CHAPTER 5

POTENTIAL CONSEQUENCES OF CLIMATE VARIABILITY AND CHANGE FOR THE SOUTHEASTERN UNITED STATES

Virginia Burkett[1,2], Ronald Ritschard[3], Steven McNulty[4], J. J. O'Brien[5], Robert Abt[6], James Jones[7], Upton Hatch[8], Brian Murray[9], Shrikant Jagtap[7], and Jim Cruise[3]

Contents of this Chapter

Chapter Summary

Physical Setting

Socioeconomic Context

Ecological Context

Climate Variability and Change

Key Issues

- Weather-related Stresses on Human Populations
- Agricultural Crop Yields and Economic Impacts
- Forest Productivity Shifts
- Water Quality Stresses
- Threats to Coastal Areas

Additional Issues

Climate Model Limitations

- Water Resources
- Impacts on Coastal Ecosystems and Services
- Health Issues Related to Water Quality
- Socioeconomic and Insurance Issues
- Urban Issues

Crucial Unknowns and Research Needs

Literature Cited

Acknowledgments

[1] US Geological Survey; [2] Coordinating author for the National Assessment Synthesis Team; [3] University of Alabama in Huntsville; [4] USDA Forest Service; [5] Florida State University; [6] North Carolina State University; [7] University of Florida; [8] Auburn University; [9] Research Triangle Institute

CHAPTER SUMMARY

Regional Context

The Southeast "sunbelt" is a rapidly growing region with a population increase of 32% between 1970 and 1990. Much of this growth occurred in coastal counties, which are projected to grow another 41% between 2000 and 2025. The number of farms in the region decreased 80% between 1930 and 1997 as the urban population expanded, but the Southeast still produces roughly one quarter of US agricultural crops. The Southeast has become America's "woodbasket," producing about half of America's timber supplies. The region also produces a large portion of the nation's fish, poultry, tobacco, oil, coal, and natural gas. Prior to European settlement, the landscape was primarily forests, grasslands, and wetlands. Most of the native forests were converted to managed forests and agricultural lands by 1920. Although much of the landscape has been altered, a wide range of ecosystem types exists and overall species diversity is high.

Climate of the Past Century

- Southeastern temperature trends varied between decades over the past 100 years, with a warm period during the 1920s-1940s followed by a downward trend through the 1960s. Since the 1970s, temperatures have been increasing, with 1990's temperatures reaching peaks as high as those of the 1920s-1940s.
- Annual rainfall trends show very strong increases of 20-30% or more over the past 100 years across Mississippi, Arkansas, South Carolina, Tennessee, Alabama, and parts of Louisiana, with mixed changes across most of the remaining area. The percentage of the Southeast landscape experiencing severe wetness increased approximately 10% between 1910 and 1997.

Climate of the Coming Century

- Climate model simulations provide plausible scenarios for both temperature and precipitation over the 21st century in the Southeast. Both of the principal climate models used in the National Assessment suggest warming in the Southeast by the 2090s, but at different rates.
- The Canadian model scenario shows the Southeast 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 by 2100 (about 20% on average, but with some differences within the region).
- Both climate model simulations indicate that the heat index (a measure of comfort based on temperature and humidity) will increase more in the Southeast than in other regions. Heat index in the Southeast is projected to rise by as much as 8 to 15ºF (4 to 8ºC) in the Hadley model and by over 15ºF (8ºC) across the entire region in the Canadian model simulation by 2100.

Key Findings

- The increase in the southeastern summer heat index simulated by both the Hadley and Canadian climate models would likely affect human activity and possibly demographics in the Southeast during the 21st century.
- Agriculture could possibly benefit from increased CO_2 and modest warming (up to 3 to 4ºF, or 2ºC) as long as rainfall does not decline, but there are differences in individual crop responses. Management adaptations could possibly offset potential losses in individual crop productivity due to increased evapotranspiration.
- Biological productivity of pine and hardwood forests will likely move northward as temperatures increase across the eastern US. Hardwoods are more likely to benefit from increases in CO_2 and modest increases in temperature than pines. Physiological forest productivity and ecosystem models suggest that, without management adaptations, pine productivity is likely to increase by 11% by 2040 and 8% by 2100 across the Southeast compared to 1990 productivity. These models suggest that hardwood forest productivity will likely increase across the region, by 25% by 2090 compared to 1990 regional hardwood productivity.
- Under the Hadley model scenario, the region's land use change in the next century is likely to be dominated by non-climate factors such as commodity prices and demographic forces. Urbanization will likely continue to convert forest and agricultural land, while continued movement of land from agriculture to forest is also expected. Under more extreme climate scenarios, land reallocation could possibly be more dramatic as the productivity of land-based activities such as forestry and agriculture is more profoundly influenced by climate.
- During the 21st century, the IPCC projects that sea-level rise will likely accelerate 2- to 5 -fold compared to the global average rate during the 1900s (which was 4-8 inches). This would very likely have dramatic effects on population centers, infrastructure, and natural ecosystems in the low-lying Gulf and South Atlantic coastal zone.
- Water and air quality are concerns given the changes in temperature and precipitation that are simulated by climate models.
- Changes in minimum temperature, rainfall, and CO_2 will likely alter ecosystem structure, but interactions are difficult to model or predict, particularly relative to disturbance patterns.
- Changes in fresh water and tidal inflows into coastal estuaries will likely alter the ecological structure and function of these highly productive and valuable ecosystems.

POTENTIAL CONSEQUENCES OF CLIMATE VARIABILITY AND CHANGE FOR THE SOUTHEASTERN UNITED STATES

PHYSICAL SETTING

The Southeast region (Fig.1) represents 15.4% of the land area of the US and 22.6% of its citizenry (US Bureau of the Census,1994). Although the Southeast has considerable variation in landforms,it is possible to divide it into five fairly distinct regions based on physical geography. The lower third of the low, flat Florida peninsula is a sub-tropical province with unique features such as the Everglades and the Florida Keys. The Coastal Plain,which dominates the region,is a broad band of territory paralleling the Gulf and South Atlantic seacoast from Virginia to Texas,with a deep extension up the lower Mississippi River valley. The Coastal Plain is relatively flat,with broad,slow-moving streams and sandy or alluvial soils. The Piedmont is a slightly elevated plateau that begins at the "fall line," where rivers cascade off the eastern edge of the plateau onto the Coastal Plain,and ends at the Appalachian Mountains. This land is rolling to hilly, with many streams. The Highlands comprise the inland mountain regions and include the southernmost Appalachian Mountains in the east and the Ozark and Ouachita Mountains in the west. The Interior Plains stretch into the north-central portion of the region,including parts of Tennessee and Kentucky. The southern portions of the State of Virginia are included in aspects of this regional analysis. The northern portions are included in the Northeast chapter with a discussion of the Chesapeake Bay watershed.

SOCIOECONOMIC CONTEXT

The 544,000 square mile southeastern "sunbelt"is one of the fastest growing regions in the US. The southeastern population increased by 21%,more than double the national rate,between 1970 and 1980 and another 11% between 1980 and 1990. Much of the historical population growth from Texas to North Carolina occurred in the 151 counties within the southeastern coastal zone,which are projected to grow another 41% between 2000 and 2025,compared to the projected national average of about 25% (NPA,1999). However, warming at higher latitudes combined with increased heat stress in the southeastern US may serve to decrease population migration towards the Southeast.

Based on the 1990 Census, about 61% of the Southeast's population is considered urban. The number of farms in the region decreased 80% between 1930 and 1997 (USDA,1999). The 20th century was one of dramatic transition from an agrarian economy to one based on a combination of natural resources,manufacturing and trade,technology, and tourism. Roughly one half of 1990 employment fell in the categories of manufacturing and wholesale/retail trade,compared with an average of less than 5% in agriculture (US Bureau of the Census,1994). Prior to 1950,corn and cotton were the most important crops. Today agriculture is more varied;soybean and hay outweigh cotton in acreage harvested and rice has become increasingly important. The Southeast still produces roughly one quarter of the nation's agricultural crops,but timber harvests are more valuable in terms of annual economic impact in most states. Forest products industries were among the top four manufacturing employers in Mississippi,Alabama,North Carolina and Georgia in 1997. The Southeast has become America's "woodbasket," producing about half of America's timber supplies. The region is also responsible for a large portion of the nation's fisheries,poultry, tobacco,oil,natural gas,bauxite,coal,and sulfur production.

According to the 1990 census,18% of the population of the Southeast region lives below the poverty level. The most poverty-prone areas include the Lower Mississippi River Valley and parts of Appalachia. While certain measurements,such as per capita income,have moved in the direction of the national averages, poverty rates in some areas are as much as two and a half times the national average. Levels of education of the population in some areas also lag behind national standards. Some of the smaller, more remote and geographically isolated areas of the region suffer from a lack of economic opportunities,have significant dependent populations,and lack the public institutions needed to support progressive development (Glasmeier, 1998). These distressed counties present a profound challenge to policy makers concerned about climate change mitigation strategies and issues,particularly in the Appalachian coal-producing and Gulf Coast oil-producing regions.

ECOLOGICAL CONTEXT

Prior to European settlement,the Southeast was dominated by upland forests, grasslands,and wetlands. Nearly one-third of the region may have been wetland (Dahl,1990),but by 1990, wetlands had been reduced to about 16% of the southeastern landscape (Hefner, et.al.,1994). A wide range of ecosystem types is presently found in the region, ranging from coastal marshes to high-elevation spruce fir forests. Diversity of both plant and animal species is high compared to other regions considering the extent of landscape alteration that has occurred. On an area basis,the Southeast has relatively high overall species richness indices (Ricketts, et.al.,1999). Vascular plant diversity is second only to Puerto Rico. Tree species richness is greatest in the Southeast,with approximately 180 tree species found in parts of South Carolina and more than 140 tree species identified in most of the remainder of the region.

Forests still dominate parts of the Southeast;the share of forestland in each state averages about 30%. About 20% of the present forests exist as pine plantations. Native longleaf pine was the predominant species in the Coastal Plain in the late 1800s but less than 3 million of the 60 million acres of southeastern longleaf pine remain today (Boyer, 1979). More than 60 species of mammals occur in a relatively small area of the southern Appalachian mountains,while 40 or fewer mammal species are found in the Coastal Plain (Currie,1991). The region has very high diversity of amphibians and reptiles. Roughly half of the remaining wetlands in the US are located in the Southeast,and more than three-quarters of the nation's annual wetland losses over the past 50 years occurred in the region.

Two types of ecosystem models (biogeochemical and biogeographical) show a wide range of potential changes in vegetation in the Southeast during the 21st century, depending upon the climate scenario selected. One of the biogeographical models (MAPSS) projects significant shifts in major biomes under the Canadian climate scenario,but not under the Hadley climate scenario. Under the Hadley climate scenario,the Southeast mixed forest retains its southern boundaries while expanding west into parts of eastern Oklahoma and Texas,and north into parts of Missouri,West Virginia, Kentucky, and Virginia. Water stress and increased fire disturbance restricts the Southeast forest under the Canadian climate scenario,and large areas of the Southeast are converted to savanna (grasslands with scattered trees and shrubs) and the Southeast forest moves into the northcentral part of the US.

One of the biogeochemistry models (TEM) used in the National Assessment projects large differences in carbon storage for the Southeast depending upon the climate scenario used. Under the Canadian climate model scenario, vegetation is projected to lose up to 20% of its carbon mass by 2030. However, under the Hadley climate scenario the same biogeochemistry model indicates that vegetation will add between 5 and 10% to its carbon mass over the next 30 years. These differences in carbon storage reflect the differences in climate scenario projections for temperature and precipitation that are greatest in the southeastern part of the US (Felzer and Heard, 1999).

Ecological models used in the National Assessment do not simulate species-level response,nor do they simulate land use changes,invasive species impacts, or other influences on ecosystems that cannot be effectively modeled based on historical or empirical evidence,unless the ecological models are linked

Land Cover Map of the Southeast Region

Figure 1. The Southeast region includes all of nine states (Alabama, Florida, Georgia, Kentucky, Louisiana, North Carolina, Mississippi, South Carolina, and Tennessee), the southern portion of Virginia, and 50 counties in east Texas. Four subregional workshops were conducted in the Southeast region. See Color Plate Appendix

with other process models,both biological and economic. For example,Harcombe and others (1998) observed that Chinese tallow, a freeze-intolerant non-native tree species,increased dramatically in southeastern Texas over the past few decades. Chinese tallow increased by a factor of 30 between 1981 and 1995,often out-competing native species when canopy gaps form in mesic (medium moisture) and wet sites (Harcombe,et.al.,1998). These kinds of interactions and changes in forest dynamics are difficult to simulate.

Mixed responses among species to fertilization effects of elevated atmospheric CO_2 further confound our ability to model ecosystem structure and productivity. Several studies showed that elevated CO_2 increased photosynthesis rates and improved water use efficiency in many forest species and agricultural crops (Acock,et.al.,1985;Allen,et.al.,1989; Nijs,et.al.,1988). Two reviews of CO_2 exposure studies with deciduous and coniferous species found that increases in growth rates varied widely, but that generally tree growth was stimulated by increases in CO_2 (Eamus and Jarvis,1989;NCASI, 1995). However, limits on the availability of soil nutrients and water in many natural or semi-natural ecosystems can severely constrain the potential improvement in water use efficiency due to suppressed transpiration induced by enhanced CO_2 levels,thereby offsetting potential gains in productivity (Lockwood,1999). Temperature,plant pests,air pollution,and light availability could also limit the potential enhancement of growth by elevated CO_2 (NCASI 1995). Hence,one should be very cautious in assuming what the net effects of CO_2 enrichment might be across a region or biome.

