat conversion and/or loss occur as successive cells from coastal waters exceed the land elevation height of inland terrestrial vegetation and the tolerance of the existing vegetation type for another more tolerant plant cover.

Because of the low relief, model simulations predict significant shoreline changes and flooding of current terrestrial vegetation zones under all three IPCC (1996) sea-level rise projections (Figure 9). Results show that there is a large landbase that will be converted from marsh to open water and forest to marsh (Figure 10). However, because of the slope of the landform, coastal marsh is predicted to increase slightly in land cover as it migrates upslope and replaces existing forest habitat. A significant portion of coastal pinelands will be lost on the order of thousands of hectares that stand at or below the 1.5-m contour by a projected sea-level increase of 0.95-m (high) over the next century (See Figure 10). There will be an effective migration of emergent marsh into forested zones though an overall net loss of terrestrial habitat to an open water environment.

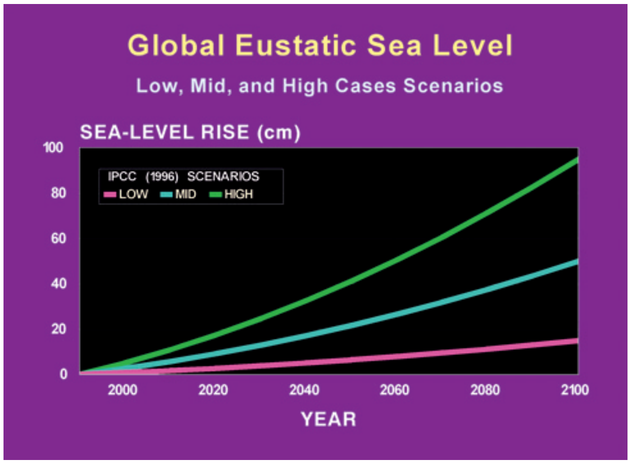


Figure 8. Eustatic sea-level rise projections for scenarios of low, moderate, and high cases based on Intergovernmental Panel on Climate Change (1996).

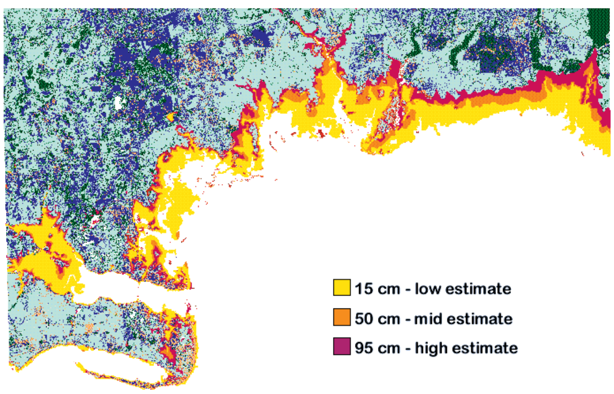


Figure 9. Predicted shoreline changes for IPCC (1996) eustatic sea-level rise projections at 15, 50, and 95 cm by year 2100.

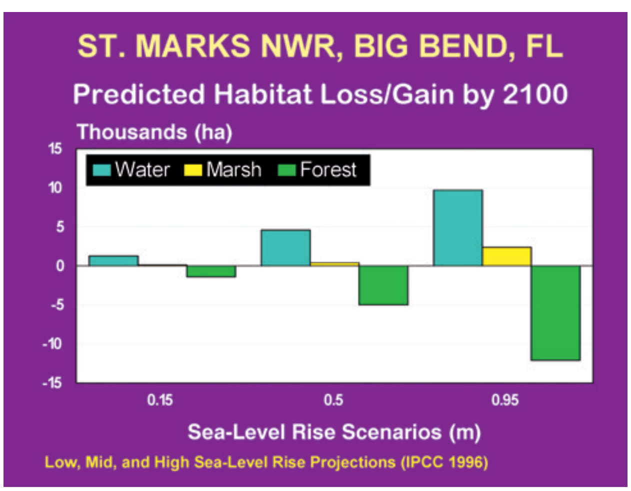


Figure 10. Predicted changes of net loss and/or gain of coarse habitat types, open water, emergent marsh, and forest for low, mid, and high sea-level rise (m) projections by the year 2100.

The use of elevation survey data and surrogate contouring based on ecotone boundaries and tide projections added to the detail and accuracy of interpolating the landform between shoreline and the 5-ft contour and for predicting habitat loss/gain under increasing sea-level conditions. This modeling approach offers a technological tool for research and policy purposes that allows for effective land and water management, risk assessment, and cumulative impact analysis of wetland systems and landscapes.

11.7 Socioeconomic Implications

Projected sea-level rise of any proportion, low or high, will effectively cause coastal transgression and reduce terrestrial habitat within the St. Marks National Wildlife Refuge. Because of its wilderness status and few inholdings, the major loss of lowland pine habitat will have little socioeconomic impact. To the contrary, model predictions for all sea-level rise cases indicate a slight gain in coastal marsh habitat that may actually enhance local fisheries and wildlife benefits. The local economy is modestly dependent on the coastal shellfish industry and a mostly upland pine forest products base. In this particular coastal reach, the U.S. Government is the primary land agent that will effectively lose a significant portion of its conservation investment on the order of thousands of hectares of coastal pine/hardwood habitat. At present, there is a sufficient buffer of extended upland sandhill forest bordering other state and federal forest preserves that these losses may only directly reduce wildlife resources carrying capacity. It is not known whether existing populations of black bear, white-tail deer, avian species, etc., can compensate for habitat losses given more intensive habitat utilization. Usually habitat losses of this scale will effectively reduce the size and security of current mammal populations and perhaps minimal consequences on resident and migratory avian populations because of how they depend on the expended resource.

Population projections for Florida counties are far above national averages. The tri-county area of Wakulla, Jefferson, and Taylor counties is no exception with projected increases of 57%, 38%, and 31% in county populations from 2000 to 2025. Most of this growth will be in and around Tallahassee and outlying populated areas that are far removed from the coast and any likely influence, direct or indirect, on these coastal resources.

11.8 Coping Strategies

Coping strategies may not be warranted given the minimal losses to the local economy and the limited options to remediate the natural process of coastal transgression. Diked systems already exist within the St. Marks National Wildlife Refuge that may be modified to slow or retard coastal transgression. Because of the shallow limestone base with underground channels to coastal waters, it is doubtful that costs and benefits could warrant any hard engineering alternatives to combat sea-level rise. It is also likely that any effective coastal revetment would do more harm than good in the near term by reducing estuary size and function, thus productivity, and spur a negative impact on the local economy.

11.9 Adaptation and Future Research

Unlike some coastal reaches where burgeoning population growth impinges on wetland health and protection, the tri-county region around St. Marks National Wildlife Refuge is still relatively undeveloped and rural. Coastal developments in the region are increasing at a modest pace but are mostly constricted to beach strands on limited stretches given the largely excluded and extensive coastline under U.S. Government protection. There are no significant impediments to coastal wetland migration to warrant consideration. Coastal adaptation strategies may be of nominal value except to determine necessary building restrictions as they relate to potential sea-level rise.

Given the long history of coastal studies relating vegetation cover and changes to tidal influence in this locale, long term monitoring of existing conditions should be implemented to document real-time events that affect coastal retreat. The study area represents a fairly isolated coastal reach largely unaffected by coastal development or upland watershed utilization so as to provide a control site for other coastal contrasts influenced directly by humans and nature. Because of the low relief and open tidal exchange of this low energy coast, this area would be ideal for investigating the contributions of short versus long term fluctuations in tidal behavior and events as related to sea-level rise and coastal transgression. For instance, little is yet known how intra-annual and inter-annual variations in climate and tidal cycles affect forest/marsh retreat and recovery.

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Chapter 12

Modeling Mangrove Forest Migration Along the Southwest Coast of Florida Under Climate Change

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Summary

Mangrove forests dominate in the intertidal zones of the tropical extent of the coast about the Gulf of Mexico, USA. Global climate change forecasts suggest that these coastal forests will be among those ecosystems most immediately threatened by projected increases in sea level and hurricanes. The interactive effects of environmental conditions that prevail in these forests and the changes that are likely to occur in a global warming climate may lead to major shifts in forest composition, structure, and function of mangrove ecosystems. The low-lying Everglades of Florida are particularly vulnerable to frequent tropical storm strikes and impending sea-level rise projected with climate change. Mangrove forests are susceptible to storm damage from wind and surge forces sufficient to alter forest structure and recovery. Computer simulation models of mangrove forest dynamics at the stand and landscape levels were developed to evaluate the impacts of increasing water levels and disturbance associated with global climate change on mangrove forests of the Everglades. A hindcast simulation for 1886-1996 indicates that the periodicity and trajectories of a few major hurricanes accounted for most of the impact on forest structure of modern day mangrove forests across south Florida. As hurricane intensity increases over the next century, model projections suggest that future mangrove forests are likely to be diminished in average height and will contain a higher proportion of red mangroves. Sea-level rise will allow mangrove encroachment into freshwater marsh and swamp environments of the interior Everglades system that with minimal coastal erosion will increase mangrove expanse and reduce freshwater marsh coverage. South Florida human population estimates will continue to grow significantly and could indirectly affect freshwater flow and circulation that could exacerbate the rate and extent of sea-level rise. Mangrove systems of south Florida are already preserved in the public land trust of various U.S. government parks and refuges. Because they are fairly remote and insulated within large public land holdings, there

is little threat from human impact of coastal development, nor are there any feasible coping strategies for abating mangrove migration into upland habitats from sea-level rise.

12.1 Current Status and Stresses

Mangrove forests occupy intertidal settings of tropical and subtropical regions worldwide (Chapman, 1976; Duke, 1992). Their predominance along the land-sea interface makes these coastal forests vulnerable to sea-level rise, tropical storms, oil spills, and other disturbances, both natural and human-induced (Snedaker and de Slyva, 1987; Field, 1995; Hogarth, 1999; Boesch, et al,. 2000). Because of their halophytic nature, mangroves tolerate the added stress of waterlogging and salinity conditions that prevail in low-lying coastal environments influenced by tides. Mangroves are highly productive ecosystems and provide valued habitat for fisheries and shorebirds (Gilmore and Snedaker, 1993). Global warming has been projected to increase sea water temperatures and expansion that may accelerate eustatic sea-level rise and further compound ecosystem stress in mangrove dominated systems (Gornitz, 1995; IPCC 1996).

