National Climate Assessment Regional Technical Input Report Series

Climate of the Southeast United States

Variability, Change, Impacts, and Vulnerability

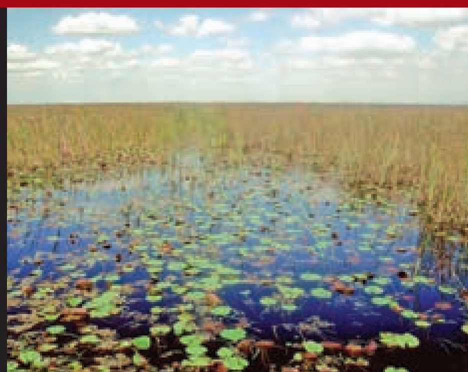
Edited by:

Keith T. Ingram

Kirstin Dow

Lynne Carter

Julie Anderson



ISLANDPRESS

About Island Press

Since 1984, the nonprofit Island Press has been stimulating, shaping, and communicating the ideas that are essential for solving environmental problems worldwide. With more than 800 titles in print and some 40 new releases each year, we are the nation's leading publisher on environmental issues. We identify innovative thinkers and emerging trends in the environmental field. We work with world-renowned experts and authors to develop cross-disciplinary solutions to environmental challenges.

Island Press designs and implements coordinated book publication campaigns in order to communicate our critical messages in print, in person, and online using the latest technologies, programs, and the media. Our goal: to reach targeted audiences—scientists, policymakers, environmental advocates, the media, and concerned citizens—who can and will take action to protect the plants and animals that enrich our world, the ecosystems we need to survive, the water we drink, and the air we breathe.

Island Press gratefully acknowledges the support of its work by the Agua Fund, Inc., The Margaret A. Cargill Foundation, Betsy and Jesse Fink Foundation, The William and Flora Hewlett Foundation, The Kresge Foundation, The Forrest and Frances Lattner Foundation, The Andrew W. Mellon Foundation, The Curtis and Edith Munson Foundation, The Overbrook Foundation, The David and Lucile Packard Foundation, The Summit Foundation, Trust for Architectural Easements, The Winslow Foundation, and other generous donors.

The opinions expressed in this book are those of the author(s) and do not necessarily reflect the views of our donors.

Climate of the Southeast United States

Variability, Change, Impacts, and Vulnerability

Printed on recycled, acid-free paper

Manufactured in the United States of America

Citation: Ingram, K., K. Dow, L. Carter, J. Anderson, eds. 2013. Climate of the Southeast United States: Variability, change, impacts, and vulnerability. Washington DC: Island Press.

Keywords: Apalachicola-Chattahoochee-Flint basin, adaptation, agriculture, air quality, assessment, atmosphere, barrier islands, biodiversity, coastal wetlands, climate change, climate impacts, climate modeling, climate variability, coastal, drought, education, electric power generation, extreme weather, flooding, forest resources, freezes, heat related illness, heat wave, hurricanes, land-use change, mangroves, mitigation, mosquitoes, natural resource management, ocean acidification, Puerto Rico, precipitation, public health, rainfall, salt-water intrusion, sea level rise, silviculture, social vulnerability, Southeast, storm surge, tropical storms, tourism, uncertainty, U.S. Virgin Islands, vector-borne disease, water resources, wetlands, wildfire

Front Cover Images: Downtown Atlanta, Georgia, courtesy of the Atlanta Convention and Visitor's Bureau (top). Other photos by row from the top left: Great Smokey Mountains at Oconaluftee Overlook, courtesy of US National Park Service; Nymphaea open water slough in Everglades National Park, Curtis J. Richardson; South Carolina coastal marsh, courtesy of the US Fish and Wildlife Service; Florida Power and Light (FPL) Desoto Solar Power Plant, courtesy of FPL; spring flowers at Mammoth Cave National Park, courtesy of US National Park Service; mouth of Miami River, Miami, Florida, Marc Averette.