Southeast US Annual Mean Temperature

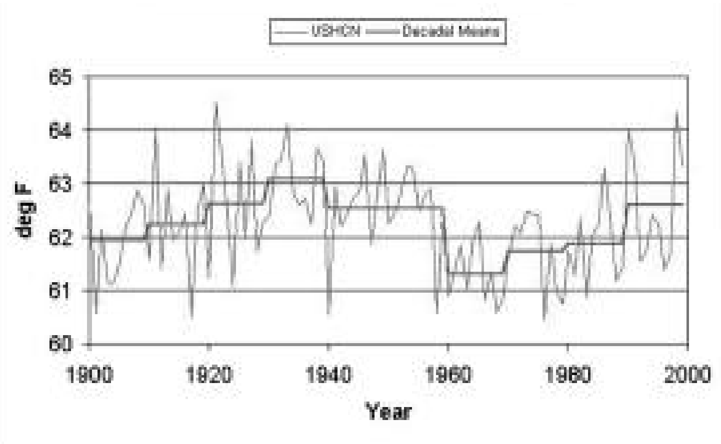

Figure 2. Decadal average temperatures in the Southeast. Source D. Eastering, NOAA National Climatic Data Center. See Color Plate Appendix

CLIMATE VARIABILITY AND CHANGE

Past Century

The Southeast has some of the warmest conditions in the US. However, it is the only region to show widespread but discontinuous cooling periods of 2 to 3.5ºF (1 to 2ºC) over almost the entire area during the past 100 years (Figure 2). Peninsular Florida, North Louisiana,and a few small areas in the Appalachian Mountains have shown a modest warming of around 2°F (1ºC) since 1900. The reason the Southeast temperature record shows a net cooling trend over the past 100 years is that there was a warm period between the 1920s and 1940s,then a significant downward trend through the late 1960s. The mid-1900s cooling trend may have been due to natural variation. Human-caused sulfate aerosol emissions during this period may have also played some role. Sulfate aerosols reflect some sunlight back into space,thereby cooling the atmosphere (Kiehl,1999). Since 1970,the average annual temperature increased,with the most significant increases occurring during the 1990s. Trends in temperature extremes over the past one hundred years exhibit a decrease of about 5 days in the number of days per year exceeding 90ºF (32.2ºC),and an increase of 6 days in the number of days below freezing over the entire region. However, over the past fifty years the average annual length of the snow season decreased by 4 days.

The Southeast receives more rainfall than any other region. Annual precipitation trends show increases of 20-30% or more over the past 100 years across Mississippi,Arkansas,South Carolina,Tennessee, Alabama,and parts of Louisiana,with mixed changes across most of the remaining area. The southern mountains of North Carolina,the southern tip of Texas,and a couple of other small areas have slightly decreasing trends in annual precipitation. Much of the increase in precipitation was associated with more intense events (rainfall greater than 2 inches or 5 cm per day). A small percentage of the increased precipitation was associated with moderate rainfall events,which are generally beneficial to agriculture and water supply. Analysis of stream flow trends during 1944-1993 showed little change in annual maximum daily discharge,but significant increases in annual median and minimum flows in the lower Mississippi Valley, and decreases in these categories in parts of Georgia and North Carolina (Linns and Slack,1999). Increased precipitation intensity in extreme events during the next century is suggested by climate models under doubled CO_2 for the US (Mearns,et.al.,1995) and there is evidence that moisture in the atmosphere is increasing over the Caribbean region (Trenberth,1999). Heavy rains are less efficient (more water runs off into the sea) and are more likely to cause flooding, which is a serious problem in the region.

Trends in wet and dry spells during the 20th century, as indicated by the Palmer Drought Severity Index (PDSI),are spatially consistent with the region's annual precipitation trends,showing a strong tendency to more wet spells in the Gulf Coast states,and a moderate tendency in most other areas. The percentage of the southeastern landscape experiencing "severe wetness"(periods in which the PDSI averages more than +3) increased approximately 10% between 1910 and 1997.

Effects of El Niño on Climate in the Southeast

The El Niño/Southern Oscillation (ENSO) phenomenon contributes to variations in temperature and precipitation that complicate longer-term climate change analysis in certain parts of the country, particularly the Southeast. ENSO is an oscillation between warm and cold phases of sea-surface-temperature (SST) in the tropical Pacific Ocean with a cycle period of 3 to 7 years. US climate anomalies (departures from the norm) associated with ENSO extremes vary both in magnitude and spatial distribution. El Niño events (the warm phase of the ENSO phenomenon) are characterized by 2 to 4°F (about 1 to 2ºC) cooler average wintertime air temperatures in the Southeast. During the spring and early summer months,the region returns to near-normal temperatures. Precipitation anomaly patterns following warm events indicate that Gulf Coast states encounter wetter than normal winters (by about 1 to 2 inches per month). By the spring, the entire eastern seaboard shows increased precipitation. In summer, climate impacts of warm events are more localized; for example,drier conditions are found in eastern coastal regions,and from north Texas to northern Alabama. El Niño events also create upper atmospheric conditions that tend to inhibit Atlantic tropical storm development, resulting in fewer hurricanes,while La Niña events have the opposite effect, resulting in more hurricanes. Figure 3 depicts US Gulf of Mexico hurricane landfall trends and the probability of hurricane landfall during El Niño and La Niña years.

Gulf Landfalling Hurricanes by Decade

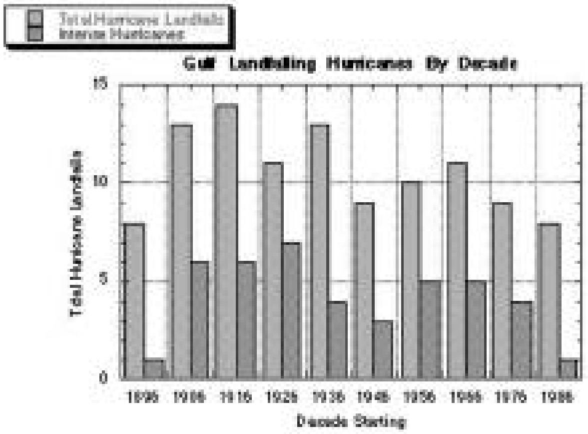

Figure 3(a). US Hurricane Landfall Trends in the Gulf of Mexico. This figure shows the number of US hurricanes making landfall in the Gulf of Mexico by decade for the past 100 years. There were peaks in activity during the 1910s and 20s, as well as a lower peak in the 1960s. The past 30 years have shown a decrease in the number and intensity of Gulf hurricanes making landfall. See Color Plate Appendix

US Hurricanes

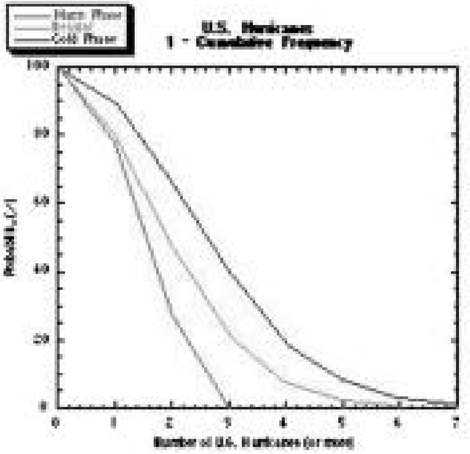

Figure 3(b). Effect of ENSO Phase on Hurricane Landfall
This figure shows the probability of the number of hurricane landfalls on the US in a given hurricane season and ENSO phase (El Niño, Neutral, La Niña). Based on the past 100-year record, the probability of at least 1 hurricane landfall is similar for all three phases, with probabilities ranging from 78% for El Niño to 90% for La Niña. For multiple landfalls, however, the differences caused by ENSO phase become apparent. The probability of at least 2 landfalls during El Niño is 28%, but is 48% in neutral years, and 66% during La Niña. The probability of at least 3 landfalling hurricanes is near 0% for El Niño, 20% for neutral years, and 50% for La Niña. It is clear that El Niño years have few multiple hurricane strikes on the US, while neutral years and La Niña years often see multiple hurricane strikes on the US coast. (Source: Florida State University, Center for Ocean-Atmosphere Prediction). See Color Plate Appendix

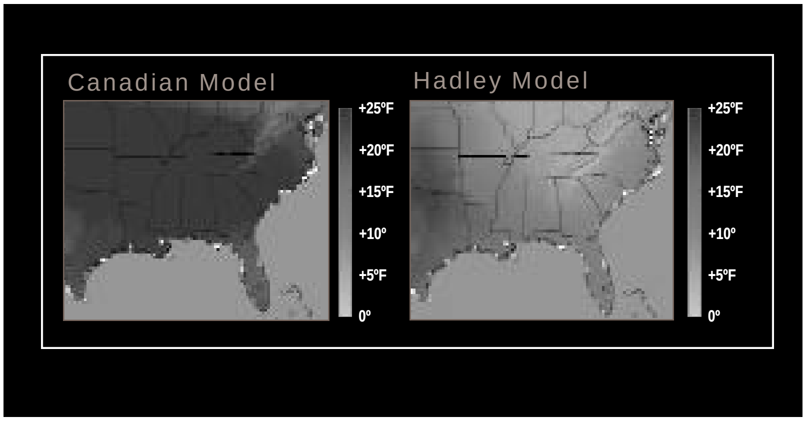
July Heat Index Change - 21st Century

Figure 4. The changes in the simulated heat index for the Southeast are the most dramatic in the nation with the Hadley model suggesting increases of 8 to 15ºF for the southern-most states, while the Canadian model projects increases above 20ºF for much of the region. Heat indices simulated for the Southeast by 2100. (source, NOAA National Climatic Data Center). See Color Plate Appendix

During La Niña events (the cold phase of ENSO),the anomalies are sometimes reversed from those associated with warm events,but not everywhere. Above-average wintertime temperatures are present East of the Mississippi. By spring,the warmer anomalies in the east are focused in the Ohio Valley and northern Florida,Georgia,and South Carolina. Wintertime precipitation patterns associated with cold events show increases (1-2 inches or 2.5-5 cm per month) in the band stretching from northern Mississippi to southwestern Pennsylvania. In the spring,Gulf Coast areas have increased precipitation. In summer, the extreme southern US is colder than normal and greater precipitation is evident in the Southeast. Dry to very dry conditions are found in parts of Texas and Louisiana. Thus,as suggested by these results,the climate anomalies associated with opposite phases of ENSO are not in direct opposition. For example, climate anomalies in Florida are nearly opposite (for cold and warm events) while those in many of the midwestern states are of the same sign for both precipitation totals and temperatures during both warm and cold events. Further evidence demonstrates that climate anomalies associated with strong warm events are not amplifications of normal warm events (Rosenberg,et al.1997).

Scenarios for the Future

The Hadley Centre climate model projects that by 2030,maximum summer temperatures in the Southeast will increase by about 2.3°F (1.3ºC) while maximum winter temperatures will increase by 1.1°F (0.6ºC). The projected increase in mean annual temperature of 1.8ºF (1.0ºC) by 2030 and 4.1ºF (2.3ºC) by 2100 represents a smaller degree of projected warming than for any other region. The smaller simulated warming rate is possibly due to the buffering affects of the oceans,large amounts of surface water for evaporative cooling,and the sulfate aerosol emissions that are prevalent throughout the eastern US. Sulfate aerosols may help explain the mid-20th century cooling trend in parts of the US;however, over the past two decades,sulfate emissions decreased,and the future cooling affect of sulfate aerosols is not expected to be as important due to Clean Air Act restrictions. Although the increase in temperature under the Hadley model is small compared to other regions,the resulting increase in the summer heat index by 8 to15ºF (4 to 8ºC) (calculated from monthly maximum temperature and relative humidity) would likely affect human activity and,possibly, demographics in the 21st century.

The Canadian Centre climate model projects higher temperature scenarios and higher southeastern heat indices by the end of the 21st century than does the Hadley model. The Canadian model simulates an increase in mean annual southeastern temperature of about 3ºF (1.7ºC) by 2030 and 10ºF (5.5ºC) by 2100. In the Canadian model,increases in maximum summer temperature are the highest in the Nation for both 2030 (5ºF or 2.8ºC) and 2100 (12°F or 6.5ºC). The Canadian climate model simulates an increase in average summer heat index above 15ºF (8ºC) across the entire region by 2100 (Figure 4).

Another important difference between the two models for the Southeast lies with the simulated changes in rainfall;the Canadian climate model simulates reduced average annual precipitation (10% less than present by 2090) while the Hadley model simulates more precipitation than present (20% more by 2090). These differences have important implications for hydrologic impacts on the Southeast, because the Canadian model simulates decreased soil moisture,while the Hadley model simulates increased soil moisture (Felzer and Heard,1999). Differences between the two models are illustrated in Figure 5,which depicts the simulated summer climate in Georgia in 2030 and 2090. According to the Hadley climate model scenario,the Southeast will remain the wettest region of the US for the next 100 years. The precipitation changes projected by the Hadley model by 2100 are consistent with other parts of the eastern and midwestern US.