Mangrove forests are prevalent along the coast of the Gulf of Mexico basin in the tropical latitudes of Texas and Florida and are limited geographically by lack of tolerance to freeze events (Odum et al., 1982). Scattered populations revegetate protected shores of the remaining northern gulf states in years between major freezes, mostly comprising the cold-hardy black mangrove, *Avicennia germinans* (McMillan, 1971; Sherrod and McMillan, 1985). Mangrove forests are universally composed of relatively few tree species and a single overstory strata (Lugo and Snedaker, 1972). Three species of true mangroves are common to intertidal zones of the Caribbean and Gulf of Mexico coasts, namely black mangrove, *Avicennia germinans* (L.) Stearn, white mangrove, *Laguncularia racemosa* (L.) Gaertn.f., and red mangrove, *Rhizophora mangle* L.

12.2 Coastal Margin of the Everglades Region, South Florida

The larger extent of mangroves in the United States lies in south Florida in Lee (14,275 ha), Collier (29,126 ha), Monroe (94,810 ha), and Dade (33,931 ha) counties surrounding the Everglades (Odum et al., 1982). The near sea-level elevation and flat slope of the protected Everglades system accounts for one of the largest contiguous tracts of mangrove forests found anywhere and punctuates their potential vulnerability to rising sea level and other climate changes. These forests are subject to coastal and inland processes of hydrology that are largely controlled by regional climate, disturbance regimes, and water management decisions. It is difficult to generalize the probable impacts of climate change given the myriad environmental settings where mangroves persist even within the Everglades.

Mangroves are adapted to tolerate coastal flooding and salinity (Lugo and Snedaker, 1972). Davis (1940) was among the first to describe the intertidal zonation and diverse geomorphic settings where mangroves colonize and persist in south Florida. While zonation has largely been attributed to salinity gradients, more recent field and experimental studies indicate that mangroves have wide tolerances to salinity and other soil factors (Hutchings and Saenger, 1987; Smith, 1992). Increases in relative sea level will eventually raise saturation and salinity conditions at ecotonal boundaries where mangroves are likely to advance or encroach upslope into freshwater marsh and swamp habitats. Other climate phenomena, such as hurricanes and lightning strikes, are frequent in south Florida and influence ecosystem health and recovery (Smith et al., 1994; Doyle et al., 1995). The impact of major hurricanes results in wide area forest damage of varying degrees from devastating blowdowns to intact, but defoliated canopies (Figure 1; Stoddart, 1963; Steinke and Ward, 1989; Roth, 1992, Wunderle et al, 1992; Doyle et al., 1995). Lightning strikes are frequent in this coastal region causing circular gaps of less than 0.1 ha wherein all trees within a given radius are killed by electrical conduction in saltwater (Figure 2; Smith et al., 1994). Other climate stressescan cause mangrove

Figure 1. Devastated mangrove forest in Everglades National Park in the aftermath of Hurricane Andrew in 1992.

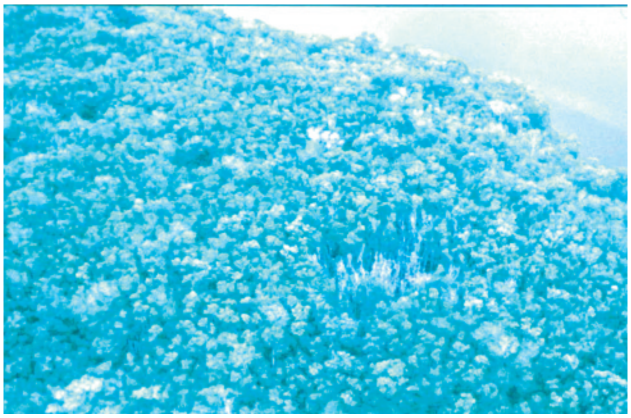

Figure 2. Aerial view of mangrove forest canopy prior to Hurricane Andrew of a lightning gap with standing dead snags.

Figure 3. Mangrove impoundment at Ding Darling National Wildlife Refuge on Sanibel Island, Florida, where multiple rain storm events in as many decades have caused recurring stress and dieback of the local mangrove population.

dieback or decline including hard freezes (Lugo and Patterson-Zucca, 1977),seve-re drought and water deficits, as well as extreme precipitation events where water levels, if impounded, can rise acutely and cause massive dieoffs (Figure 3; Doyle, 1998). Rapid substrate collapse (subsidence) can occur following mangrove dieoff as a result of root zone decomposition that can be substantial enough to prohibit recolonization and spur coastal erosion (Wanless et al., 1994; Cahoon et al., 1998).

12.3 Hurricane Effects on South Florida Mangrove Communities

Mangrove ecosystems dominate the coastal areas of the lower Florida peninsula, where hurricanes frequently strike. Tropical storm frequency along any given stretch has been estimated at one event every 5-10 years. Climate change studies predict that tropical storm events may become more intense in a warming global environment (Emanuel, 1987). Numerous field studies have documented the susceptibility and vulnerability of neotropical mangrove species and systems to hurricane disturbance (Craighead and Gilbert, 1962; Stoddart, 1963 Craighead 1964, 1971; Roth, 1992, Wunderle et al., 1992; Smith et al., 1994).

More recent investigations by Doyle et al. (1994, 1995) of effects of Hurricane Andrew (1992) on south Florida mangroves relate how the physical and biological elements interact to explain the varying degrees of windthrow and mortality relative to hurricane intensity, path, and direction. Permanent field sites were established to assess the extent of forest damage and to monitor the rate and process of forest recovery following Hurricane Andrew (Figure 4). Canopy trees suffered the highest mortality particularly for sites within and immediately north of the storm's eyewall. The type and extent of site damage, windthrow, branch loss, and defoliation, generally decreased exponentially with increasing distance from the storm path. Right quadrant impacts were greater than left quadrant effects for the same given distance from storm center. Stand exposure, both horizontally and vertically, increased the propensity and probability of forest damage accounting for much of the local variability (Figure 5). Slight species differences were found where *Laguncularia race-*

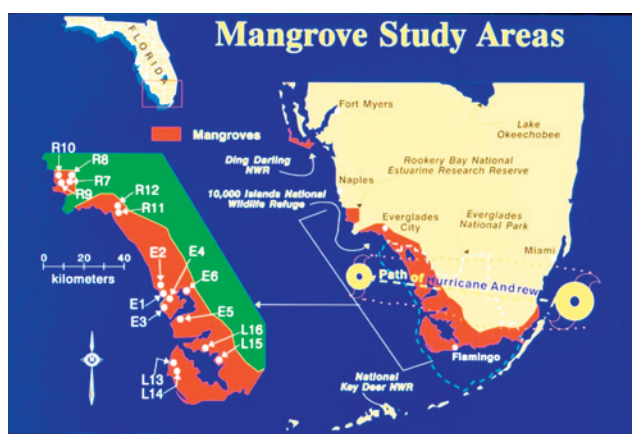

Figure 4. Map of mangrove extent and field plots in south Florida parks and refuges with overlay of storm track of Hurricane Andrew.

mosa exceeded *Avicennia germinans* and *Rhizophora mangle* in damage potential under similar wind conditions. Azimuths of downed trees were strongly

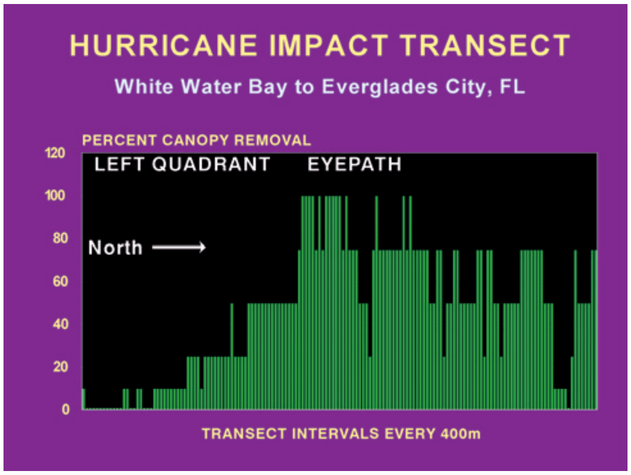

Figure 5. Damage profile of mangrove cover along a coastal transect of Everglades National Park perpendicular to the eyepath of Hurricane Andrew demonstrating the imprint of forward and backside impact (after Doyle et al., 1994).

correlated with predicted windspeed and vectors based on a computer simulation of Hurricane Andrew. Lateral branch loss and leaf defoliation on sites without windthrow damage indicated a degree of crown thinning and light penetration equivalent to treefall gaps under normally intact forest conditions. Forest damage and tree mortality functions were constructed in relation to predicted windspeeds from these empirical data and incorporated into a mangrove forest simulation model for south Florida (Figure 6).

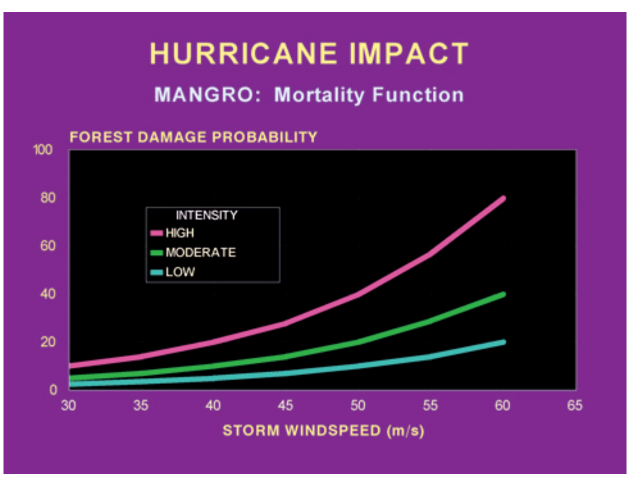

Figure 6. Forest damage probabilities and tree mortality functions constructed from field observations in relation to predicted hurricane windspeeds used for mangrove forest model application.