About This Series

This report is published as one of a series of technical inputs to the Third National Climate Assessment (NCA) report. The NCA is being conducted under the auspices of the Global Change Research Act of 1990, which requires a report to the President and Congress every four years on the status of climate change science and impacts. The NCA informs the nation about already observed changes, the current status of the climate, and anticipated trends for the future. The NCA report process integrates scientific information from multiple sources and sectors to highlight key findings and significant gaps in our knowledge. Findings from the NCA provide input to federal science priorities and are used by U.S. citizens, communities and businesses as they create more sustainable and environmentally sound plans for the nation's future.

In fall of 2011, the NCA requested technical input from a broad range of experts in academia, private industry, state and local governments, non-governmental organizations, professional societies, and impacted communities, with the intent of producing a better informed and more useful report. In particular, the eight NCA regions, as well as the Coastal and the Ocean biogeographical regions, were asked to contribute technical input reports highlighting past climate trends, projected climate change, and impacts to specific sectors in their regions. Each region established its own process for developing this technical input. The lead authors for related chapters in the Third NCA report, which will include a much shorter synthesis of climate change for each region, are using these technical input reports as important source material. By publishing this series of regional technical input reports, Island Press hopes to make this rich collection of information more widely available.

This series includes the following reports:

Climate Change and Pacific Islands: Indicators and Impacts
Coastal Impacts, Adaptation, and Vulnerabilities
Great Plains Regional Technical Input Report
Climate Change in the Midwest: A Synthesis Report for the National Climate Assessment
Climate Change in the Northeast: A Sourcebook
Climate Change in the Northwest: Implications for Landscapes, Waters, and Communities
Oceans and Marine Resources in a Changing Climate
Climate of the Southeast United States: Variability, Change, Impacts, and Vulnerability
Assessment of Climate Change in the Southwest United States

Electronic copies of all reports can be accessed on the Climate Adaptation Knowledge Exchange (CAKE) website at *www.cakex.org/NCAreports*. Printed copies are available for sale on the Island Press website at *www.islandpress.org/NCAreports.*

Climate of the Southeast United States

Variability, Change, Impacts, and Vulnerability

EDITORS

Keith T. Ingram (University of Florida)

Kirstin Dow (University of South Carolina)

Lynne Carter (Louisiana State University)

Julie Anderson (Louisiana State University)

EDITORIAL ASSISTANCE

Eleanor K. Sommer (Gainesville, Florida)

ISLANDPRESS

Washington | Covelo | London

Acknowledgements

Funding for this project was provided in part by the United States Global Climate Research Program (USGCRP) and the National Aeronautic and Space Agency (NASA). In addition, many federal, state, and local agencies and organizations generously contributed the time of their staff to work on this document.

The editors and authors extend special appreciation to Courtnay Cardozo, University of Florida graduate student in Agricultural and Biological Engineering, who checked references for this report, to Elayna Rexrode for providing proofreading services, and to Rebekah Jones and Wendy McMillen for assistance in translating some graphics into readable formats for bblack and white printing.

Editor's Note: Access to color maps and graphs for this document are available at http://www.cakex.org/NCAreports. Click on Climate Change in the Southeast United States: Variability, Change, Impacts, and Vulnerabilities

Contents

Chapter 1

Climate Change in the Southeast USA: Executive Summary

LEAD AUTHORS

Keith T. Ingram (ktingram@ufl.edu; Southeast Climate Consortium, University of Florida, Gainesville, Florida)

Lynne Carter (Southern Climate Impacts Planning Program, Louisiana State University, Baton Rouge, Louisiana)

Kirstin Dow (Carolinas Integrated Sciences and Assessments; Department of Geography, University of South Carolina, Columbia, South Carolina)

CONTRIBUTING AUTHORS

Julie Anderson (School of Renewable Natural Resources, Louisiana State University Agricultural Center, Baton Rouge, Louisiana)

Senthold Asseng (Agricultural and Biological Engineering Department, University of Florida, Gainesville, Florida)