The Max Planck Institute climate model (ECHAM4/OPYC3),one of a few models with sufficient resolution in the tropics to adequately simulate narrow equatorial upwelling and low frequency waves,simulates more frequent El Niño-like conditions and stronger La Niñas under a doubling of CO_2, which is consistent with the Hadley model projections with a doubling of CO_2. The Max-Planck model also suggests that the mean climate in the tropical Pacific region will shift toward a state corresponding to present-day El Niño conditions (Timmermann,et.al.,1999). McGowan,Cayan,and Dorman (1998) showed that the frequency of warm sea surface events off the western coast of North America increased since 1977,but relationships between this trend and reduced hurricane landfall in the Gulf Coast region have not been established.

Summer Climate Changes from Hadley Centre Scenario

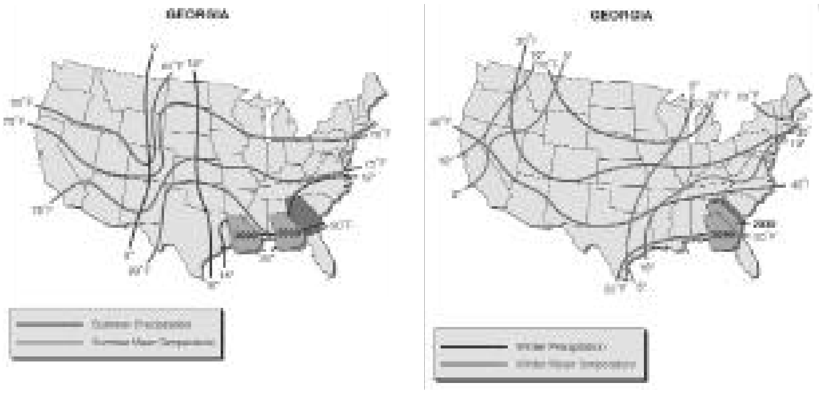

Figure 5. Illustration of how the summer and winter climates in Georgia would shift under the Hadley climate scenario (HADCM2). For example, the summer climate in Georgia in the 2030s would be more like the current climate of the Florida panhandle. Source: NOAA, National Climatic Data Center. See Color Plate Appendix

Table 1: Billion-Dollar Southeast Weather Disasters, 1980-1999

Disaster	Year	Estimated Damages/ Costs*	Estimated Deaths**
AR/TN Tornadoes	1999	$ 1.3 billion	17
TX Flooding	1998	$ 1.0 billion	31
Hurricane Georges	1998	$ 5.9 billion	16
Hurricane Bonnie	1998	$ 1.0 billion	3
Southern Drought/Heat Wave	1998	$ 6.0-9.0 billion	200
El Niño/Tornadoes and floods	1998	$ 1.0 billion	132
MS/OH Valley Floods/Tornadoes	1997	$ 1.0 billion	67
Hurricane Fran	1996	$ 5.0 billion	37
Hurricane Opal	1995	$ 3.0 billion	27
TX/OK/LA/MS Severe Weather	1995	$ 5.0-6.0 billion	32
TX Flooding	1994	$ 1.0 billion	19
Tropical Storm Alberto	1994	$ 1.0 billion	32
Southeast Ice Storm	1994	$ 3.0 billion	9
Summer Drought/Heat Wave	1993	$ 1.0 billion	***
Hurricane Andrew	1992	$ 27.0 billion	58
Hurricane Bob	1991	$ 1.5 billion	18
TX/OK/LA/AR Flooding	1990	$ 1.0 billion	13
Hurricane Hugo	1989	$ 9.0 billion	57
Hurricane Juan	1985	$ 1.5 billion	63
Hurricane Elena	1985	$ 1.3 billion	4
Florida Freeze	1985	$ 1.2 billion	0
Florida Freeze	1983	$ 2.0 billion	0
Hurricane Alicia 1999	1983	$ 3.0 billion	21
Total		$ 83.7-87.7 billion	856

* not adjusted for inflation,** US only, *** undetermined (Source:National Climatic Data Center, 1999)

KEY ISSUES

1. Weather-related Stresses on Human Populations
2. Agricultural Crop Yields and Economic Impacts
3. Forest Productivity Shifts
4. Water Quality Stresses
5. Threats to Coastal Areas

Changes in average climate and weather extremes have important economic implications in the Southeast. There are several reasons why this region is of relatively high interest and concern. First,there is a strong ENSO signal,primarily in the Gulf Coast states,that results in seasonal and year-to-year variations in temperature and precipitation. Understanding potential future climate change in the context of current natural variability can provide an important contribution to ongoing discussions of mitigation options. A second consideration is that the Southeast experiences many extreme climate events such as hurricanes, heat waves,tornadoes,ice storms, floods,and lightning storms that cause significant economic losses to industry and local communities. The agriculture and forestry sectors make substantial contributions to the regional and national economy and these sectors are quite vulnerable to climate variability. Water resources,air quality, coastal resources,and land use are other important regional issues that may be strongly influenced by climatic trends and variability.

1. Weather-related Stresses on Human Populations

The US experienced 42 weather-related disasters over the past 20 years that resulted in damages/costs in excess of $1 billion each;23 of these disasters occurred in Southeast states, resulting in total damages/costs of about $85 billion. Most of the property damages were associated with floods and hurricanes. Low-lying Gulf and South Atlantic coastal counties are particularly vulnerable to storm surge. Between 1978 and 1998,56% of the National Flood Insurance Program (NFIP) policies in force and 74% of total NFIP claim payments occurred in southeastern coastal counties (Heinz Center, 1999).

In addition to the projected shift towards more frequent El Niño-like conditions in the Southeast,some climate models suggest that rainfall associated with El Niño events will increase as atmospheric CO_2 increases. Increased flooding in low-lying coastal counties from the Carolinas to Texas could possibly have adverse effects on human health. Floods are the leading cause of death from natural disasters in the Southeast and nationwide. Flooding,however, is not the only problem stemming from unusual meteorological events. The southern heat wave and drought of 1998 resulted in damages in excess of $6 billion.

El Niño and the 1998 Florida Wildfires

Florida consistently ranks among the top five states in terms of wildfire frequency and acreage affected, due largely to frequent thunderstorms and a warm moist climate that promotes lush growth of volatile understory plants. To limit the accumulation of fuels that promote disastrous wildfires,landowners in Florida routinely treat close to 2 million acres a year with prescription fire. The unseasonably warm weather and copious rainfall brought about by El Niño conditions during the winter of 1997-98 resulted in even higher plant growth than usual and high soil moisture that limited the acreage that could be treated effectively with dormant-season prescription fire. As El Niño conditions began to subside in March,1998, record breaking rainfall changed to record-setting drought. Many prescription burns were postponed further because of the increasing probability of crown fires and root damage to trees. Lightning activity picked up as usual in May, but with lower than average rainfall. By June 1,drought indices reached record heights. During the ensuing six weeks,more than 2,500 fires burned roughly 500,000 acres in Florida,destroying valuable timber and damaging roughly 350 homes and businesses. Predicting El Niño conditions holds obvious benefits for fire preparedness and prevention. Changes in El Niño patterns would have both ecological and economic implications.

Also of concern in the Southeast are the effects that elevated surface temperatures have on human health as a result of prolonged or persistent periods of excessive summertime heat events coupled with droughty conditions. For example,it is known that urban surface temperatures in cities in the Southeast can be elevated as much as 5 to 10ºF (approximately 3 to 5ºC) over non-urbanized areas (Lo,et.al., 1997;Quattrochi and Luvall,1999). These elevated urban surface temperatures are a heat stress to humans and can significantly contribute to increasing both the duration and magnitude of photochemical smog,particularly ozone concentrations (Southern Oxidants Study, 1995;Quattrochi,et.al., 1998). Increases in maximum summer temperatures are of particular concern among lower income households that lack sufficient resources to improve insulation and install and operate air conditioning systems.

Adaptation Options

Understanding the risks and vulnerability of communities to weather-related hazards (considering hidden and reported costs and the actual frequency with which these disasters occur in the Southeast) is important to the quality of adaptation strategies. Across the region, intense precipitation has increased over the past 100 years and some models suggest that this trend will continue as the atmosphere warms. Traditional approaches to mitigation such as flood proofing, elevated structures, and building codes, are no longer adequate in themselves, particularly in the coastal zone. Even if storms do not increase in frequency or intensity, sea-level rise alone will increase the propensity for storm surge flooding in virtually all southeastern coastal areas.

The National Oceanic and Atmospheric Administration (NOAA) and the Federal Emergency Management Agency (FEMA) commissioned a study on the true costs and mitigation of coastal hazards in 1996. The report of this study calls for a strategic shift in hazard mitigation and focuses on model state programs developed in Florida and others parts of the country to foster more disaster-resilient communities. Recommendations include improvements in disaster cost accounting and risk assessment, insurance/mitigation policy linkages, integrated approaches to coastal management/development, and community-based mitigation planning (Heinz Center, 1999). Changes in climate and sea-level rise should be an integral consideration as Southeast coastal communities develop strategies for hazard preparedness and mitigation. Several states have implemented permanent "set backs" or "rolling easements" to prevent further development in areas that will become more flood-prone as sea level rises (see Coastal and Marine Resources chapter).

Health advisory systems, community-wide heat emergency plans, improved weather prediction capabilities, and other adaptations that would likely reduce urban heat stress and air pollution-related health effects are presented in the Northeast and Health Chapters.

2. Agricultural Crop Yields and Economic Impacts

Current Conditions

Great agricultural changes have taken place in the Southeast over the past 150 years. In 1849, the South produced more corn than the Midwest; Southeast acreage in corn was higher than in cotton. Cotton production expanded greatly after the Civil War, and by the late 1920s, cotton was more dominant in the South than it was a century before. There was complete mechanization of crop production in the Southeast after World War II and millions of sharecroppers moved to the big cities in the North. This had an important impact, not only on labor requirements, but on the whole economic structure of agriculture. There has also been a shifting cropland base in this region. For example, over the last 50 years soybeans changed from a minor forage crop to an agricultural staple second only to corn in value of production. As soybeans and rice replaced corn and cotton, farmers chose soils most suitable for the new crops. Drained wetland soils in Arkansas were more productive in soybeans than the old Piedmont soils abandoned by cotton farmers.

In terms of agricultural potential, one of the Southeast's most important assets is its potential to expand the acreage devoted to crops beyond the current level. The land from which new cropland can be drawn is currently about evenly divided between pasture and forestland. Although the Southeast could substantially increase acreage devoted to agriculture, it fares poorly in terms of native

Table 2: Principal Crops in the Southeast

(10^3 acres)

(source, USDA, Census of Agriculture, 1996).

	1929	1949	1969	1987	1996
Corn	23,940	20,417	7,896	4,309	5,005
Cotton	23,228	13,031	4,711	3,345	5,931
Peanuts	2,207	2,348	1,046	971	927
Rice	598	1,011	1,194	1,654	2,156
Soybeans	1,321	2,599	13,894	25,645	12,303

Dryland Crop Yield Changes

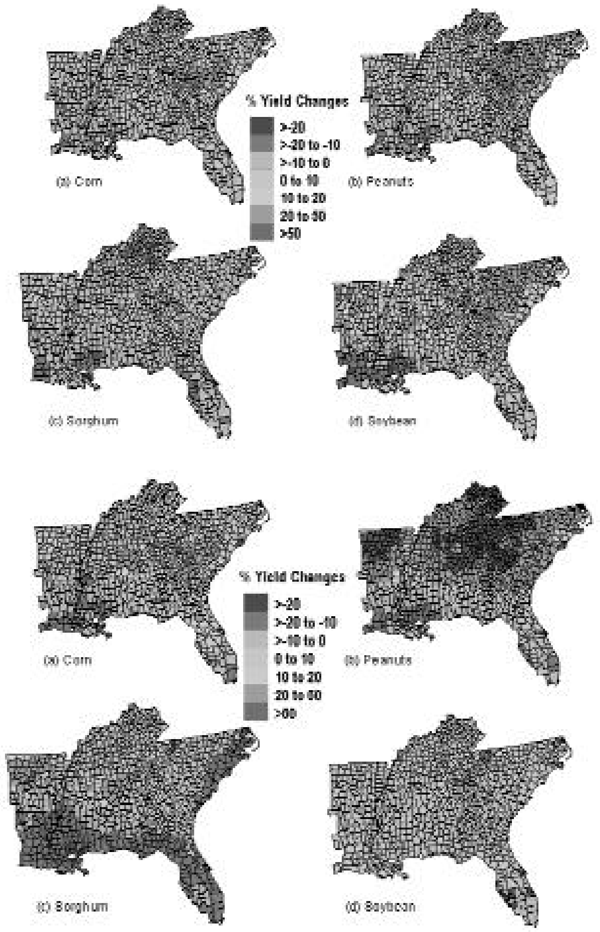

Figure 6. Dryland crop yield changes in 2030 (a) and 2090 (b) without adaptation for various climate sensitivity scenarios (source: Auburn University, Global Hydrology and Climate Center; University of Florida, Agricultural and Biological Engineering Department). See Color Plate Appendix

soil fertility. In addition to having low fertility, millions of acres of soils in the Southeast are moderately to severely eroded,the result of decades of continuous corn and cotton production under poor soil management. However, another of the region's agricultural assets is its latitude and proximity to the warm Gulf and Caribbean maritime influence. Overall,the Southeast has a consistent 30- to 90-day longer growing season than the Corn Belt and the Great Plains. The Southeast has enormous supplies of fresh water in the form of rainfall,surface water flowing through streams and creeks,and groundwater. Water availability gives the Southeast some substantial advantages,including irrigation possibilities that have barely been exploited.