12.4 HURASIM Hurricane Model: Spatial Reconstructions of Hurricane History

A hurricane model, HURASIM, and a mangrove forest model, MANGRO, were combined in a spatially distributed landscape application to review the impact of hurricane history over the last century on forest structure of mangrove communities across south Florida (Doyle and Girod, 1997). A landscape modeling application was applied to test the importance of hurricanes in controlling mangrove forest structure and dynamics and to project the potential impact of increasing hurricane intensity of future storms under climate change (Doyle, 1998). HURASIM is a spatial simulation model of hurricane structure and circulation for reconstructing estimated windforce and vectors of past hurricanes (Doyle and Girod, 1997). The model uses historic tracking and meteorological data of dated North Atlantic tropical storms from 1886 to present and a graphics interface and for display (Figure 7). The model generated a matrix of storm characteristics (i.e., windspeed, direction, and distance) within discrete geographic units of the south Florida landscape that were then passed to the

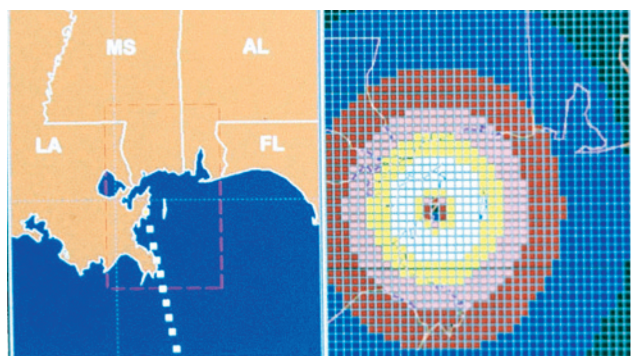

Figure 7. Sample graphics interface and spatial articulation of a reconstructed storm path of Hurricane Camille (1969) extracted from the HURASIM hurricane simulation model.

MANGRO model to predict forest response. This integrated, landscape-modeling approach offers the ability to evaluate the temporal and spatial variability of hurricane disturbance over the last century and in the future under climate at both the local and regional scale.

12.5 MANGRO Forest Model

MANGRO is a spatially explicit, stand-simulation model constructed for Neotropical mangrove forests composed of black mangrove, white mangrove, and red mangrove (Figure 8). MANGRO is an individual-based model composed of a species-specific set of biological functions predicting the growth, establishment, and death of individual trees. MANGRO predicts the tree and gap replacement process of natural forest succession as influenced by stand structure and environmental conditions. The position of each tree is explicitly defined on a planar coordi-

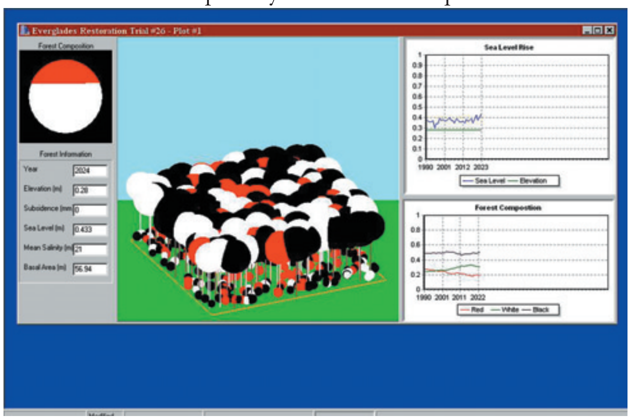

Figure 8. Sample graphics interface of the MANGRO model and a recruitement phase of mixed mangrove species composition.

nate system with a default stand area of 1 ha (100-m per side). Canopy structure is modeled as a three-dimensional process of crown height, width, and depth in relation to sun angle and shading by neighboring trees. Tree growth was based on growth potential for a given tree size reduced by the degree of light availability to the individual tree and species response to shade. Mortality was modeled as a stochastic process of age, suppression, and hurricane impact derived from damage probability curves developed from observed data of Hurricane Andrew (1992) impact (Doyle et al., 1994; 1995) (See Figure 6).

12.6 Hindcast Simulations of Hurricane Strikes and Mangrove Ecosystem Response

Both the MANGRO and HURASIM model simulations were projected onto a compartmentalized landscape of south Florida at a scale equal to a 7.5 minute quadrangle (Doyle and Girod, 1997, Doyle 1998). In total, 41 cells of an uneven matrix design were identified across the lower peninsula of Florida that contained distributions of mangrove habitat. Each cell represented an intact forest condition approximated by an independent simulation of the MANGRO model. Figure 9 shows a landscape template of mangrove distribution on a 10-km scale and the reconstucted frequency of hurricanes from 1886 to present across the south Florida peninsula produced with the HURASIM model. The model demonstrates that hurricane incidence varies greatly over the range of mangrove distribution in south Florida. Four treatment effects were implemented including a no-hurricane simulation contrasted with a low, mod-

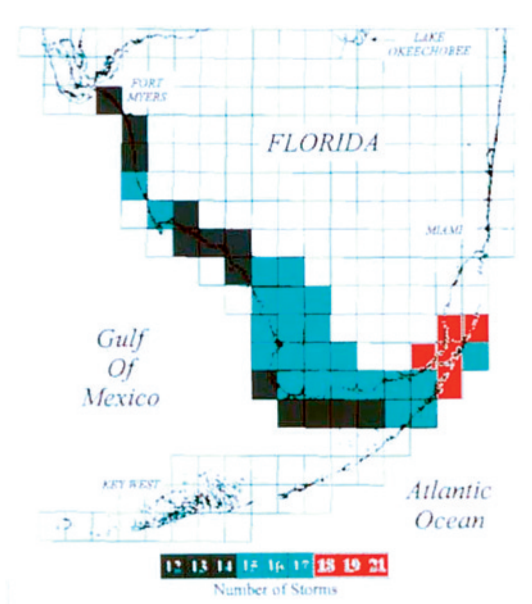

Figure 9. Landscape template of mangrove distribution on a 10-km scale and the reconstucted frequency of hurricanes from 1886 to 1996 across the south Florida peninsula produced with the HURASIM model (Doyle and Girod, 1997).

erate, and high mortality effect that increases with corresponding increases in windspeed (See Figure 6). A hindcast simulation for the period 1886 through 1989 was achieved by passing hurricane and site-specific information from the HURASIM model to the associated MANGRO simulation for common cells.

A cumulative assessment of hurricane impact was achieved by averaging stand attributes and size for the entire simulated landscape and hindcast interval (1890-1990). Simulations of hurricane tracks and history for south Florida showed that storm frequency and intensity varied across the landscape. Hurricane frequencies by quadrangle for the period of record showed that the number of storms with winds exceeding 30 m/s were more numerous on the Atlantic side than gulf side of Florida's lower peninsula (See Figure 9). The combined layering of hurricane impact showed that there are portions of the south Florida landscape that have received more frequent and more intense storm activity than other portions with either less frequent or less intense storm history. This finding indicates that different locations of the south Florida landscape have experienced a greater or lesser disturbance regime related to hurricane history. Hindcast simulations of actual hurricane tracks and conditions seem to account for the structural composition of modern day mangrove forests across south Florida. The periodicity of major storms every 30 years in the 20th century may be the most important factor controlling mangrove ecosystem dynamics in south Florida. The most significant changes in forest structure followed major storms with tracks that subtended the larger distribution of mangrove habitat (See Figure 10). Global climate change models predict an increase in hurricane intensity over the next century that could further alter the structure and composition of this mangrove landscape. As damage potential increased from low to high, forest structure was increasingly reduced. Model results of climate change scenarios (high damage probability) indicate that future mangrove forests are likely to be diminished in stature and perhaps include a higher proportion of red mangroves (See Figure 10).

Present day forest structure from select locations across the south Florida landscape compared similarly to model results from the moderate storm damage function. The integrative modeling approach of combining physical models like HURASIM with biological models like MANGRO offers the ability to assess large scale and long-term processes of climate-related phenomena on our natural ecosystems. Decadal and longer time scale changes in hurricane behavior and regularity may be much more significant in shaping mangrove community structure and distribution on the landscape than can be evaluated by field studies alone.

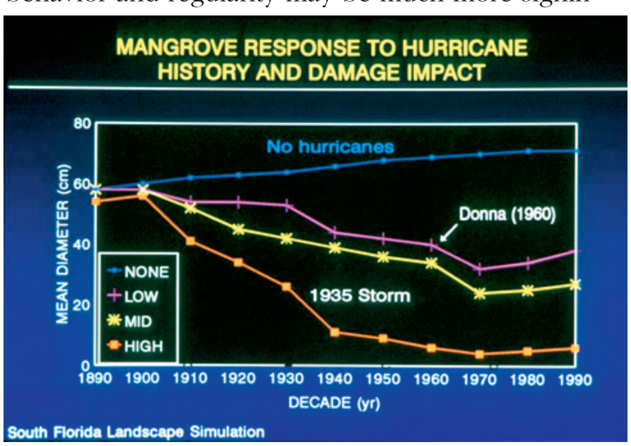

Figure 10. Predicted changes in the composite structure of mangrove forest based on mean stand diameter for 1890-1990 for low, moderate, and high damage probability functions. Major storms are labeled and demonstrate the potential impact of single storms on landscape level.

12.7 Development of an Everglades Digital Elevation Model

Coastal forests of South Florida are subject to coastal and inland processes of hydrology largely controlled by regional climate, disturbance regimes, and water management decisions. The complex of climate change factors, namely sea-level rise, seasonal precipitation and temperature fluctuations, lightning storms, and hurricanes, will likely affect coastal margin habitats, including mangroves, to a greater degree than upland habitats of the Everglades. Modest changes in the climate cycle, particularly sea-level conditions, short- and long-term, can alter the hydrologic balance and tidal prism sufficient to alter habitat type and boundaries. Model applications were conducted to forecast mangrove migration under projected climate change scenarios of sea-level rise and saltwater intrusion for the Everglades coastal margin.