Charles Hopkinson (Department of Marine Sciences, University of Georgia, Athens, Georgia)

Charles Konrad (Southeast Regional Climate Center, University of North Carolina, Chapel Hill, North Carolina)

Steven McNulty (Eastern Forest Environmental Threat Assessment Center, USDA Forest Service, Raleigh, North Carolina)

Kenneth Mitchell (Region IV, US Environmental Protection Agency, Atlanta, Georgia)

Kevin Moody (Region IV, US Department of Transportation, Atlanta, Georgia)

Dale Quattrochi (Marshall Space Flight Center, National Aeronautics and Space Administration, Huntsville, Alabama)

Paul Schramm (Centers for Disease Control and Prevention, Atlanta, Georgia)

Ge Sun (Eastern Forest Environmental Threat Assessment Center, Southern Research Station, USDA Forest Service, Raleigh, North Carolina)

LaDon Swann (Mississippi-Alabama Sea Grant Consortium and Auburn University Marine Extension and Research Center, Mobile, Alabama)

This book is based on a technical report the National Climate Assessment (NCA) document that was prepared for submission to the President of the United States and the United States Congress. That document summarized the scientific literature with respect to climate impacts on the Southeast (SE) USA, in particular the literature that has been published since 2004. A national assessment was produced in 2009; however, no technical report was developed in support of that document.

For the Third US National Climate Assessment, the Southeast region includes 11 southern states (Figure 1.1), Puerto Rico, and the US Virgin Islands. This region differs slightly from the previous National Climate Assessment in that it follows state borders and does not include the Gulf Coast of Texas.