The Southeast's mild climate and frequent rainfall predispose the region to an array of agricultural pest problems more serious than anywhere else in the nation. Agricultural pests can reduce crop yields and raise production costs. Another consequence of the region's pest problems has been relatively high use of pesticides. Although the Southeast accounts for only 14% of the nation's cultivated cropland,it consumes 43% of the insecticides and 22% of the herbicides used by farmers (USDA,Census of Agriculture 1994).

Potential Impact of Climate Change on Crop Yield and Water Use at the Field Scale

Two families of mechanistic crop simulation models CROPGRO (for soybean and peanut) and CERES (for corn,wheat, rice,and sorghum) in DSSAT V 3.5 (Tsuji et al.,1998; Jones et al.,1999) were used to simulate potential dryland and irrigated crop production using state- and crop-specific management practices throughout the Southeast. The Hadley Centre model was chosen for this analysis by the Southeast working group because this model was gridded properly for the region at the time the analysis was begun,and because the model performed best,among those tested,at hindcasting southeastern ENSO-related climate anomalies.

Crop yield changes simulated under dryland (non-irrigated) conditions suggest that yields were sensitive to the Hadley climate change and CO_2 fertilization and that the response varied by crops and locations (Figure 6). Dryland crop yields generally decreased along the Gulf Coast by 1 to 10% due to water stress. Furthermore,increased demand for water by other sectors under higher temperatures is likely to amplify these impacts. Increases in atmospheric CO_2 concentrations may reduce crop water use to some extent,due to increases in leaf stomata resistance,but cannot fully compensate for increases in crop water demand due to the higher temperatures in climate change scenarios.

In the crop simulation model,dryland corn yield increased by 1 to 30% in the Coastal Plain and decreased up to 10% in Louisiana and large parts of Mississippi,Arkansas,and Kentucky. The shorter growing cycle reduced yield while increased CO_2 and rainfall boosted yield. Due to lower water use efficiency, the model suggests that it could possibly become uneconomical to irrigate corn,prompting farmers to increase dryland corn production. Sorghum yields increased in the model results by 1 to 30% in parts of Alabama,Georgia,South Carolina, and North Carolina where seasonal rainfall increased by 5 to 15%. Simulated yields from irrigated sorghum were 4 to 7% lower almost everywhere, even where higher yields were predicted under dryland conditions,largely due to shorter growing seasons.

Table 3: Temperature Tolerance Limits for Various Crops

to the projected rainfall changes in 2030s and 2090s.

	445 ppmv CO_2 as in 2030s Change in Current Rainfall			680 ppmv CO_2 as in 2090s Change in Current Rainfall		
	-20%	0%	20%	-20%	0%	20%
	Temperature Tolerance					
Soybean	+0	+1	+3	+1	+3	+4
Peanuts	+0	+2	+3	+2	+3	+4
Corn	+0	+0	+1	+2	+3	+3
Sorghum	+0	+0	+1	+1	+1	+1
Wheat	+0	+1	+2	+3	+3	+3

Simulated soybean and peanut yields increased by 1 to 30% mostly within the Coastal Plain and mid-south and more than 30% in parts of North and South Carolina. Yields also increased,in parts of Arkansas and upper Mississippi,where dryland corn and sorghum yields decreased. Irrigated yields increased 1 to 10% over almost all of the region including where losses had been predicted under dryland conditions. The models simulated decreases of up to 30% in dryland peanut yields in the lower Delta and along the Gulf Coast,but when irrigation was added in the same areas,yield increased by over 30%. If the model-simulated changes were to occur slowly over next 25 to 45 years, farmers would be likely to slowly increase irrigation as the marginal value of irrigation increased. The spatial variation in simulated yield induced by climate change suggests that many farmers in the lower Delta and Gulf Coast may drop dryland production of peanuts while production of these crops may expand in other parts of the region.

Simulated winter-wheat yield increased in all regions except in the lower Delta and parts of Arkansas. Simulated irrigated yields increased following a similar trend as the dryland yield. Demand for irrigation increased by 20 to 50% in the Delta where rainfall decreased,and evaporation increased due to higher temperatures. Over the same period,irrigated yields declined. In parts of Arkansas and Louisiana,where irrigated rice dominates,the model simulated 1 to 10% yield losses by the 2030s and 3 to 39% increases by the 2090s. One of the major threats to rice production is increasing competition for and increasing costs of irrigation water.

Sensitivity Analysis of Crop Response to Climatic Change

To avoid the narrow range of the climate conditions simulated by the Hadley model, we conducted a sensitivity analysis in 10 agriculturally-dominant southeastern areas using 25 combinations of anticipated temperature and rainfall at 445 and 680 ppm CO_2 levels superimposed on the current climate. The sensitivity analysis identified the climate conditions that would be particularly damaging to the dryland production (see Table 3) and allowed us to consider to what extent yields can be maintained with current management practices. Results indicate that yield would likely decrease compared to the current values if temperature exceeds the current value more than the corresponding value for change in rainfall amount.

Figure 7 shows that under simulated 2030s CO_2 levels,+1ºC (1.8ºF) change in temperature increased dryland production of soybean,peanuts,and wheat under current rainfall,while yields of corn and sorghum declined. A 2ºC (3.6ºF) increase in temperature in 2030 resulted in further yield losses for all crops simulated. In contrast,the effects of 2ºC (3.6ºF) temperature increase in 2090 with no change in rainfall suggested a generally positive effect on crop yields. However, decreases in rainfall by 20% accompanied by temperature increases of 1 to 2ºC (1.8-3.6ºF) almost doubled yield losses for all dryland crops studied. Under conditions of lower or the same growing season rainfall amounts,yields of all crops increased more due to increased CO_2 levels than due to higher seasonal rainfall. For all crops and combinations of temperature and CO_2 changes,decreases in precipitation resulted in differential decreases in crop yields. Changes in yields with 20% lower rainfall were of similar magnitude at all other temperatures and CO_2 levels simulated. Furthermore, results showed that crop yields were much less sensitive to changes in temperature compared to changes in precipitation. An increase in growing season rainfall of about 20% almost completely offset the negative effect of temperature increase. Irrigated yields were simulated assuming current rainfall by varying only the temperatures

Simulated Changes in Dryland Yields for Southeastern Crops based on the Hadley (HADCM2) Scenario

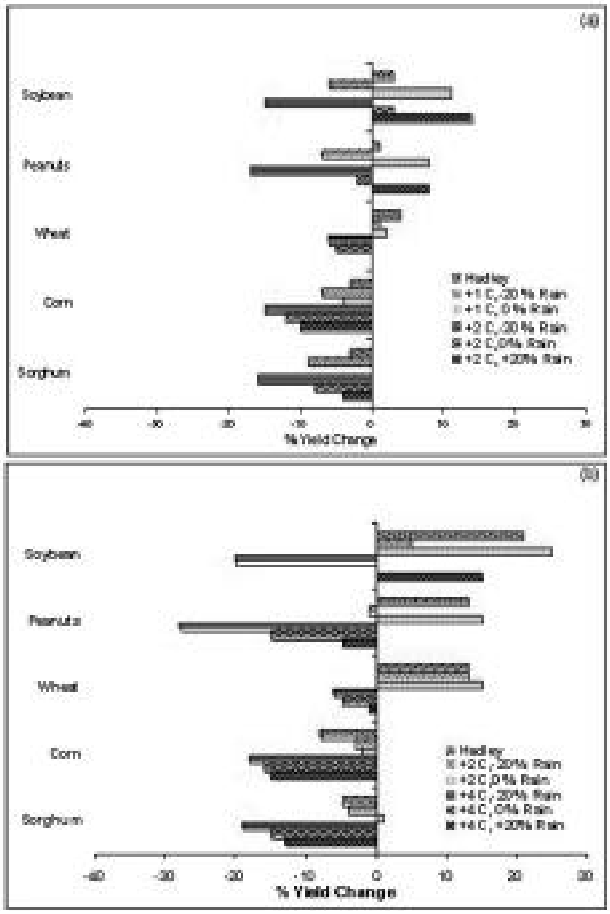

Figure 7. Dryland yields changes in 2030(a) and 2090(b) without adaption for various climate sensitivity scenarios. (source: Auburn University, Global Hydrology and Climate Center; University of Florida, Agricultural and Biological Engineering Department). See Color Plate Appendix

from +1 to +5ºC (1.8 to 9ºF). If future rainfall is higher, then irrigation requirements will likely decrease,and if it is lower, irrigation needs will likely increase. Most irrigated crops were sensitive to simulated climate changes and CO_2 fertilization.

Implications for Field Scale Adaptation

Future climate change may strongly affect agriculture in the Southeast. In cropping systems,a wide range of low cost adaptations to climate change may exist to maintain or even increase crop yields under future climates. Farmers may be able to respond to changes in environmental conditions by choosing the most favorable crops,cultivars,and cropping systems. Our findings indicate that changes in planting dates and maturity groups could possibly increase yield under the climate change conditions studied. In the simulations,all crops benefited from variety and planting date adaptations either by shifting from a decreased yield without management changes to an increased yield when management was changed. For most dryland crops,adaptation did not completely eliminate yield loss under a 20% less rainfall condition. For corn,peanuts,sorghum, and wheat,there may be little need to change currently adapted varieties under all combinations of temperature and rainfall changes,in part due to strong CO_2 fertilization effects on crop yields.

Sub-regional Impacts on Productivity and Profitability

The largest threat to crop production in the Southeast appears to occur where decreases in precipitation coincide with higher temperatures. This combination of climate change would likely increase evapotranspiration demands in a climate with lower water availability, which would increase water stress and reduce crop growth and yields. In many areas of the Southeast,however, projected temperature rises of no more than 3 or 4ºF (2ºC or less) together with declining needs for irrigation, should enhance crop production. The Hadley model scenario for 2030 indicates improved conditions for water availability in the Tennessee Valley, coastal North and South Carolina,and the lower Mississippi Valley. Water supplies are projected to be much worse in the Mississippi Delta and slightly worse in Louisiana,Southern Alabama,the Florida panhandle,and the Coastal Plain of Georgia. By 2090 they also become much worse in Northern Mississippi,Southern Alabama,and Southwestern South Carolina.

A farm management model was used to simulate changes in crop mix, water use,and farm income associated with the climate-induced yield changes described above (Hatch et al.,1999). Of the major crop growing areas of the Southeast,the southern Mississippi Delta and Gulf Coast areas are more negatively impacted,while the northern Atlantic Coastal Plain is more positively impacted. Analyses indicate that farmers could possibly mitigate most of the negative effects and possibly benefit from changes in CO_2 and moisture that benefit crop growth. The discussion that follows is organized around the two principal row crop growing areas of the Southeast, the Mississippi Delta and Atlantic Coastal Plain.

The southern portion of the Mississippi Delta is expected to endure the severest negative impacts with the northern portion relatively less impacted. In both 2030 and 2090,simulated crop yield, water use,and income all are relatively worse off in the southern area of the Delta,particularly Louisiana, Mississippi,and Arkansas. This picture contrasts rather sharply with the largely beneficial impacts in much of the Coastal Plain,especially the northern tier. Southern Alabama,the Panhandle of Florida, and southwest Georgia,the crop growing areas in proximity to the Gulf coast,are the areas of the Coastal Plain that are negatively impacted. The rest of this important crop growing area,that stretches from central Georgia to North Carolina,is expected to see beneficial impacts from the climate-induced yield changes and the resultant changes in farm management.

Simulated changes in water use for irrigation of row crops show a distinct north-south pattern. That is, the southern tier of the Southeast is expected to increase its needs for irrigation water whereas the northern tier is expected to decrease its relative need for irrigation water. This pattern is somewhat evident in the 2030 simulation and very pronounced in the 2090 crop and management simulations.

Economic sensitivity to increased temperatures was also investigated. Two sensitivity scenarios were analyzed to provide an indication of sensitivity to increased temperature without any changes in precipitation. The sensitivity scenarios were "hot"and "very hot;"the former was an increase of 1ºC in 2030 and 2ºC in 2090,and the very hot scenario increased temperature by 2ºC in 2030,and 5ºC in 2090. These temperature changes were selected because they roughly reflect the temperature changes associated with the Hadley and Canadian models, respectively, without the simulated changes in precipitation. The "hot"scenario had a slightly more negative impact than the Hadley scenario in many areas of the Southeast because the hot scenario did have the Hadley's accompanying increase in moisture. The "very hot"scenario produced rather dramatic negative effects, again because these were not mitigated by additional moisture.

The heterogeneous growing conditions of the Southeast and the great diversity of crops and management systems used in the region make broad generalizations about regional climate effects on agriculture very difficult. The Southeast is one region of the nation that is very likely to experience changes in the mix of crops that can be profitably grown. As a result,the Southeast is a region that will gain from improved information on climate effects and on improved dissemination of this information to farm managers. Improvements in understanding climate and forecasting weather will improve the ability of managers to deal effectively with these and future changes, for example by providing them with forecasts based on ENSO phase (Legler, et.al., 1999).

Additional Adaptation Options

Expected changes in productivity and profitability will very likely stimulate adjustments in management strategies. As yields change,commodity prices will also change. Producers have several options by which they can adapt to changes in yield and price expectations. As previously pointed out,they can change to alternative crops. They can also grow the same crops,but adjust cultural practices, varying planting dates,seeding rates, row spacing,patterns of water usage,crop rotations,and the amounts,timing,and application methods for crop nutrients and pesticides.