A high resolution model of surface topography was needed to predict the rate and fate of coastal inundation from sea-level rise over the next century. Tidal inundation and circulation are key factors controlling mangrove distribution in this coastal environment. The ability to predict landward transgression of mangroves caused by sea-level rise depends on the relationship between landward slope and elevation in relation to tide range and extent plus an understanding of relative sea-level rise (Figure 11). A historic topographic and drainage map produced by Davis (1943) with 1-ft contour intervals across the south Florida Everglades was rectified and digitized into a geographic information systems application. Boundary zones of major habitat classes were also digitized from the natural vegetation map of Florida produced by Davis (1943) to delineate the lower and upper elevations of the intertidal zone as defined by mangrove extent. The coastline was assigned an elevation of mean sea level while the upper transition zone of mangrove extent was approximated at mean high water for available tide datums along the southwest coast of Florida. These combined data sources and proxy contours served as baseline elevation values for constructing a digital elevation model (DEM) of south Florida.

A digital elevation model of the Everglades was developed to track the process and pattern of coastal inundation over space and time for various projections of sea-level rise. The TOPOGRID algorithm within the ARC-INFO geographic information system program was used to interpolate a high resolution,

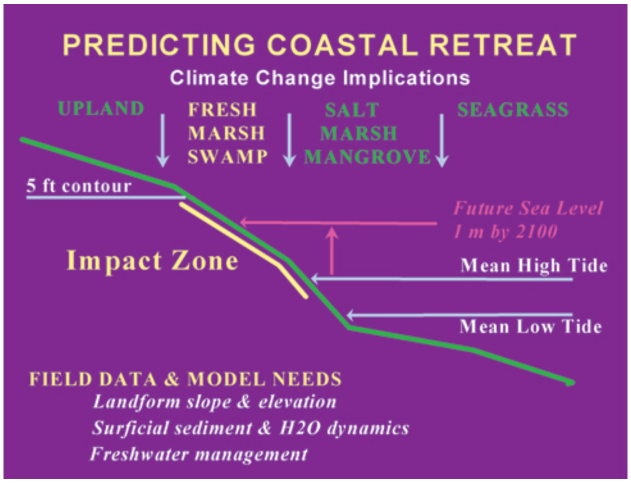

Figure 11. Concept diagram illustrating the relationship between landward slope and elevation in relation to the tidal prism and potential impact of sea-level rise.

100-m, DEM of the Everglades from the collective contour line graphs (Figure 12). The vegetation map layers were similarly classified into a raster-based image of habitat of the same scale to serve as base layers for the SELVA-MANGRO simulation model applications.

12.8 Forecasting Sea-Level Rise and Mangrove Migration across South Florida

The SELVA-MANGRO model represents a hierarchically integrated landscape model that manages the exchange of scalar information up, down, and across scale between linked simulation models SELVA and MANGRO (Doyle and Girod, 1997). SELVA is the Spatially Explicit Landscape Vegetation Analysis model that tracks predicted changes in the biotic and abiotic conditions of each land unit (1 sq ha) on an annual basis for the entire simulated landscape. SELVA passes necessary information of environmental change to the MANGRO model at the stand level for each and all land units in the landscape profile. MANGRO returns a state condition of stand structure and composition to SELVA as predicted for each growth season or calendar year. Composite maps are produced that exhibit the predicted changes in species composition and forest migration, loss or gain, as influenced by changes in sea level.

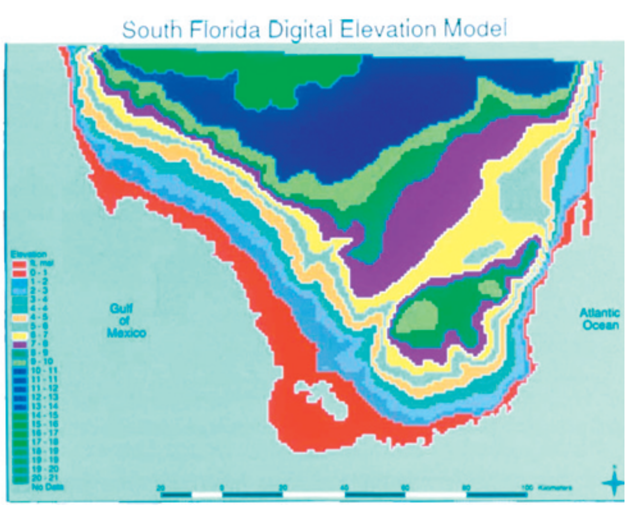

Figure 12. Digital elevation model (DEM) of south Florida based on spatial interpolation of elevation contour and proxy zonation heights taken from vegetation and topographic maps published by Davis (1943).

Sea-level rise was modeled as a function of historic sea-level conditions at Key West, Florida, based on mean annual tide records (1940 to present) projected into the 21st century with the addition of curvilinear rates of eustatic sea level expected from climate change (Figure 13). The historic record was retained to mimic the natural cycle of high and low tidal variation attributed to astronomical and meteorological causes. The data record was extended into the next 100 years with the addition of multiple cases of eustatic rates of sea-level rise based on IPCC (1996) low, mid, and high projections obtained from global climate change models. Model simulations were achieved for each sea-level rise scenario by resetting the tidal prism for each case by calendar year.

The model is updated annually as to the predicted tide height which is then contrasted with the land elevation of each land unit to determine flood height or deficit. Flood height is then used to predict favored habitat condition and species regeneration based on probability functions of species and community tolerance to water level and salinity. Mangrove species establishment was modeled as a function of tidal sorting and presence or absence of parent trees in adjoining land units. Seeding probabilities favored red mangrove in persistently inundated soils, while black mangrove and white mangrove seedlings were favored in irregularly flooded soils. Mangrove regeneration and migration were allowed in any land unit where tidal inundation exceeded soil elevation for any given year. In years where flood height exceeds tolerance for the prevailing habitat condition and favors a different habitat type, the model updates the habitat array to reflect a change in ecological succession. Model output consists of land unit counts and hectares of converted habitat, loss and/or gain, by calendar year.

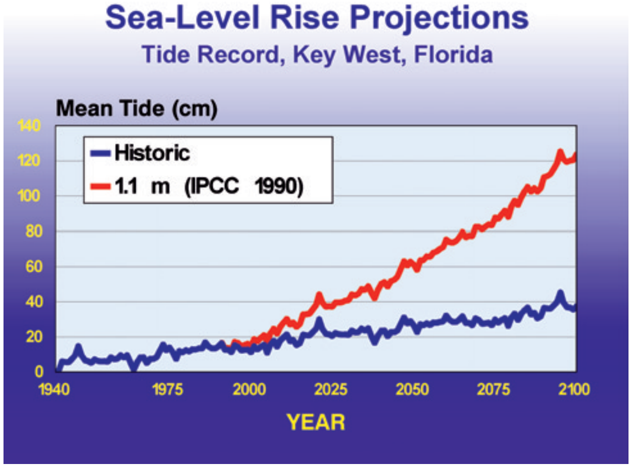

Figure 13. Sea-level rise functions of historic sea-level conditions at Key West, Florida based on mean annual tide records (1940 to present) projected to year 2100. Projected eustatic sea level rates were from climate change of up to 1.1-m were constructed for model applications.

Model results show that species and forest cover changed over space and time with increasing tidal inundation across the simulated landscape for all sea-level rise scenarios. Figure 14 contrasts the degree of mangrove migration compared with contemporary distribution and selected sea-level scenarios, low, moderate, and high, expected by 2100. The greater the rate of sea-level rise the faster or more extensive the encroachment of mangroves onto the Everglades slope. The model shows that freshwater marsh and swamp habitats will be displaced as the tidal prism increases over time as it moves upslope. Under these modeling assumptions, mangrove habitat will increase over the next century under climate change and conversely, freshwater marsh/swamp is expected to decrease. Figure 15 shows the predicted land area that mangroves will gain at the expense of other freshwater habitats over the next century relative to a host of predicted estimates of climate change-induced sea-level rise. Coastal erosion is a realistic probability driven more from hurricane influence than just sea-level rise alone. In spite of major storm strikes along the southwest coast where some tidal flats once dominated by mangroves remain unvegetated due to hurricane impact, the coastline over the last 60 years has remained remarkably stable. The land building qualities of mangroves to capture and hold marine sediment deposition is sufficient to buffer normal wave energy of the Gulf of Mexico in the absence of severe tropical storms.

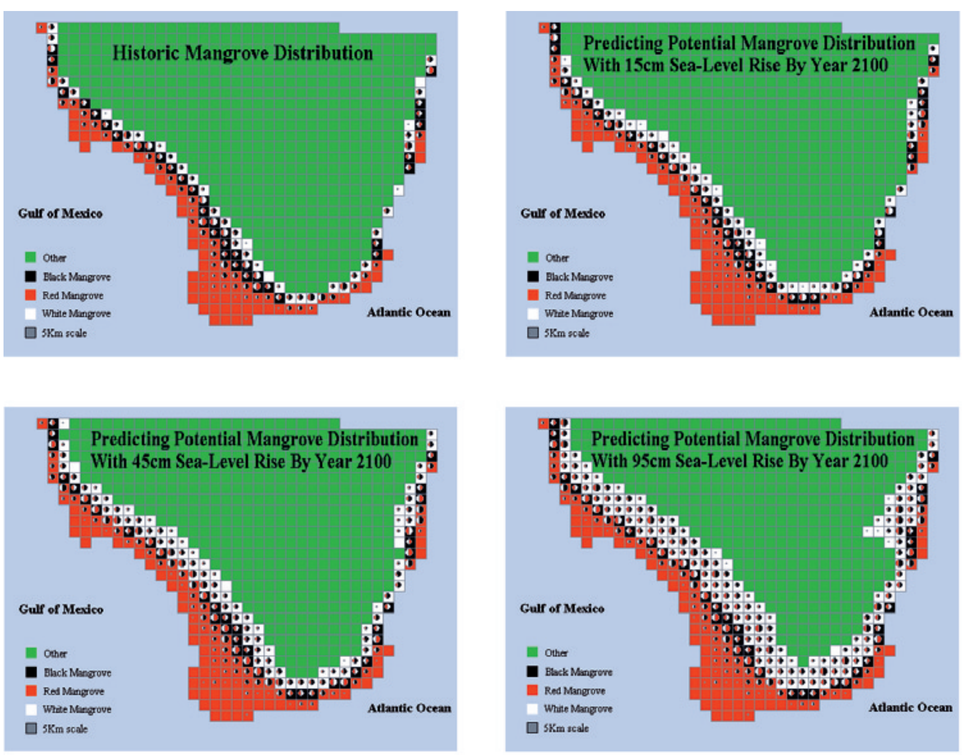

Figure 14. Contemporary and predicted distributions and species composition from inland mangrove migration under selected IPCC (1996) sea-level scenarios, low (15 cm), moderate (45 cm), and high (95 cm), expected by 2100.