Technology can also be expected to respond with new products and methods to optimize production under changing climatic conditions. Plant breeders will very likely respond by developing new varieties to accommodate climatic changes. Combinations of technological advances and adaptive management practices could very likely minimize the potential adverse effects and amplify the potential positive effects of climate change on agricultural productivity in the Southeast.

3. Forest Productivity Shifts

Current Conditions

Most of the Southeast's native forests were converted to farmland by 1920,with a large percentage of this conversion occurring prior to the Civil War. By 1860, about 43% of the total land area in the Southeast was reported as farmland,but a substantial part of the farm holdings remained in forest, which was often used as a place for grazing livestock (USFS,1988). With continued expansion of settlements,timberland continued to decline until the early 1920s. Significant changes in agriculture took place after 1920 that caused abandonment of large areas of crop and pasturelands. These included the boll weevil infestation,which made cotton growing unprofitable in many parts of the Southeast. Some of the abandoned land was planted with trees,but the majority reverted naturally to forest leading to increases in timberland acreage (USFS 1988).

By the late 1950s and early 1960s,the decline in timberland began again in the Southeast,caused primarily by the clearing of forest for soybean and other crop production. Much of this timberland reduction occurred in the bottomland hardwood forest areas of the Mississippi Delta. Forest reductions were further fueled by growth in urban areas, highways, power lines, and related development. Throughout the 1970s, timberland was cleared for agricultural use and for an expanding export market. In the decade 1982-92, the National Resources Inventory reports roughly a half million-acre loss (less than 1%) in forestland in the Southeast.

Land use changes in the region are sensitive to any projected changes in the value of agricultural and forest lands. Expansion of urban and built-up areas in the Southeast also represents a significant demand for land, but one that will continue to be small relative to the total land base. For example, although developed land increased about 27% in the decade 1982-92, the total land use in this category represents only 8% of the total land use in the Southeast. Future land use changes are likely to have major impacts on things which do not have market prices: wildlife and habitat, topsoil, aesthetics, pollution of groundwater by agricultural chemicals, soil erosion, sedimentation, and loss of wetlands. The management of these natural resources and their relationships with climate variability and change remains an integral part of the economic well being of the Southeast.

Potential Southern Pines and Hardwoods Net Primary Productivity (NPP)

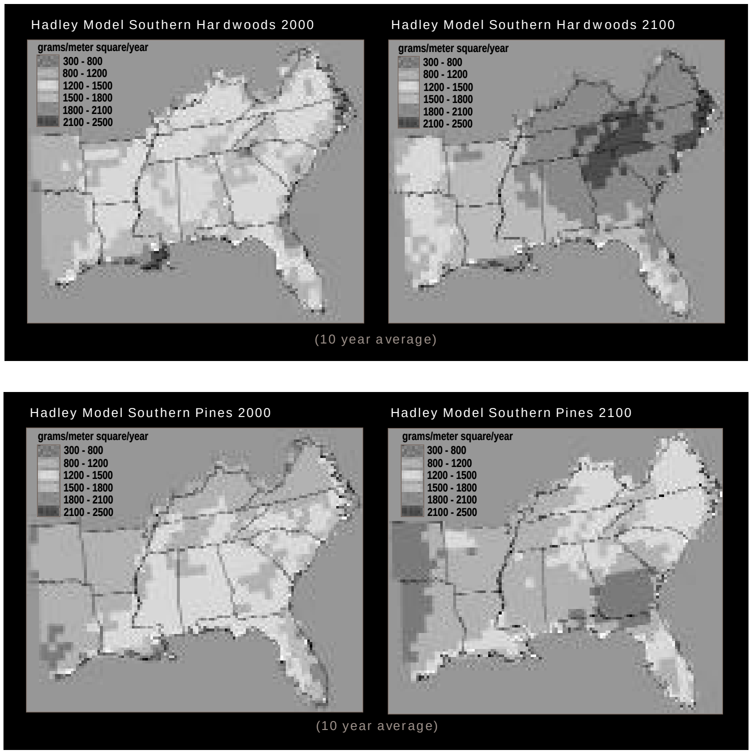

Figure 8. Potential net primary productivity (NPP) of loblolly pine and southern hardwoods simulated by the PnET model with the Hadley climate scenario (HADCM2). (Source: USDA Forest Service, Southern Global Change Program). See Color Plate Appendix

Potential Impacts of Climate Change

As part of this Assessment, PnET-II, a physiologically-based forest process model, combines climate, soil, and vegetation data to simulate annual soil water stress, drainage and biological productivity in southern US forests (Aber, et.al., 1993; McNulty, et.al., 1994). Using Forest Inventory and Analysis data from the USDA Forest Service, predictions of forest productivity per unit area were projected into regional growth using current volume for southern pine forests (USDA, 1988). Model projections of future forest productivity included the influence of doubled CO_2. The Hadley climate scenario (the wetter of the principal climate models used in the National Assessment) was used for reasons cited earlier. Total changes in standing volumes were calculated by multiplying growth per unit area by the total area of pine forest across the region.

The PnET-II model indicated a 12% increase in overall southeastern forest productivity by 2100, but there were important differences between hardwoods and pines. In model simulations using the Hadley scenario, southern pine plantations experienced an 11% increase in productivity by 2040 and an 8% increase by 2100, while hardwood and mixed pine hardwood forest (which represent 64% of the total forest area) experienced a 22% increase in productivity by 2040 and a 25% increase by 2100 compared to 1990 productivity estimates. This difference would likely be accentuated under the warmer temperatures simulated by the Canadian model. This is significant because pines (used for pulp and paper), presently account for almost two-thirds of the region’s forest industry land and about half of the nation’s softwood inventory. Climate models used as input in both the forest and VEMAP models suggest a northward shift in forest productivity over the next century, but they do not consider changes in management that could potentially ameliorate adverse effects. At least two ecosystem models run with the Canadian climate scenario suggest that there will be a 25 to 50% increase in fires and that part of the southeastern pine forest will be replaced by pine savannas and grasslands due to increased moisture stress (see Vegetation and Biogeochemical Scenarios Chapter).

Figure 8 shows PnET-II model outputs for southern forest net primary productivity in the Southeast at present (baseline), and at 2040 and 2090 decadal averages under the Hadley model climate scenario.

The principal factor influencing the lower increase in pine relative to hardwood productivity by 2090 is the fact that pines have greater water demands than do hardwoods on a year-round basis. Even with the increased water use efficiencies associated with increased atmospheric CO_2, the southern pines are limited by water as evapotranspiration rates increase with air temperature.

The impact of climate change on the distribution and impact of forest pests and diseases remains uncertain. Southern pine beetles caused over $900 million in damage to southern US pine forests between 1960 and 1990. Higher winter air temperatures will increase over-wintering beetle larva survival rate,and higher annual air temperatures will allow the beetles to produce more generations per year. Both of these factors could increase beetle populations. On the one hand, field research has demonstrated that moderate drought stress can increase pine resin production and therefore reduce the colonization success rate of the beetle. However, severe drought stress reduces resin production and greatly increases the susceptibility of trees to beetle infestation. Insufficient evidence currently exists to predict which of these factors will control future beetle populations and impacts (McNulty, et.al.,1998).

Potential Effects on Timber Markets

The Sub-Regional Timber Supply (SRTS) model (Abt, et.al.,2000) was developed to link forest inventory models with timber market models. The model uses estimated relationships between prices,harvest,and inventory to model market impacts of shifts in supply or demand. The SRTS model uses the spatially explicit and species specific growth changes from PnET-II to modify inventory accumulation. The cumulative nature of inventory tends to dampen the market impacts of the variability found in annual growth rates.

This analysis of the future of the forest sector comes at an important turning point in historical trends. Since the turn of the century, southern inventories have been increasing due to recovery from exploitation in the 1920s and the emergence of industrial forestry in the 1950s. During the last decade, removals of both hardwoods and softwoods have increased rapidly and are approximately equal to growth. This implies that even subtle climate change impacts may influence the direction of future inventory changes. Overall,the SRTS model (using the Hadley climate scenario) indicated that climate change would more likely favor the Mid-Atlantic over the East Gulf, and hardwoods over softwoods,and that growth over the 2000-2020 period would be significantly lower than over the 2020-2050 time period. This,along with currently favorable growth/removal ratios in the Mid-Atlantic region,led to shifts northward in pine and hardwood harvest in all model runs.

Beyond the spatial and market adjustments to climate change within the forest sector, land-use feedbacks from the agricultural sector, discussed below, also tend to move inventory and harvest to areas with comparative advantages. Sensitivity analysis to higher temperatures (Hadley +2ºC,or 3.6ºF) indicated that the northern shift in inventories and markets became more pronounced and regional prices increased as the mid-Gulf region experienced significant growth declines.

Potential Effects on Forestland Area

Although forests and agriculture dominate the Southeastern landscape,the effect of a changing climate on the relative productivity of these activities is just one of many factors that will determine how the region’s land will be used in the 21st century. Urban and other developed uses,while currently a relatively small part of the regional land base,have expanded substantially in the last two decades and are likely to continue to do so in the future. In recent years, much of the forest area lost to development in the region was about equally offset by gains from forest establishment on previously agricultural land due to the decline in agricultural returns. This has tended to stabilize net forest area trends while exacerbating losses in agricultural land.

Without accounting for climate change, forest area is projected to remain fairly stable in aggregate to 2040. But within the region,there are expected to be areas with substantial land use change (Figure 9). Urbanized areas in the North Carolina and Georgia piedmont and southern Florida are projected to continue the conversion of forestland and agricultural land to developed use,but on a regional basis, these losses are expected to be offset by movement of land from agriculture to forest in other areas, such as the Mississippi delta.

Relative changes in forest and agricultural returns brought on by climate change could possibly change the pattern of stable forest areas in the future if, as some scenarios suggest, agriculture can adapt to climate change in some parts of the region better than forests can. Under the Hadley base climate scenario,our model simulations suggest relatively little change in the way that land is allocated between forests and other uses between now and 2040,though some northern migration of forest area

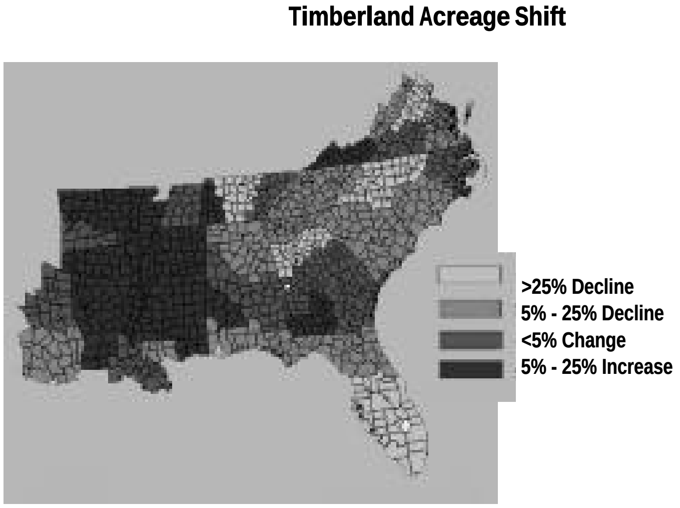

Figure 9 (a). Changes in land use based on timberland acreage shift for 1993-2040: baseline without climate change. Forestland losses are projected in the more urbanized areas of the Southeast, from northern Virginia through the Georgia piedmont and southern Florida. The movement of land from agriculture to forest is projected in many parts of the mid-South. See Color Plate Appendix

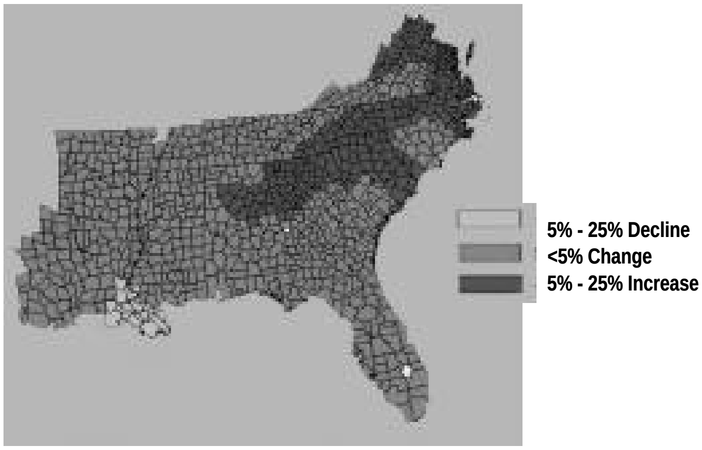

Figure 9(b). Timberland acreage shifts by 2040 due to Hadley climate change. In 2040, forestland is projected to be slightly higher with Hadley base climate change than without climate change in some of the northern reaches of the Southeast, but slightly lower under climate change in parts of the deep South. Year 2040 land allocation effects in most of the region are fairly neutral. (Source: North Carolina State University, Department of Forestry; Research Triangle Institute, Center for Economics Research). See Color Plate Appendix

is expected (Figure 9). However, sensitivity analysis reveals that substantial variation from the Hadley base scenario (e.g.,+2 or 4ºC,3.6ºF or 7.2ºF) would likely have more dramatic effects on land allocation and lead to larger net losses in forest area. These projections should be evaluated with caution,however, as the land use model has employed more limited information on the sensitivity of agricultural economic returns to climate change than on on economic returns to forestry.

Adaptation Options

In general,the biological productivity of southeastern forests will likely be enhanced by atmospheric carbon enrichment,as long as precipitation does not decline or air temperature increase soil moisture stress to a level that would offset potential CO_2 benefits on productivity. The modeling system employed to analyze regional impacts of climate change captures some adaptation through its modeling of economic behavioral responses to changes in the biophysical conditions in forestry and agriculture. For instance,the northward shift in forest productivity is projected to lead to relative increases in the proportion of regional timber harvests that come from the northern reaches of the region. This will tend to compensate for the biophysical effects of climate by reducing harvest pressures in the more negatively affected southern parts and increasing pressure in the more positively affected northern parts. In addition,landowners are projected to shift land between forests and agriculture in places and at times where the change in relative productivity warrants it.

Other potential adaptation strategies not modeled in this Assessment include genetic and silvicultural system improvements that increase water use efficiency or water availability. The knowledge of the role of fire,hurricanes,droughts,and other natural disturbances will be important in developing forest management regimes and increasing stand productivity in ways that are sustainable over the long term. Under a hotter, drier climate,an aggressive fire management strategy could prove to be very important in this region.

Timber productivity associated with increased temperature, growing season length,and carbon enrichment may be further enhanced by improved genetic selection,bio-engineering,use of marginal agricultural land for tree production,and more intensive forest management. Reduction of air pollutants (e.g.,ozone,nitrogen oxides) could also be an important strategy for increasing forest productivity.

4. Water Quality Stresses

Current Conditions

The Southeast has abundant surface water resources,most of which are intensively managed. Almost all major river systems in the region have been dammed and there are few minor streams that have not been affected by landscape alteration, channelization,surface or ground water withdrawals,or other human activities. Based on 50-year or longer streamflow records at 395 stations,Lins and Slack (1999) found that the conterminous US is getting wetter. Exceptions were noted in parts of the Southeast and the Pacific Northwest,where some stream gauges showed a decrease in minimum daily discharge. Parts of Florida and Georgia appear to be experiencing a trend towards decreased minimum flows,while the Lower Mississippi River Valley stations showed an increase in both annual median daily and annual minimum daily discharge (Lins and Slack,1999). In Louisiana,when Keim and others (1995) modeled historical streamflow based on precipitaion,streamflow per unit drainage area increased significantly since 1900.

Potential Impacts of Climate Change

Changes in climate that result in decreased runoff during early summer generally reduce water quality in the Southeast (Mulholland,et.al.,1997). Summer low flows occur when water quality (particularly dissolved oxygen) of many southeastern streams and rivers is at its lowest (Meyer, 1992). Reduced dissolved oxygen during summer months can result in massive fish kills and harmful algal blooms in both coastal and inland waters.

An assessment of southeastern water quality associated with changes in climate was conducted using EPA's GIS-based BASINS model to evaluate current and future water quality conditions under both mean and extreme hydrologic conditions in the Southeast. Analyses were conducted for each of the US Geological Survey's eight-digit Hydrologic Unit Codes (HUCs). Water quality indices included dissolved oxygen,nitrogen and nitrates,and pH. The assessment included three steps:identification of basins with current and potential water quality problems,prediction of general change in stream flow conditions under scenarios of future climate, and re-evaluation of affected basins using the Hadley climate model scenarios for 2030 and 2100.

While water quality problems across the Southeast are not critical under current conditions,quality attainment status is not met in several cases during the majority of the year, and can become critical under extreme low flow conditions during some portions of the year. Stresses on the water quality of the Southeast appear to be associated with intensive agricultural practices,urban development,coastal processes,and possibly mining activities. As might be expected,the impacts of these stresses appear to be more frequent during extreme conditions,probably associated with dry weather. Analysis of the current status (based on 1990-97 observations) of the watersheds in the Southeast for dissolved oxygen revealed few problems under average conditions. However, it must be recognized that because the BASINS database is indexed to major USGS hydrologic units,it necessarily consists of observations of conditions on the larger streams in the regions. Thus,smaller tributaries may exhibit water quality degradation that was not apparent at the larger scale of this analysis.

The analysis suggested that only scattered HUC watersheds in a few states currently exhibit dissolved oxygen (DO) conditions below, or nearly below the recommended 5 mg/l during average conditions. However, dissolved oxygen problems under extreme low flows do arise at a few locations in most,if not all,states. Nitrate levels in streams in the Southeast are used as an indication of nutrient content in these HUCs. While some nutrients are essential for ecosystem health, excessive levels can result in harmful conditions such as algal blooms, which can negatively impact DO levels. The current status (1990-97) based on observations for total average nitrate nitrogen content for streams of the Southeast reveals that many exhibit levels above 0.5 mg/l and in some cases above 4 to 5 mg/l,which is 3- to 4-times higher than levels common in most southeastern streams.

One interesting observation is that streams that currently exhibit low dissolved oxygen levels do not correspond to those basins where nutrient levels appear to be high. However, in both cases,the problems are most prevalent in watersheds with intensive forestry or agricultural operations.

Climate scenarios for the southeastern US provide contrasting results in terms of temperature and precipitation estimates over the region,so that in some cases conditions may improve while in others they may degrade. The Canadian model results show little overall change until 2030, followed by drier weather in most of the region over the next seventy years. On the other hand,the Hadley Centre model predicts a slight decrease in overall precipitation over the region during the next 30 years,after which precipitation increases significantly. The Hadley model results also show significantly decreased precipitation during the first six months of the year with rainfall returning to normal,or near normal, for the last six months,particularly by the end of the century. These results are particularly striking for the immediate Gulf Coast region and indicate that this area may be exceptionally vulnerable to degraded conditions. Intensive agricultural activity including disking and planting in the early spring, fertilizer application in the late spring/early summer, and harvesting in the fall may significantly exacerbate water quality conditions during this period.

Preliminary hydrologic analyses based on the Hadley scenario suggest that streamflow in the Southeast (particularly along the Gulf Coast) may decline by as much as 10% during the early summer months over the next 30 years (Cruise,et.al.,1999;Ritschard,et. al.,1999). These results lead to the conclusions that water quality conditions may become critical during more frequent periods of extreme low flow. Correlation of the hydrologic analyses with the land use in basins where water quality problems already exist suggests that the problems may be most acute in areas of intensive agricultural activity, in coastal areas,or near coastal streams (Cruise et al.,1999).

Many of the basins with high nitrate levels form the boundary between two states. The Chattahoochee boundary between Georgia and Alabama and the Tombigbee boundary between portions of Alabama and Mississippi are two outstanding examples. The Hadley scenario suggests decreased water availability throughout much of this region over the next 50 years. As streamflow and soil moisture decrease, intensity of fertilizer application may increase and irrigation needs may become critical. These issues would likely lead to intense competition for scarce water resources and conflicts between these states over runoff treatment and water quality.

Water quality is also a concern in nearshore marine environments. Both the Canadian and Hadley climate models suggest an increase in rainfall in the Upper Mississippi Valley (see Great Plains and Midwest chapters). A large (8,000 to 18,000 km^2 during 1985-1997) zone of oxygen-depleted (hypoxic) coastal waters is found in the north-central Gulf of Mexico and is influenced in its timing,duration, and extent by Mississippi River discharge and nutrient flux (Rabalais,et.al.,1999; Justic et al.,1997). Nitrate delivered from the Mississippi Basin to the Gulf of Mexico,principally from non-point agricultural sources,is now about three times larger than it was 30 years ago as a result of increases in nutrient loading per unit discharge (Goolsby, et.al.,1999). Hypoxia,which is most prevalent in the lower water column,can adversely affect marine life and is a growing concern to those who harvest and manage Gulf fisheries. An increase in Upper Mississippi Basin streamflow, where the majority of the nitrogen and phosphorus loading occurs,portends an increase in the hypoxic zone offshore.

5. Threats to Coastal Areas

Current Conditions

Few regions have the combination of special characteristics and vulnerabilities found in southeastern coastal areas. The interaction of sea-level rise, storms,beach erosion,subsidence,salt water intrusion,urban development,and human population growth,and shifts in the transition zone where land meets ocean,creates conditions for potential adverse effects on the largest segments of the southeastern population. Large cities located in the coastal zone (such as Houston,Charleston,and New Orleans) already suffer frequent and severe flood damages.

Potential Impacts of Climate Change

Sea-level rise is regarded as one of the more certain consequences of increased global temperature,and sea level has been rising gradually over the past 15,000 years. Globally, average sea level rose 4 to 8 inches (10 to 20 cm) during the past 100 years and this average rate is projected to accelerate 2 to 5-fold over the next 100 years (IPCC,1998). Parts of the City of New Orleans that are presently 7 feet below mean sea level may be 10 or more feet below sea level by 2100,due to a combination of rising sea level and subsidence of the land surface.

Low-lying marshes and barrier islands of the southeastern coastal margin are considered particularly vulnerable to sea-level rise,but all are not equally vulnerable. Cahoon and others (1998) found that some Gulf coastal marshes and one mangrove site in south Florida are being gradually submerged because they do not accumulate sediment quickly enough to keep up with present rates of sea-level rise. In coastal Louisiana,landforms created by Mississippi River sediment deposition over the past 8,000 years are naturally de-watering and compacting. As sea level rises,inundation or displacement of coastal wetlands and barrier islands is occurring. The impacts of subsidence (the lowering of the land relative to sea level) are aggravated by human activities such as levee construction along the Mississippi River, ground water withdrawals,and canal dredging though marshes,passes,and barrier islands. Changes in tidal amplitude have caused salt-water intrusion into many formerly fresh and brackish water habitats. Roughly one million acres of south Louisiana wetlands have been converted to open water since 1940,and Louisiana’s barrier islands have eroded to two-thirds of the size they were in 1900.

If sea-level rise accelerates during the 21st century as predicted by the Intergovernmental Panel on Climate Change (IPCC),many other southeastern coastal areas will experience shoreline retreat and coastal land loss. Under the IPCC's "best estimate" of average global sea-level rise over the next 100 years,the Big Bend area of the Florida Gulf coast will likely undergo extensive losses of salt marsh and coastal forest (Doyle,1998, Figure 11). Since 1980,losses of coastal forests in parts of Florida, South Carolina,and Louisiana have been attributed to salt water intrusion and/or subsidence. Since 1991,landowners and public land managers in Florida have observed extensive die-offs of Sabal palm along a 40-mile stretch of coast between Cedar Key and Homosassa Springs. Williams and others (1999) attribute the forest decline to salt water intrusion associated with sea-level rise. Since 1852, when the first topographic charts were prepared of this region,high tidal flood elevations have increased approximately 12 inches.

Rising sea levels due to climate warming may also affect estuaries and aquatic plant communities. Sea-level rise reduces the amount of light reaching sea-grass beds (light penetration decreases exponentially with water depth),thereby reducing growth rates. Some marine grass beds may be eliminated because their shoreward migration is impeded by shoreline construction and armoring (Short and Neckles,1999). Increased tidal range associated with sea-level rise may have deleterious effects on estuarine and fresh water submerged aquatic plants by altering both salinity and water depth. (See Compounding Stresses on Major Estuaries and Bays in the Northeast chapter for a discussion of sea-level rise effects on salinity in the Chesapeake Bay.)

Sea Level Rise and Marsh Changes

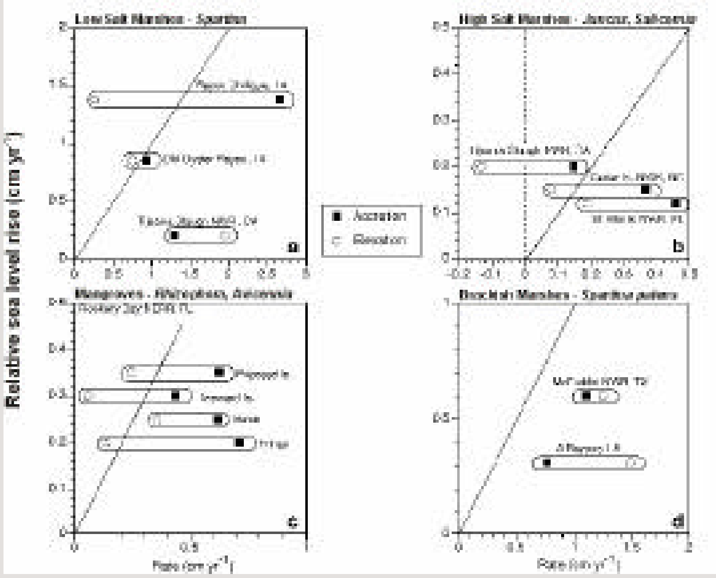

Figure 10. Relationship of vertical accretion and marsh surface elevation change with local relative sea level-rise for sites located in a) low salt marsh, b) high salt marsh, c) mangrove forest and d) brackish marsh. The diagonal line indicates parity between accretion or elevation change and sea-level rise. (source: Cahoon et al., 1998) See Color Plate Appendix