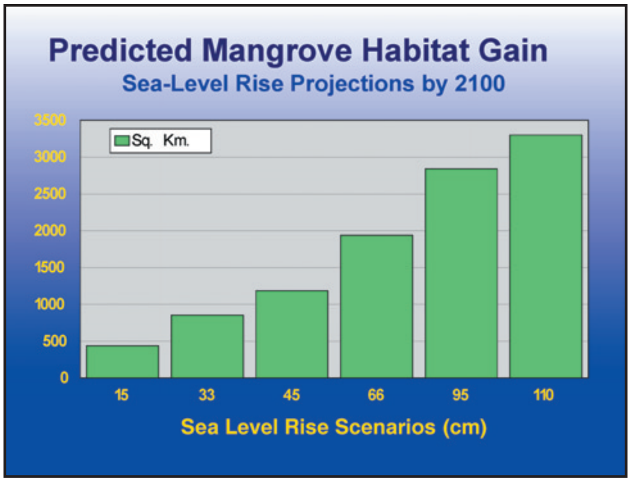

Figure 15. Predicted land area that mangroves will gain at the expense of other freshwater habitats over the next century relative for various projected estimates of climate change induced sea level rise.

12.9 Socioeconomic Implications

Projected human population growth of south Florida is among the highest rates nationally. Coastal counties, Collier, Lee, and Monroe, along the southwest "Gold" coast of Florida neighboring the northern Everglades, are projected to grow at 83%, 62%, and 28%, respectively by year 2025. The burgeoning growth of south Florida places a high demand on public resources, such as electricity, water, and land. The competing needs for freshwater may be the first and most critical resource that will likely impinge on surrounding conservation areas and coastal preserves. Changes in freshwater storage and flow, above and below surface, will indirectly, if not directly, speed the effect and extent of sea-level rise without mitigating strategies. The Greater Everglades Ecosystem Restoration Program has been funded by Congress to insure that natural systems will be enhanced with more responsible freshwater controls. Public demand for potable water supplies must be met by other means such as desalinization plants and other conservation measures.

Study findings show that projected sea-level rise of any rate will result in further inland penetration of saltwater that will effectively prompt mangrove migration into upslope marsh and swamp habitats across the coastal margin of the Everglades. Because of the protected status and isolation of the larger Everglades system, sea-level rise will likely increase mangrove distribution and reduce the proportion of some freshwater habitats with little or no socioeconomic impact depending on any changes in freshwater management. Model predictions for all sea-level rise cases indicate significant gains in coastal mangrove habitat that could actually enhance local fisheries, but could also compromise other wildlife benefits. The local economy is mostly dependent on tourism and recreation which will be unaffected by these climate change impacts.

The U.S. Government holds in public trust the entire land area encompassing the coastal margin of the Everglades. There are no private or commercial interests that will suffer directly from the probable shift in habitat proportions from freshwater dominated systems to coastally dominated habitats. While the model predicts no actual land acreage losses, it is possible that the interaction of sea-level rise and hurricanes may promote more coastal scouring than is predicted. The projected losses of freshwater habitat could negatively impact wildlife resources more dependent on freshwater wetlands than mangroves. It is not known whether existing animal populations can compensate for these habitat losses with more intensive habitat utilization.

12.10 Coping Strategies

Coping strategies are likely not warranted given the minimal losses to the local economy and the limited options to remediate the natural process of coastal transgression. Freshwater control structures and long-term management strategies are in place to restore and revitalize historic flow and habitat conditions. The use of freshwater head may be sufficient to slow or retard mangrove migration where and when warranted.

12.11 Adaptation and Future Research

Freshwater conservation measures must be implemented to accommodate the current population boom in south Florida counties to prevent any problems of water utilization and wastewater disposal on surrounding ecosystem health. Coastal developments in the region are highly regulated though inland developments that alter watershed relations and recharge could be of greater concern. As a state, Florida has advanced environmental regulation for coastal development and mangrove protection that is sufficient to preserve their coastal resources. The absence of any inholdings or other private or commercial investments in the Everglades presents no significant impediments to coastal wetland migration to warrant consideration. Coastal adaptation strategies are neither warranted nor cost effective considering what control could already be in place to moderate freshwater flow through the Everglades as an alternative to sea-side engineering projects. Given the legacy and high profile of the Everglades and recent government funding for water management control and ecosystem restoration, it should be recommended that long term monitoring of existing conditions should be implemented to document real-time events that affect mangrove/marsh migration or decline. Monitoring efforts would also be useful to calibrate and validate model applications such as described herein to refine current predictions.

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Chapter 13

Assessing the Vulnerability of the Alabama Gulf Coast to Intense Hurricane Strikes and Forest Fires in the Light of Long-term Climatic Changes

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Summary

Any realistic assessment of the impacts of future climatic changes on the Gulf coast region must take into consideration the effects of global warming on hurricane activity. It has been hypothesized that the hazard of wildfire increases significantly after an intense hurricane strike. However, the lack of long-term records on intense hurricane landfalls and major wildfires has prevented a vigorous evaluation of the hypothesis of hurricane-fire interactions. In this paper, we present a 1200-year record of intense hurricane strikes and wildfires on the Gulf coast based on a study of overwash sand layers, fossil pollen and dinoflagellates, and microscopic charcoal particles in a sediment core retrieved from Little Lake, Alabama. Our data suggest that intense hurricanes (category 3-5 according to the Saffir-Simpson scale) directly struck coastal Alabama at least seven times during the past 1250 years, implying an overall return period of about 180 years. Three of the four peaks in charcoal concentrations are associated with overwash sand layers, implying that major wildfires occurred shortly after intense hurricane strikes. Recent studies suggest that a climatic shift after 1995 may result in heightened hurricane activity along the Gulf coast in the next several decades. This could also lead to increased fire hazard for the forests of the Gulf coast states.

13.1 Introduction

Any comprehensive assessment of climate change impacts on the Gulf of Mexico coast must take into consideration the physical, ecological, and societal impacts of intense hurricanes. During the past 100 years for which instrumental observations are available, the Gulf coast was repeatedly struck by hurricanes, including catastrophic ones like Camille of 1969, a category 5 hurricane that is the strongest to have made landfall on the mainland U.S. coast during the historical period. How vulnerable is the Gulf coast to destructive impacts due to landfalling hurricanes of category 3 – 5 intensities (here referred to as intense hurricanes)? This question can be tackled by statistically analyzing the historical record of hurricane landfalls to derive an estimate of return period or landfall probability for each county along the Gulf coast (Elsner and Kara, 1999; Murnane et al., 2000). However, the period of instrumental observation for hurricane activity is essentially confined to the past 100 years (Neumann et al., 1999), a period too short to include many direct hits by intense hurricanes for most coastal locations. An alternative approach to address this question is by means of *paleotempestology,* a new field of science that studies past hurricane activity by means of geological proxy techniques (Liu and Fearn, 2000a, 2000b). In their pioneer study on Lake Shelby, Alabama, Liu and Fearn (1993) used overwash sand layers found in

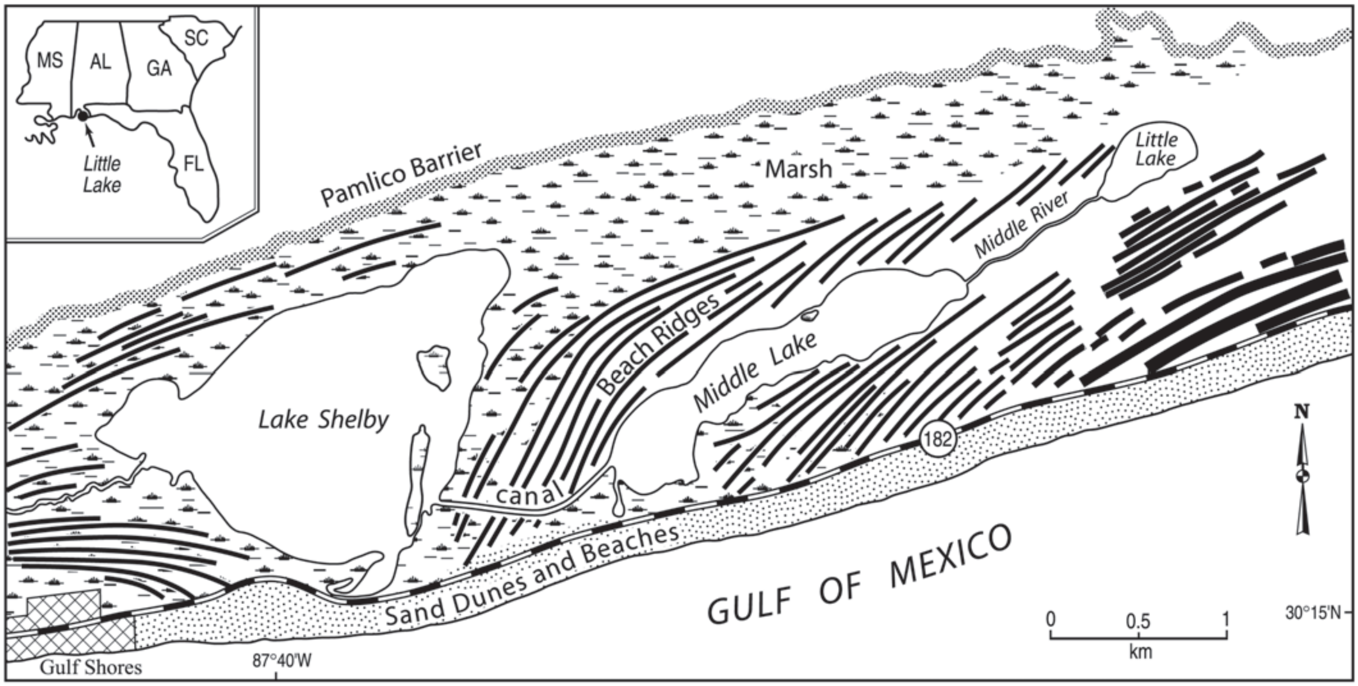

Figure 1. Map showing the location and geomorphic setting of Little Lake, Middle Lake, and Lake Shelby in coastal Alabama. Thick black lines are beach ridges. Black and white line is Alabama State Highway 182.