Coastal Wetland Vulnerability

Thresholds at which sea-level rise results in coastal wetland loss vary among sites due to differences in rates of vertical accretion (sediment build up) and local subsidence or uplift processes. Cahoon and others (1998) estimated the potential for submergence of 10 southeastern wetlands by simultaneously measuring surficial sediment accretion and soil surface elevation changes,and then comparing these rates to observed sea-level change from tide gauges. Three of the 10 sites are experiencing a net elevation deficit relative to sea-level rise. The other sites are presently accumulating enough sediment to keep pace with sea-level rise. If sea-level rise were to accelerate 4-fold,the Oyster Bayou site would be submerged by about the year 2045. The Oyster Bayou site would not be submerged if sea-level rise increases 3-fold or less,unless the site is impacted by a hurricane or other disturbance. Both long-term processes (e.g.,accretion,compaction,and decomposition) and episodic events (e.g.,hurricanes) affect the threshold at which coastal wetlands are submerged by sea-level rise.(See Figure 10)

Changes in Florida's Big Bend

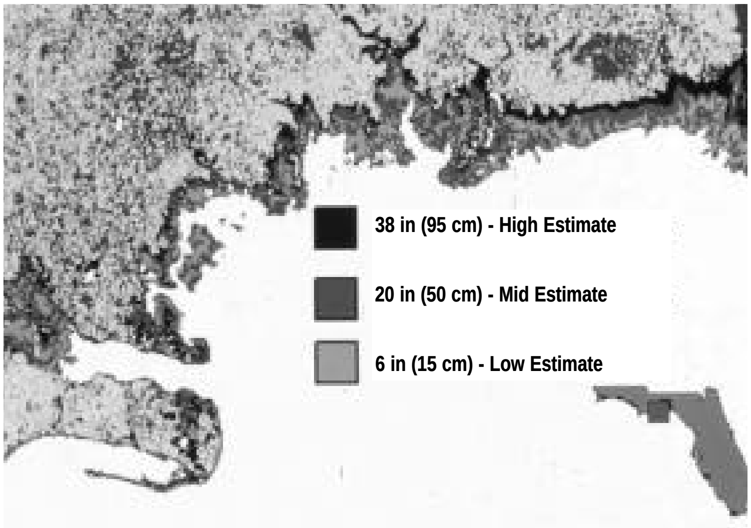

Figure 11. Changes in Florida's Big Bend region forest, marshes, and open water under IPCC (1998) sea-level rise scenarios. (Source: Doyle, 1998). See Color Plate Appendix

Storm surge is intensified as sea level rises and natural coastal defenses deteriorate. It is important to note that even if there is no significant climate-change-driven increase in the frequency or intensity of Atlantic hurricanes,these storms will be more damaging when making landfall on coastal regions as sea level rises and coastal landforms erode. South Atlantic and Gulf coastal populations increased 15% between 1980 and 1993. During this period,the value of insured coastal property in the US increased by 179%(Insurance Institute for Property Loss Reduction and Insurance Research Council, 1995). Florida topped the list of coastal states with potential hurricane damages,with $872 billion in insured properties. Insurance Research Council demographic projections suggest that the number of persons living in the most hurricane prone counties will have increased to 73 million by 2010,a doubling since 1995 (Insurance Institute for Property Loss Reduction and Insurance Research Council, 1995).

During the past 30 years,the Gulf of Mexico has seen a decrease in the number of hurricanes making landfall. Hurricanes Andrew, Hugo,and Brett are the only Category 4 storms to make landfall since 1969, but since 1900,35% of all hurricanes hit Florida and along the middle Gulf Coast,and 50% or more of all hurricanes making landfall are Category 3 or higher (Heinz Center, 1999). Property losses due to hurricanes increased from less than $5 billion per decade between 1900 and 1940 to about $15 billion per decade during the 1960s to 1980s;however, the number of deaths attributed to hurricanes declined dramatically since the 1950s (Pielke and Pielke, 1997).

Adaptation Options

There are few practical options for protecting coastal communities and ecosystems as a whole from increased temperature, changes in precipitation,or rapidly rising sea level. Still,a variety of management measures could be applied on a site-by-site basis to increase the resiliency of specific communities and ecosystems or to reduce or partially compensate for impacts. Many of these measures could be justified based solely upon non-climate threats to coastal regions. For example,increased protection for existing coastal wetlands and removal of other stresses (such as dredge-and-fill activities and water pollution) may not only reduce the sensitivity of coastal communities, wetlands,and barrier islands to small changes in average sea level but also achieve broader conservation goals (Burkett and Kusler, 2000).

Other no-risk measures for achieving broader objectives and reducing climate change impacts include: limiting construction in areas where coastal wetlands may be displaced as sea level rises;installing sediment diversions for dams;linking presently fragmented wetlands and waters to provide the corridors needed for plant and animal migration;using water control structures for some wetlands to enhance particular functions and address decreased precipitation and/or increased evaporation;increasing management programs for invasive species control;and implementing various coastal restoration measures (Burkett and Kusler, 2000).

ADDITIONAL ISSUES

Six additional climate-related issues for the Southeast region are:

- Climate Model Limitations: Existing general circulation models cannot adequately resolve some components of climate or certain geographic or topographic features that are important because of their interaction with regional climate features. For coastal regions, much uncertainty exists about the effects of global climate change and variability on tropical storms,the most important natural hazard affecting regional vulnerability. Effects of climate change on areas of hurricane origination and threshold for hurricane formation,intensity, frequency, and tracks are poorly understood.

- Water Resources: Fresh water plays an important role in many sectors including coastal resources, health, agriculture,estuarine fisheries,and forestry. Competing demands from urban development, agriculture,and recreation for already stressed ground water systems would likely be exacerbated by changes in precipitation and salt water intrusion due to sea-level rise.
- Impacts on Coastal Ecosystems and Services: Sea-level rise, changes in fresh water delivery to coastal estuaries,and increased atmospheric temperature and CO_2 all portend changes in the structure and function of coastal and estuarine systems. Losses of coastal marshes and submerged aquatic vegetation will have impacts at higher trophic levels. Gulf coastal states currently produce most of the Nation's shrimp, oysters, and crabs,and each of these estuarine fisheries is dependent upon the primary productivity of coastal ecosystems.
- Health Issues related to Water Quality: The effects on surface waters of changes in precipitation have important health implications in the region. Increased precipitation promotes the transportation of bacteria as well as other pathogens and contaminants by surface waters throughout the region. Health consequences may range from shellfish infections transmitted to humans to ground water contamination associated with saltwater intrusion.
- Socioeconomic and Insurance Issues: In the ultimate analysis,the issue of climate change and the need for an assessment of potential consequences will be relevant to the degree that it is placed on a human scale. To this end,the potential societal impacts of climate change must be identified and understood. Insurance exposure and/or the insurability of coastal and island facilities are issues that should be examined in the context of climate change and variability.
- Urban Issues: A distinctive characteristic of southeastern coastal regions is their current high level of urbanization and rate of population growth,which could possibly be affected by changes in climate that are presented in this Assessment. The urban environment will have its own responses to the impacts of climate change and variability. While responses will be driven by stakeholder and policymaker decisions,they need to be evaluated and understood within the framework of different potential regional scenarios of climate change consequences. Design and construction factors,building code issues,infrastructure and lifelines,energy use,structural vulnerability to natural hazards,land use and zoning issues,traffic patterns,and evacuation/shelter infrastructure are all important areas for potential mitigation and future research. The potential impacts of climate change on oil,natural gas,and navigation infrastructure is also of concern in the region.

CRUCIAL UNKNOWNS AND RESEARCH NEEDS

Precipitation Uncertainties

The Southeast is the only region for which current climate models simulate large and opposing changes in precipitation patterns over the next 100 years. The range of differences is so great that it is difficult to state with any degree of confidence that precipitation will increase or decrease in the Southeast over the next 30-100 years as atmospheric CO_2 increases. Until climate models are improved (or until there is a way to validate and compare the accuracy of the existing models),people in this region must consider a wide range of potential future changes in soil moisture and runoff, as we have in this Assessment.

Human Health

There are serious human health concerns related to the plausible increases in maximum temperature for this region,particularly among lower income households. Similarly, the flood prone nature of coastal counties from the Carolinas to Texas could have significant human health implications in addition to the economic losses discussed earlier. Approaches for modeling human health effects should include these aspects of the population in addition to the climatic science. Water quality degradation could possibly become a more serious human health problem in the region;improvements in our capability to model streamflow and water quality in both inland and coastal waters are needed.

Agriculture and Forestry

Our current understanding of the potential consequences of climate change on agriculture in the Southeast is focused on a few key row crops. In the future,it will be important to include the affects of climate variations on other high value crops (e.g.,citrus and vegetables) and on animal management practices. Furthermore,the role of climate on pests and pest management systems needs to be included in future assessments. It will also be necessary to develop, validate, and evaluate new technology capabilities such as new genetic varieties that will help farmers cope with any changes in future climate. The effects of biotechnology (e.g., transgenic crops) on future agricultural productivity in this region, including the benefits of using less fertilizer, pesticides, or water, need to be evaluated in light of plausible climate scenarios. Because the incorporation of new climate-related technological capabilities into agriculture is relatively new and yet unproven, future pilot studies should explore the communication of such information to the agriculture community.

The potential effects of climate change on agricultural prices are an equally complex interaction of physical effects and managerial responses worldwide. Spatial equilibrium economic models that would address these market issues require that the information from all regions be reasonably similar. In the case of climate change, detailed information from one region set against very general information from many important competing crop growing areas would not provide a consistent framework for understanding worldwide response in the agriculture sector. Thus, it would be very useful to investigate in greater detail climate-induced production effects in major international crop areas to integrate such farm management results from important growing areas worldwide to address potential climate-induced price effects.

Although extensive laboratory and field research has been completed on the individual impacts of changing air temperature, precipitation, ozone, carbon dioxide, and nitrogen availability on forest productivity, water use, and carbon sequestration, there is still little understanding of the synergistic impacts of environmental change on southern forests. Field experiments with multiple treatment factors (e.g., variables) are quite costly, and there are scaling problems associated with laboratory experiments. Therefore, improved development, testing, and validation of integrated stress impacts through computer modeling are crucial future research needs. Models can provide a mechanism for examining changing atmospheric and socioeconomic impacts on forest structure and function. However, before any confidence can be given to such model projections, priority needs to be given to testing, model verification, and analysis.

Aquatic and Coastal Resources

If precipitation patterns continue to change on a scale similar to that observed over the past 100 years, many southeastern aquatic ecosystems, including estuaries, will be affected by changes in streamflow. There are several additional unknown variables corresponding to future conditions that might affect the quality of southeastern water resources. They fall into two categories: future pollutant loadings (natural and anthropogenic) and biophysical reactions. The pollutant loadings, both point and non-point, will be directly related to changes in land use activity including the presence of confined animal systems and growing population centers. Also, atmospheric deposition of nitrogen will be tied to continued emissions of nitrogen oxides (NOx). The biophysical reactions on the land surface that might serve to uptake nitrogen and other constituents will be associated with land cover conversion and vegetation. Future research programs that include these three critical unknowns seem crucial to gaining a clearer understanding of the relationship between variations in climate and water quality in the Southeast.

Quantitative data describing the response of native southeastern plant communities to atmospheric carbon enrichment, water quality (e.g., salinity), and changes in temperature and soil moisture are limited to a few key species. Moreover, very few studies have addressed the potential interactions among climate variables and between plant species, and even fewer studies deal with climate effects at secondary and higher levels in the food web. Several recent studies suggest that a number of invasive species will be favored by climatic change in the Southeast, such as the freeze-intolerant Chinese tallow, which is now a serious invader in the Gulf coastal plain. Models that integrate environmental change, species responses, and interactions among species are needed to describe pathways that are likely to alter plant and animal community structure. Research is also needed to determine secondary and higher-order effects on ecosystem goods and services. Carbon sequestration is one ecological function that has been poorly described in this region of abundant wetlands and forests that play potentially significant roles as carbon sinks.

Research and demonstration projects are needed to identify and prioritize methods that may be implemented to minimize the adverse ecological effects of climatic change on native southeastern flora and fauna. Monitoring is needed to evaluate long-term trends in the abundance and distribution of native and non-native species, focusing on species and groups that are considered highly sensitive to the range of predicted climatic changes in the region (e.g.,amphibians in pine flatwood ponds,benthic invertebrates in coastal estuaries,and salt-tolerant invasive aquatic plants that could out-compete native plant species that are important wildlife food sources).

Extreme Events/Disturbance Patterns

Changes in disturbance patterns (e.g.,hurricanes, floods,droughts) are possibly more significant in terms of potential economic losses than longer-term changes in precipitation or temperature. Ecosystems are also impacted by climate-related disturbance. Disturbance is a natural process that,in many cases,not only structures ecosystems but sustains them as well. Our limited understanding of the role of disturbance in natural ecosystems and our inability to predict climate extremes is problematic for those interested in mitigating the potential adverse impacts of climate change. Research should be undertaken to examine potential changes in disturbance regimes that may be expected as the climate warms and precipitation patterns change. Disturbance topics should not be limited to weather events,however. Fire,harmful algal blooms,and insect outbreaks are ecological disturbances that may be heavily influenced by climatic conditions. The ecological effects of these types of disturbances are difficult to model or predict because they are often poorly understood. Basic information is needed to identify ecological changes that are likely to occur as the type,frequency, and spatial patterns of disturbance are altered as the climate changes.

LITERATURE CITED

Aber, J. D.,C.Driscoll,C.A. Federer, R.Lathrop, G. Lovett, J. M.Melillo, P. Steudler, , and J. Vogelmann, A strategy for the regional analysis of the effects of physical and chemical climate change on biogeochemical cycles in northeastern (U.S.) forests, *Ecological Modeling*, *67*, 37-47,1993.