coastal lake-sediment cores as a proxy for catastrophic landfalls by hurricanes of category 4-5 intensity. Their results suggest that the Alabama Gulf coast near Lake Shelby was directly hit by catastrophic hurricanes about once every 300 years during the last 3200 years (Liu and Fearn, 1993, 2000a, 2000b; Liu, 1999). In this paper, we present a sediment-stratigraphic record from Little Lake, Alabama, a small lake adjacent to Lake Shelby, from which a 1200-year history of intense hurricane landfalls was reconstructed. The Little Lake record supplements the paleotempestological record from neighboring Lake Shelby because this new record registers not only strikes by categories 4 and 5 hurricanes but those by category 3 hurricanes as well.

In addition to disturbance from hurricanes, ecosystems along the Gulf of Mexico coast are also vulnerable to significant disturbance and destruction caused by fires, both of natural and anthropogenic origins. Southeastern pine forests, which are an important natural resource for the Gulf Coast states, are especially fire-prone (Platt, 1999). The linkage between hurricanes and fires has been the subject of many speculations and field observations (e.g., Myers and van Lear, 1998; Webb, 1958; Wade, et al., 1993; Putz and Sharitz, 1991). However, none of these previous studies is based on long-term observations that span more than a few years or at most a few decades after the hurricane impact. Does the risk of fire increase significantly after a severe hurricane impact? One way to answer that question is to study the microscopic charcoal fragments associated with the hurricane overwash sand layers in a sediment core, and compare the charcoal abundance quantitatively with the background charcoal abundance occurring in the organic (non-hurricane) sediments. In this study, we also investigated the history of wildfires in coastal Alabama by means of charcoal and pollen analyses of the same sediment core from Little Lake that has yielded the paleotempestological record. The results allow us to address questions concerning the interactions between hurricane impacts and fire, and shed light on the variability of fire hazard as a function of long-term changes in the hurricane climate along the Gulf coast.

13.2 The Study Site

Little Lake is the smallest of three coastal lakes situated in Gulf State Park between Gulf Shores and Orange Beach, Alabama (Fig. 1). All three lakes (Little Lake, Middle Lake, Lake Shelby) are enclosed by a complex system of beach ridges that may be formed at different times after the mid-Holocene (Liu and Fearn, 1993). The beach ridge plain separating Little Lake from the Gulf of Mexico is about 1.1 km wide, and is fringed on the seaward side by a sandy beach with 1-2 m high dunes. Much of the narrow

Figure 2. Photograph of Little Lake showing the usual calm conditions and the pine-dominated forest along the north shore of the lake.

land strip behind the beach has been converted to paved roads (state highway 182), condominiums, and tourist facilities. Little Lake is a freshwater lake (salinity 0.1 ppt) that drains only a small basin. It has no inflowing stream and connects downstream with Middle Lake only by a very small channel. The lake is about 1.2 m (4 ft) deep, has a flat bottom, and has a maximum length of about 600 m.

Vegetation around Little Lake is a subtropical maritime forest characterized by a diverse association of pines, oaks, hickories, hollies, waxmyrtle, magnolia, and sweetgum (Fig. 2). Pines and sclerophyllous oaks are especially abundant on the sandy beach ridge plain and in drier sites, often with saw palmetto in the understory. Like many pine-dominated communities in the southeastern U.S., the vegetation around Little Lake is a fire-adapted ecosystem.

13.3 Material and Methods

A piston core (core 3) about 60 cm long was taken from Little Lake in the summer of 1997. In the laboratory, the entire core was sampled continuously at 1 cm interval for loss-on-ignition analysis. The sediment samples were heated at 105^{o}C, 550^{o}C, and 1000^{o}C to determine the water content, organic matter content, and carbonate content, respectively (Dean, 1974). The loss-on-ignition technique has been proven to be an effective way to reveal the sediment stratigraphy and to detect the presence of sand layers in the core (Liu and Fearn, 2000a).

Sixty samples, each 0.9 ml in volume and also taken consecutively at 1 cm intervals, were collected throughout the core for pollen and charcoal analyses. Chemical processing for pollen and charcoal analysis followed standard laboratory procedure, which involved treating the samples with 10% hydrochloric acid (HCl), 10% potassium hydroxide (KOH), 49% hydroflouric acid (HF), acetolysis solution, glacial acetic acid, tertiary butanol alcohol (TBA), and repeated centrifuging and decanting (Faegri and Iversen, 1975). During chemical treatment, the samples were stirred gently with a wooden applicator to ensure thorough contact between sediment and the chemical, but caution was taken not to cause excessive breakup of fragile pollen and charcoal particles. One *Lycopodium* tablet containing 12,542 +/- 200 spores was added to each sample before chemical processing to permit estimation of pollen and charcoal concentration in the sample (Stockmarr, 1971). The residues were suspended in silicone oil and mounted on microscopic slides for pollen and charcoal counting.

At least 300 pollen grains were counted in each sample. For *Pinus* (pine) pollen, the intact and broken grains were tallied separately. The number of broken pine pollen (usually fragments of the saccus or corpus) was summed and divided by 3, and that quotient was added to the number of intact pine pollen for the calculation of total *Pinus* percentage in each sample. The abundance of broken pine pollen was also calculated as a percentage of total pine pollen, and this percentage was used as a measure of the degree of mechanical breakage during deposition or during laboratory processing (see below). Dinoflagellates, a marine microorganism, were counted on the same slide as pollen; their presence was used as

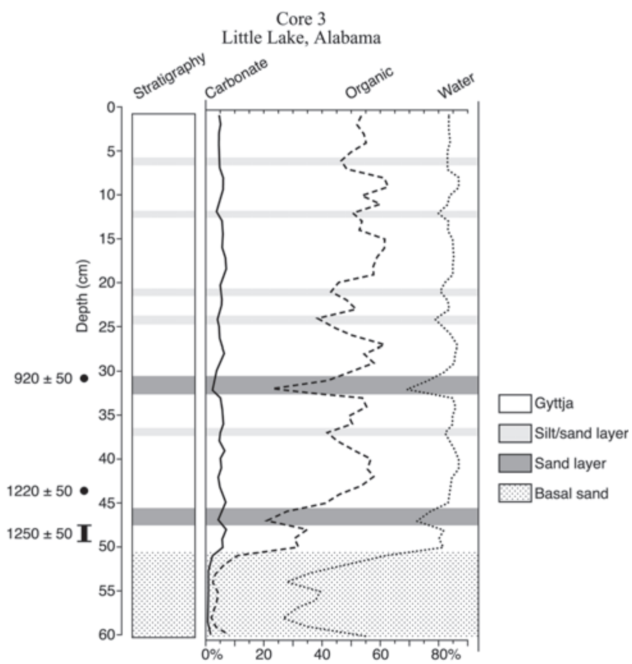

Figure 3. Sediment stratigraphy and loss-on-ignition curves for the core from Little Lake, showing percentages of water, organic matter content, and carbonate content. The AMS radiocarbon date is shown on the left of the depth scale.

an indicator of saltwater influx into this freshwater lake. Microscopic charcoal was also counted on the same slide. Only those charcoal fragments >10 micron in size were counted. Charcoal counts range from 57 to 515, but for most samples the counts are between 100 and 400. In this report, we focus on the information derived from the charcoal, dinoflagellates, and broken pine pollen.

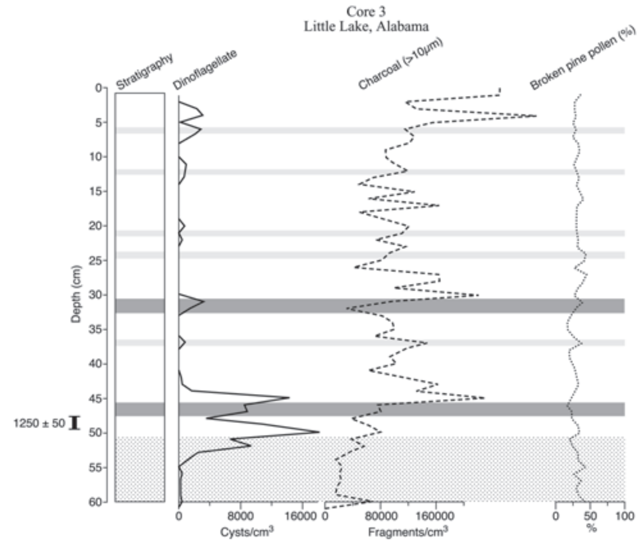

Figure 4. Curves showing the abundance of dinoflagellates, microscopic charcoal, and broken pine pollen (as a percentage of total pine pollen) in the Little Lake core, plotted in relation to the sediment stratigraphy. Sediment symbols are the same as Figure 3.

13.4 Results and Discussion

13.4.1 Sediment Stratigraphy and Hurricane History

The sediment stratigraphy consists of 50 cm of gyttja (organic lake mud) overlying 10 cm of basal sand. An AMS radiocarbon date of 1250 +/- 50 yr BP was obtained from the bulk organic sediment near the base. Two thin but distinct layers of sand were observed at 32 cm and 47 cm in the core. Loss-on-ignition analysis revealed the presence of another five indistinct layers of fine sand or silt (Fig. 3). These sand or silt layers were probably caused by storm overwash associated with intense hurricane landfalls in the past. Little Lake is a small, quiet-water lake with no inflowing streams (Fig. 2). It is situated on a flat topography with virtually no slopes in its surrounding basin. Given this geomorphic setting, it is highly unlikely under normal circumstances for sand or silt to be transported and deposited in the central part of the lake, as evidenced by the highly organic (organic matter content 50 – 60%) sediments contained in the core. Only high-energy events, such as hurricane-force wind and storm overwash occurring during an intense hurricane landfall, would have been possible to mobilize the sand or silt from the beach ridges and sand dunes to deposit in the middle of this otherwise quiet-water lake.

Our interpretation that these sand or silt layers represent overwash events associated with past intense hurricane landfalls is supported by data from dinoflagellates in the core. Dinoflagellates are marine microorganisms that are normally absent or rare in coastal freshwater environments. In the Little Lake core, dinoflagellate cysts are absent in the core top and in most samples in the organic sediments above 44 cm (Fig. 4). However, they occur in great abundance in the lower part of the core from 54 to 44 cm, especially at the top of the basal sand and in and above the distinct sand layer at 47 cm. In the organic section, dinoflagellates occur only sporadically, but virtually all the isolated peaks are associated with the sand or silt layers. The dinoflagellate evidence therefore supports the notion that these sand and silt layers were formed by overwash events, which also introduced seawater into this otherwise freshwater lake.

The two distinct sand layers at 47 and 32 cm have interpolated ^{14}C ages of ca. 1200 yr BP and 830 yr BP, respectively. These are correlative with two major sand layers found in a series of sediment cores from neighboring Lake Shelby, which have been directly dated to 1330 +/- 60 and 1360 +/- 80 yr BP, and 770 +/- 70, 770 +/- 60 and 980 +/- 60 yr BP, respectively (Liu and Fearn, 1993). The sand layers from Lake Shelby have been interpreted to reflect direct hits by catastrophic hurricanes of category 4-5 intensity during prehistoric times. The two sand layers identified from the Little Lake core corroborate the Lake Shelby record and most probably reflect the same catastrophic hurricanes that made landfall on the Alabama coast around 1300 and 800 ^{14}C years ago.

The other five sand or silt layers, at 6, 12, 21, 24, and 37 cm, were less distinct than the two just described (Fig. 3), and probably reflect events of somewhat lower magnitude. Notably, Hurricane Frederic, a category 3 hurricane that devastated the Gulf Shore area when it made landfall in Alabama in 1979, caused a 4.8 m-high storm surge that inundated the coastal plain adjacent to Little Lake (Liu and Fearn, 1993). Thus these five sand or silt layers probably reflect overwash events caused by category 3 hurricanes. Their inferred ages are approximately 940, 630, 520, 290, and 160 ^{14}C yr BP.

The sediment-stratigraphic record from Little Lake therefore suggests that the Alabama Gulf coast near Gulf Shores was directly hit by intense hurricanes (i.e., category 3-5) at least seven times over the last 1250 years, implying an overall return period of 180 years. It should be pointed out, however, that on a millennial timescale, the past millennium was marked by relatively low hurricane activity along the Gulf of Mexico coast. Liu (1999) has reported that the landfall probabilities on the Gulf Coast increased dramatically during a "hyperactive" period between 3400 and 1000 ^{14}C years ago. These millennial-scale variations in hurricane landfalls are probably controlled by long-term shifts in the position of the Bermuda High, which may be ultimately related to long-term changes in the North Atlantic Oscillation (NAO) (Elsner et al., 2000a).

13.4.2 Charcoal Record and Fire History

The curve for microscopic charcoal fragments has a saw-tooth shape with multiple peaks and troughs, but four spikes stand out at 1 cm, 4 cm, 30 cm, and 45 cm (Fig. 4). Remarkably, three of these four peaks occur immediately above a sand layer. This invites the speculation that a connection exists between intense hurricane strikes and fire occurrence. It has been hypothesized that fire hazard in coastal plain forests in the southeastern U.S. increases significantly after an intense hurricane strike (Myers and van Lear, 1998). This is mainly due to an increase in fuel accumulation caused by a great abundance of dry litter on the forest floor, as well as the creation of a drier microclimate resulting from increased insolation and higher wind velocity due to a more open canopy. Although such hurricane-fire interaction has been postulated in a number of post-hurricane ecological studies (Webb, 1958; Craighead and Gilbert, 1962; Loope et al., 1994; Wade et al., 1993; Putz and Sharitz, 1991), few empirical data or direct observations are available to test it. This hypothesis may not be easily testable based on recent hurricane events due to fire suppression and post-hurricane mitigation efforts conducted by modern societies, which alter the natural fire regime of forest ecosystems. Our long-term charcoal record from Little Lake seems to support the hypothesis that catastrophic fire is likely to occur shortly after an intense hurricane strike.

An alternative explanation for the stratigraphic association between sand layers and charcoal abundance is that charcoal particles are more likely to break up into smaller fragments in the turbulent depositional environment during and after an overwash event, thus resulting in an inflated count of broken charcoal fragments. It is also possible that upon vigorous stirring of the sediment sample during laboratory processing, charcoal particles are more likely to break up into small pieces in a sandy matrix than in a more soft organic matrix, which would also result in higher counts of charcoal fragments in sandy samples. To test this hypothesis, we plotted the percentages of broken pine pollen in relation to the charcoal curve and the stratigraphy of the sand layers (Fig. 4). The rationale is that if charcoal abundance is mainly a function of the degree of mechanical breakup of charcoal fragments due to a turbulent depositional environment or stirring vigor, then the abundance of broken pine pollen would also be high in the same samples where charcoal abundance is high. The results show that the four prominent peaks in charcoal abundance do not correspond with peaks in broken pine percentages. Therefore we conclude that the four charcoal peaks reflect the occurrence of wildfires and are not an artifact of the depositional process or the laboratory processing technique.

13.5 Conclusions and Implications for the Future

Long-range socio-economic development and planning for the Gulf coast must be based on realistic assessments of the risks posed by intense hurricane strikes and, perhaps to a somewhat lesser extent, catastrophic wildfires. Until recently there was no empirical means by which both hurricane and fire risks could be estimated, because long-term records (i.e. those spanning more than one or two centuries) of these hazards were lacking. In this paper, we have presented a 1200-year record of intense hurricane strikes and wildfires for the Alabama Gulf coast based on a stratigraphic study of overwash deposits, charcoal, and microfossils in a core from Little Lake. The major findings are summarized as follows.

(1) Over the last 1250 years, the Little Lake area of the Alabama Gulf coast was directly struck by intense hurricanes at least 7 times. Five of these strikes may have been by hurricanes of category 3 intensity, and the other two were probably by hurricanes of category 4 – 5 intensity. The two catastrophic hurricane landfalls, at ca. 800 and 1200 ^{14}C yr BP, were also recorded in the sediments of neighboring Lake Shelby.

(2) For the Alabama Gulf coast around Little Lake, the return period for a direct hit by an intense hurricane (category 3 – 5) is approximately 180 years (7 times in 1250 years). The return period for catastrophic hurricanes (category 4 – 5) only is approximately 600 years (twice in 1250 years). These translate into landfall probabilities of 0.56% per year for all intense (category 3 – 5) hurricanes, and 0.17% per year for category 4 – 5 hurricanes. However, these should be regarded as minimum estimates, because the proxy record may be incomplete (see discussion in Liu and Fearn, 2000a), especially in view of the fact that the Little Lake record is only based on one core. Another caveat is that on a millennial scale, the past millennium, which spans most of the Little Lake record, is characterized by relatively few catastrophic hurricane landfalls along the Gulf coast as compared with the “hyperactive” period 1000 – 3400 years ago (Liu, 1999; Liu and Fearn, 2000a).

(3) The abundance of microscopic charcoal fragments in the Little Lake sediments suggests that wildfires have been common in the coastal ecosystems in Alabama. Of the four prominent charcoal peaks found in the Little Lake core, three lie immediately above sand or silt layers, suggesting that these large fires probably occurred within a few years after an overwash event. These preliminary findings lend support to the hypothesis (Myers and van Lear, 1998) that fire hazard increases significantly after an intense hurricane strike. Since wildfire is a major factor in the management of forest resources for the Gulf coast states, an understanding of the history of fire, and its interaction with hurricanes and climatic changes, is of both scientific and societal significance.

A long-term perspective is necessary for any realistic assessment of hurricane and wildfire risks confronting the Gulf coast region. Our study offers such a long-term perspective by providing a 1250-year proxy record of intense hurricane strikes and wildfire occurrences from coastal Alabama, and documents a possible link between hurricane and fire. What are the implications for the future? Modeling results and theoretical considerations suggest that tropical cyclones (hurricanes) could become more intense in the future if global warming occurs (Emanuel, 1987, 1997; Knutson et al., 1998). Liu and Fearn (2000a) found that, from 3400 to 1000 years ago, the Gulf coast experienced a much more active hurricane regime than what has occurred during the past millennium, implying that if future climatic conditions return to those characteristic of the “hyperactive” period, the Gulf coast may conceivably experience a much higher frequency of catastrophic hurricane strikes. On a decadal timescale, recent studies have revealed a dramatic increase in North Atlantic hurricane activity since 1995 (Goldenberg et al., 2001; Elsner et al., 2000b). The post-1995 increase, which is due to an increase in North

Atlantic sea surface temperature and a decrease in vertical wind shear, is likely to persist for another 10-40 years (Goldenberg et al., 2001). Of greatest relevance to the future climate of the Gulf coast region is the fact that this recent trend is also associated with a return of the “tropical-only” type of hurricanes to the Atlantic basin and a relaxation of the North Atlantic Oscillation (Elsner et al., 2000b; Kimberlain and Elsner, 1998). This may be a bad omen for the Gulf coast region because a weak or neutral NAO is statistically linked to higher probabilities of major hurricane landfall on the Gulf coast (Elsner et al., 2000a; Jagger et al., 2001).