Abt,R.C., F.W. Cubbage,and G. Pacheco, Forest resource assessment using the subregional timber supply model (SRTS), *Forest Products Journal, 50*(4),25-33,2000.

Acock,B., V. R.Reddy, H. F. Hodges, D. N. Baker, and J. M. McKinion,Photosynthetic response of soybean canopies to full-season carbon enrichment, *Agronomy Journal, 77*, 942-47,1985.

Allen,L.H.,K. J. Boote, J.W. Jones,A. J. Rowland-Bamford, G. Bowes, D.A.Graetz,K.R.Reddy,Temperature and CO_2 effects on rice:1988. US Department of Agriculture,Carbon Dioxide Research Division, Washington,DC,1989.

Boyer, W. D.,Regeneration of natural longleaf pine forest, *Journal of Forestry, 77*, 572-575,1979.

Burkett, V.,and J. Kusler, Climate change: Potential impacts and interactions in wetlands of the United States, *Journal of American Water Resources Association*, *36*(2),313-320,2000.

Cahoon, D. R., J.W. Day, D. J. Reed,and R.S. Young, Global climate change and sea-level rise: estimating the potential for submergence of coastal wetlands,in *Vulnerability of Coastal Wetlands in the Southeastern United States: Climate Change Research Results*, US Geological Survey, Biological science report USGS/BRD/BSR 1998-0002, pp.21-34,1998.

Cruise, J. F.,A.S.Limaye,and N. Al-Abed,Assessment of the impacts of climate change on water quality in the southeastern United States, *Journal of American Water Resources Association*, *35*(6),1539-1550,1999.

Currie, D. J.,Energy and large-scale patterns of animal-and plant-species richness, *American Naturalist*, *137*(1),27-49,1991.

Dahl, T. E.,Wetland losses in the United States:1780’s to 1980’s,US Department of Interior, Fish and Wildlife Service, Washington DC, 21 pp.,1990.

Doyle, T. W., Modeling global change effects on coastal forests, in *Vulnerability of Coastal Wetlands in the Southeastern United States: Climate Change Research Results*, US Geological Survey, Biological Science Report USGS/BRD/BSR 1998-0002, Lafayette, Louisiana, pp. 67-80, 1998.

Eamus, D., and P. G. Jarvis, The direct effects of increases in the global atmospheric CO_2 concentration on natural and commercial temperate trees and forests, *Advances in Ecological Research*, *19*, 1-55, 1989.

Felzer, B., and P. Heard, Hydrological implications of GCM results for the US national assessment, *Journal of American Water Resources Association*, *35*(6), 1327-1339, 1999.

Glasmeier, A., The history of Central and Southern Appalachia: A socioeconomic analysis, paper presented at the Central and Southern Workshop on Climate Variability and Change, Morgantown, West Virginia, May 27-28, 1998.

Goolsby, D. A., W. A. Battaglin, G. B. Lawrence, R. S. Artz, B. T. Aulenbach, R. P. Hooper, D. R. Keeney, and G. J. Stensland, Flux and source of nutrients in the Mississippi-Atchafalaya River Basin, In Review, White House Office of Science and Technology Policy, Committee on Environment and Natural Resources, Hypoxia Working Group, May 1999, pp. 13-37, 2000.

Harcombe, P. A., R. B. W. Hall, J. S. Glitzenstein, E. S. Cook, P. Krusic, and M. Fulton, Sensitivity of Gulf Coast forests to climate change, in *Vulnerability of Coastal Wetlands in the Southeastern United States: Climate Change Research Results*, US Geological Survey, Biological Science Report, USGS/BRD/BSR 1998-0002, Lafayette, Louisiana, pp. 47-67, 1998.

Hatch, U., S. Jagtap, J. Jones, and M. Lamb, Potential effects of climate change on agricultural water use, *Journal of American Water Resources Association*, *35*(6), 1551-1562, 1999.

Hefner, J. M., Southeast wetlands: Status and trends, mid-1970's to mid-1980's, US Department of Interior, Fish and Wildlife Service, Atlanta, Georgia, 32 pp., 1994.

Heinz Center, *The Hidden Costs Of Coastal Hazards: Implications For Risk Assessment And Mitigation*, Island Press, Washington, DC, 220 pp., 1999.

Insurance Institute for Property Loss Reduction and Insurance Research Council, Community exposure and community protection: Hurricane Andrew's legacy (IIPLR and IRC). Wheaton, IL (IILPR) and Boston, MA (IRC), 1995.

Intergovernmental Panel on Climate Change, *The Regional Impacts of Climate Change: An Assessment of Vulnerability*, Cambridge University Press, United Kingdom, 514 pp., 1998.

Jones, J. W., S. S. Jagtap, and K. J. Boote, Climate change: implications of soybean yield and management in the USA, paper presented at the World Soybean Research Conference VI, Chicago, Illinois, August 7, 1999.

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

Keim, B. D., G. E. Faiers, R. A. Muller, J. M. Grymes, and R. V. Rohli, Long-term trends of precipitation and runoff in Louisiana, USA, *International Journal of Climatology*, *15*, 531-541, 1995.

Kiehl, J. T., Climate change enhanced: Solving the aerosol puzzle, Science, *283*(5406), 1273-1275, 1999.

Legler, D. M., K. J. Bryant, and J. J. O'Brien, Impact of ENSO-related climate anomalies on crop yields in the US, *Climatic Change, 42*(2), 351-375, 1999.

Lins, H. F., and J. R. Slack, Streamflow trends in the United States, *Geophysical Research Letters, 26*(2), 227-230, 1999.

Lo, C. P., D. A. Quattrochi, and J. C. Luvall, Application of high-resolution thermal infrared remote sensing and GIS to assess the urban heat island effect, *International Journal of Remote Sensing*, *18*, 287-304, 1997.

Lockwood, J. G., Is potential evapotranspiration and its relationship with actual evapotranspiration sensitive to elevated CO_2 levels?, *Climatic Change*, *41*(2), 193-212, 1999.

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

McNulty, S. G., P. L. Lorio, Jr., M. P. Ayres, and J. D. Reeve, Predictions of Southern Pine Beetle populations using a forest ecosystem model, in *The Productivity and Sustainability of Southern Forest Ecosystems in a Changing Environment*, edited by R. Mickler and S. Fox, Springer Publishing, pp. 617-634, 1998.

McNulty, S. G., J. M. Vose, W. T. Swank, J. D. Aber, and C. A. Federer, Landscape scale forest modeling: Data base development, model predictions, and validation using a GIS, *Climate Research*, *4*, 223-231, 1994.

Mearns, L. O., F. Giorgio, L. McDaniel, and C. Shields, Analysis of daily variability of precipitation in a nested regional climate model: Comparison with observations and doubled CO_2 results, *Global Planetary Change, 10*, 55-78, 1995.

Meyer, J. L., Seasonal patterns of water quality in blackwater rivers of the coastal plain, southeastern United States, in *Water Quality in North American River Systems*, edited by C. D. Becker and D. A. Neitzel, Battelle Press, Columbus, Ohio, pp. 249-276, 1992.

Mulholland, P. J., G. R. Best, C. C. Coutant, G. M. Hornberger, J. L. Meyer, P. J. Robinson, J. R. Stenberg, R. E. Turner, F. Vera-Herra, and R. G. Wetzel, Effects of climate change on freshwater ecosystems of the southeastern United States and the Gulf Coast of Mexico, *Hydrological Processes, 11*, 949-970, 1997.

National Climatic Data Center, Billion dollar US weather disasters, 1980-1999, PDF version, www.ncdc.noaa.gov/ol/reports/billions.html. July 20, 1999.

National Council of the Paper Industry for Air and Stream Improvement (NCASI), Global change and forest responses: theoretical basis, projections, and uncertainties, NCASI, New York, Technical Bulletin No. 690, pp. 11-18, 1995.

Nijs, I., I. Impens, and T. Behacghe, Leaf and canopy responses of *Lolium perenne* to long-term elevated atmospheric carbon-dioxide concentration, *Planta 177*, 312-320, 1988.

Pielke, Jr., R. A., and R. A. Pielke, Sr., Vulnerability to hurricanes along the US Atlantic and Gulf coasts: Considerations of the use of long-term forecasts, in Hurricanes: *Climate and Socioeconomic Impacts*, edited by H. F. Diaz and R. S. Pulwarty, Springer Publishing, New York, 147-184, 1997.

Quattrochi, D. A., J. C. Luvall, M. G. Estes, Jr., C. P. Lo, S. Q. Kidder, J. Hafner, H. Taha, R. D. Bornstein, R. R. Gillies, and K. P. Gallo, Project ATLANTA (ATlanta Land use ANalysis: Temperature and Air quality): A study of how the urban landscape affects meteorology and air quality through time, Preprints, *American Meteorological Society*, 104-107, 1998.

Quattrochi, D. A., and J. C. Luvall, Urban sprawl and urban pall: Assessing the impacts of Atlanta's growth on meteorology and air quality using remote sensing and GIS, *Geographical Information Systems, 9*, 26-33, 1999.

Rabalais, N. N., R. E. Turner, D. Justic´, Q. Dortch, and W. J. Wiseman, Characterization of hypoxia, *Topic #1, Gulf of Mexico Hypoxia Assessment*, NOAA Coastal Program Decision Analysis Series, National Oceanic and Atmospheric Administration, Coastal Ocean Office, Silver Spring, Maryland, 144 pp. plus 3 appendices, 1999.

Ricketts, T. H., E. Dinerstein, D. M. Olson, and C. Loucks, Who's where in North America? Patterns of species richness and the utility of indicator taxa for conservation, *BioScience*, *49*(5), 369-381, 1999.

Ritschard, R. L., J. F. Cruise, and L. U. Hatch, Spatial and temporal analysis of agricultural water requirements in the Gulf Coast of the United States, *Journal of American Water Resources Association*, *35*(6), 1585-1596, 1999.

Rosenberg, N. J., R. C. Izaurralde, M. Tiscareño-Lopéz, D. Legler, R. Srinivasan, R. A. Brown, and R. D. Sands, Sensitivity of North American agriculture to ENSO-based climate scenarios and their socio-economic consequences: Modeling in an integrated assessment framework, Pacific Northwest National Laboratory, Seattle, Washington, 146 pp., 1997.

Short, F. T., and H. A. Neckles, The effects of global climate change on seagrasses, *Aquatic Botany*, *63*, 169-196, 1999.

Southern Oxidants Study Team. 1995. The state of the Southern Oxidants Study: Policy-relevantFindings in ozone pollution research, 1988-1994. Southern Oxidants Study, Raleigh, North Carolina, 94 pp.

Timmermann, A., J. Oberhuber, A. Bacher, M. Esch, M. Latif, and E. Roeckner, Increased El Niño frequency in a climate model forced by future greenhouse warming, *Nature, 398*, 694-697, 1999.

Trenberth,K.E.,Conceptual framework for changes of extreme of the hydrological cycle with climate change, *Climatic Change, 42,* 327-339,1999.

Tsuji, G., G. Hoogenboom, P.Thornton,(Eds.), *Understanding Options for Agricultural Production,* Kluwer Academic Publishers,399 pp.,1998.

US Bureau of the Census,County and City Data Book, US Government Printing Office,Washington,DC,GPO #003-024-08753-7,1994.

US Department of Agriculture,Census of Agriculture, National Agricultural Statistics Service,Washington,DC, 1994.

US Department of Agriculture,Census of Agriculture, National Agricultural Statistics Service,Washington,DC, 1996.

US Department of Agriculture, Census of Agriculture, National Agricultural Statistics Service,Montgomery, Alabama,1999.

US Forest Service,The South's fourth forest:alternatives for the future, US Department of Agriculture, Forest Service,Washington DC, Forest Resource Report No. 24, 512 pp.,1998.

Williams,K.,K.C.Ewel,R. P. Stumpf, F. E.Putz,and T.W. Workman,Sea-level rise and coastal forest retreat on the west coast of Florida, *Ecology, 80*(6), 2045-2063, 1999.

ACKNOWLEDGMENTS

Dedication
This chapter is dedicated to Dr. Ronald Ritschard, a good friend, colleague, and scientist, without whose efforts this Assessment would not have been possible. Ron will be deeply missed.

Many of the materials for this chapter are based on contributions from participants on and those working with the

Central and Southern Appalachians Workshop Team
William T. Peterjohn (PI), West Virginia University
Richard Birdsey, USDA Forest Service
Amy Glasmeier, Pennsylvania State University
Steven McNulty, USDA Forest Service
Trina Karolchik Wafle, West Virginia University

Gulf Coast Workshop and Assessment Team
Zhu Hua Ning*,Southern University and A & M College
Kamran Abdollahi*,Southern University and A & M College
Virginia Burkett,USGS National Wetlands Research Center
James Chambers,Louisiana State University
David Sailor,Tulane University
Jay Grymes,Southern Regional Climate Center
Paul Epstein,Harvard University
Michael Slimak,US Environmental Protection Agency

Southeast Workshop and Assessment Teams
Ron Ritschard*,University of Alabama – Huntsville
James O'Brien*,Florida State University
James Cruise*,University of Alabama – Huntsville
Robert Abt,North Carolina State University
Upton Hatch,Auburn University
Shrikant Jagtap,University of Florida
James Jones,University of Florida
Steven McNulty, USDA Forest Service
Brian Murray, Research Triangle Institute

* signifies Assessment team chairs/co-chairs