If landfalls by intense hurricanes become more frequent in the Gulf coast region in the next several decades, how would that affect wildfire occurrence? Given the association between hurricane strikes and wildfire occurrence established in this study, it is expected that the overall fire hazard from the aftermaths of hurricane strikes will also increase. Currently, Alabama and adjacent Florida have the highest frequency of wildfires among the Gulf coast states (National Interagency Fire Center, 2001). Moreover, the Gulf coastal zones of Alabama and Florida have the highest frequency of thunderstorm days in the nation (Christopherson, 2000, p. 216), where the hazard of lightning is also high (Curran et al., 1997; Marshall Space Flight Center, 1998). Collectively, these factors suggest that, if there is no human intervention, the risk of post-hurricane wildfires should be high in the Gulf coast region. If future climate change results in more frequent intense hurricane landfalls and increased post-hurricane fire risks for the Gulf coast region, new strategies should be made in our societal response to these important natural hazards.

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Appendices

Peer Review Process for This Publication

The Gulf Coast region climate change impact assessment findings were complied based on the regional assessment research, outreach, and education results. Prior to the publishing, a three level technical peer review and stakeholder review was conducted.

First level:

We conducted a technical peer review by scientists/peers/technical experts and stakeholders for scientific and technical accuracy and validity. For this publication, there were minimum of two reviewers for each chapter of each part corresponding to the expertise required to review each chapter. All reviewers were from outside of the assessment team and Southern University. The review process were coordinated by the Assessment Team Leader/Project Director Dr. Zhu H. Ning, who provided a central distribution and receiving point for written reviews and oral review comments. The team members were responsible for documenting the responses to written review comments of the respective chapter.

Second level:

We identified the stakeholder groups and individuals for their review, including all of the groups that participated the regional first stakeholder workshop in 1998. We also sent the manuscripts to many stakeholder groups we have contacted, met with, and/or presented information to since the inception of the assessment. We provided adequate time for a general comment period by the stakeholders.

Third level:

After the first two levels of review were accomplished and all comments and responses were documented, we conducted an overall peer review for the technical and editorial responsiveness. For the overall peer review, we had a batch of reviewers who have broad expertise and reviewed all of the chapters and any summaries, conclusions and connections that were made in this publication that cut across the parts and chapters. All documentations of response to reviewers' comments are available and can be obtained by contacting Dr. Zhu Hua Ning at zning@subr.edu or (225) 771-2262 ext. 267 (phone) or (225) 771-3286 (fax).

Brief Biographic Sketches of the Assessment Team Member

Dr. Zhu Hua Ning is a Professor and the Director of the Gulf Coast Regional Climate Change Assessment Program at Southern University and A&M College, Baton Rouge, LA. She is also the Project Director of many research projects funded by the US Department of Agriculture, US Environment Protection Agency, National Aeronautics and Space Administration, Department of Energy, and the National Urban and Community Forestry Advisory Council. Her research projects focus on CO_2 sequestration, climate change assessment, O_3, NOx, particle pollution, effects of soil flooding, forested wetlands, and bioremediation. She has published 6 books, a book chapter, and more than 50 research articles. She received The Faculty Award for Excellence for Outstanding Research Performance at Southern University College of Agricultural, Family and Consumer Sciences in 1996-1998 and 2000-2003. She has initiated and established collaboration between Southern University and the US Global Change Research Program, The USGS National Wetland Research Center, National Center for Atmospheric Research, and the Chinese Academy of Sciences. A significant portion of her research is concentrated on climate change assessment and ways to mitigate environmental problems. This led to her recognition in 1998 by the Director of the White House Office of Science and Technology Policies, Governor of Louisiana, and Permanent Parliamentary Secretary for Environment, Ottawa Canada. Dr. Ning is the Chair-elect of the Society of American Foresters Urban and Community Forestry Working Group, and Board member of the 7th American Forest Congress Communities Committee.

Dr. R. Eugene Turner is the Distinguished Professor in Louisiana Environmental Studies, Coastal Ecology Institute, Louisiana State University. He is sometimes an oceanographer and at other times a wetland ecologist. He serves as Chair of the International Association for Ecologists (INTECOL) Wetlands Working Group, and as Treasurer of INTECOL. He was the recipient of the 1998 National Wetland Award, and along with Nancy Rabalais, of the 1999 Blasker Award for Science and Engineering for their work on the low oxygen zone off the Mississippi River (the DEAD ZONE).

Dr. Thomas W. Doyle is a research ecologist with the U.S. Geological Survey National Wetlands Research Center in Lafayette, Louisiana. He received his M.S. and Ph.D. in systems ecology and environmental science from the University of Tennessee in Knoxville. He has more than 20 years of field and modeling experience in temperate and tropical forest ecosystems of southeastern U.S. and the Caribbean. His research disciplines focus on wetland ecosystem analysis and modeling, forest stand and landscape simulation, tree-ring analysis, plant competition and growth modeling, and disturbance ecology. His tree-ring studies of southeastern coastal plain forests have produced growth chronologies of tree and species responses to climate, flood, fire, wastewater application, atmospheric CO_2, hurricanes, and land-use change. Growth models by species groups have been used in individual-based forest models to predict historic and future effects of climate change, altered freshwater flow, sea-level rise, hurricanes, and water quality issues. Landscape simulation models have been developed and integrated with stand-level models for various parks and refuges across the Southeast to forecast potential threats of habitat loss or conversion by natural and man-induced disturbances and climate change in mangrove, pine flatwood, and bottomland hardwood ecosystems.

Dr. Kamran K. Abdollahi is a Professor of Urban Forestry, Division of Agricultural Sciences, College of Agricultural, Family and Consumer Sciences at Southern University, Baton Rouge, Louisiana. Dr. Abdollahi was instrumental in establishing the first Urban Forestry B.S. degree granting program in the nation. His research expertise is in tree physiology, forest ecophysiology, phyto-remediation, and global change. Currently he directs 8 research projects emphasizing on quantification of tree species in removing pollutants from urban atmosphere and GIS-based ecosysterm analysis. Dr. Abdollahi is the Co-Director of the Gulf Coast Regional Climate Change Assessment Program and the co-author of five books on climate change assessment. He was selected by the US Secretary of Agriculture to serve on National Urban and Community Forestry Advisory Council. He served as the Chair of the Society of American Foresters Urban and Community Forestry Working Group, and the State Director and Regional Board member for the International Society of Arboriculture. He serves on the executive board of the National Associations of State Colleges and Universities (NASULGC), Ecology Section. Dr. Abdollahi is the recipient of the Faculty Award for Excellence for Outstanding Teaching Performance at Southern University College of Agricultural, Family and Consumer Sciences in 1998-2000, 1999 and 2003 University Research Grantsmanship Award, 1998 Louisiana Arborists Association Award, and 1994 Honors College Exemplary Faculty Award.

Dr. Enrique Reyes is an Assistant Professor at the Department of Geology and Geophysics, University of New Orleans in New Orleans, LA. His research focuses on development of ecosystem models, landscape ecology, approaches to coastal resource management using systems ecology, and analysis of ecosystem dynamics and processes in wetlands and tropical watersheds. His academic experience lies on "big picture" approaches to ecosystem analysis. Using simulation modeling as a research tool, his interests have been to understand how coastal areas respond to diverse impacts, natural and man made. Dr. Reyes has been active in several modeling efforts that span from plant productivity, fish migration, mesocosm experiments, to landscape simulation. Current project sites include the coast of Louisiana, the Everglades in Florida, and several coastal lagoons in the Mexican Caribbean.

Dr. Dubravko Justić is an Associate Professor at the Coastal Ecology Institute and in the Department of Oceanography and Coastal Sciences, Louisiana State University, Baton Rouge, LA. Over the past fifteen years Dr. Justić has worked extensively on problems dealing with eutrophication, hypoxia, and impacts of climate change on coastal ecosystems.

Mr. Erick M. Swenson is a Research Associate in the Coastal Ecology Institute, a research unit within the School of the Coast and Environment at Louisiana State University in Baton Rouge, Louisiana. His research has focused on the investigation of human impacts on the hydrologic regime of coastal marsh systems. His research interests include measurement and analysis of velocity, sea level and salinity measurements in shallow-water, coastal, and estuarine systems. Mr. Swenson has worked on the analysis of long term historical data sets (water level, salinity, and climate) from Louisiana coastal ecological systems with emphasis on wetland restoration and management. Mr. Swenson serves as an Academic Advisor to the Environmental Working Group for the Coastal Wetlands Planning, Protection and Restoration Act (CWPPRA).

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Dr. Kam-biu Liu is the James J. Parsons Professor of Geography at Louisiana State University. He is widely recognized as a pioneer and leader in a new field of science called paleotempestology, which studies past hurricane activity by means of geological proxy techniques and historical documentary evidence. Since 1989, Liu has conducted extensive research on the sedimentary records of lakes and marshes along the Gulf of Mexico coast and Atlantic coast of the U.S. to study the chronological and spatial patterns of catastrophic hurricane strikes during the last 5,000 years. His broader research interests include the use of pollen and ice cores to reconstruct the history of climatic and vegetational changes in the Amazon Basin, Tibetan Plateau, Yangtze River valley, and the Canadian boreal forest. His research has been featured in national and international mass media such as the New York Times, Science Magazine, The New Scientists, Science News, Fortune Magazine, The Economist, CNN, BBC, and the Discovery Channel.

Dr. Alma Thornton is the Director of the Center for Social Research and Professor of Sociology at Southern University and A & M College. Her research has focused on psychosocial factors in health and nutrition disparity in the lower Mississippi Delta region. Other research interests include community development and revitalization that is comprehensive, locally based, centered on citizen participation, and involving public-private partnerships, and collaborations. She specialized in comprehensive planning and assessment, community building, capacity building, program evaluation, logic-based modeling, theory based models of change, and measurement and analysis. In addition, she works closely with non-profit, and faith-based organizations as community developer assisting in building and implementing programs.