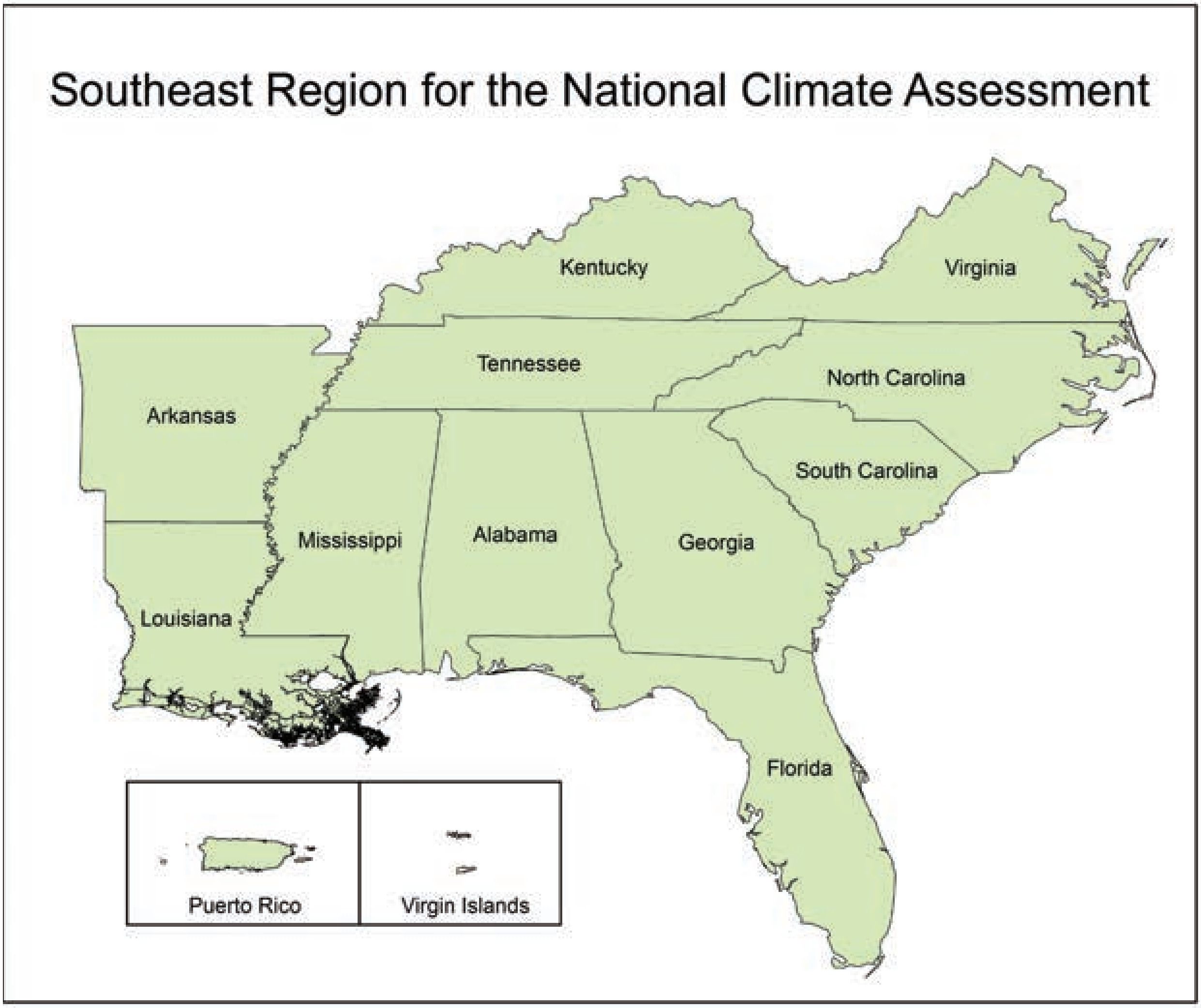


Figure 1.1 Map of the states in the Southeast region for the US National Climate Assessment. Note that the region and report also covers Puerto Rico and the US Virgin Islands.

1.1 Diversity and Vulnerabilities

The SE USA is characterized by great diversity in terms of climate, natural and managed ecosystems, social and political attitudes, and vulnerabilities. While most of the SE is classified as humid, temperatures vary widely across the regions, with a transition from tropical rainforests in Puerto Rico and the US Virgin Islands to temperate forests in the southern Appalachian Mountains. This climatic diversity, which is described in detail in Chapter 2, results from a range of weather patterns that affect the region, including frontal systems that dominate during fall and winter, convective systems that dominate during the spring and summer, tropical systems that are important during the summer and fall, and sea breeze systems that are important for the coastal regions. In addition, the region is prone to other extreme weather phenomena, including droughts, floods, winter storms, and tornadoes.

The region also is subject to related risks that interact with climate variability and change. For example, sea level change and salt water intrusion already threaten many coastal communities (Chapter 5) and ecosystems (Chapters 9 and 11). Sea level change, which includes both sea level rise and land subsidence in parts of Louisiana, Mississippi, and Alabama, makes the region more vulnerable to storm surges produced by tropical storms or winter storms in the Gulf of Mexico (Mitchum 2011). Increasing atmospheric carbon dioxide concentrations might benefit agricultural (Chapter 7) and forest systems (Chapter 8) of the region through increasing photosynthesis, but benefits are likely to be offset by losses of productivity that would result from increased temperatures. Increasing atmospheric carbon dioxide concentrations are also projected to acidify surface waters, which would likely inhibit the growth of corals, shellfish, and crustaceans (Chapter 9). Finally, increasing atmospheric carbon dioxide increases pollen production by many plant species, which has been linked with increased levels of asthma and respiratory illnesses (Chapters 3 and 7).

Climate also interacts with social conditions in the Southeast, which has experienced unprecedented population growth during recent decades. All states in the region had positive growth from 2000 through 2010, with overall population growing by 8.9 million people, or about 13% (Table 1.1). Population grew the most in North Carolina (18.5%), Georgia (18.3%), Florida (17.6%), and South Carolina (15.3%), and most of that population growth has been in urban and peri-urban areas (Mackun and Wilson 2011). In the region, only Puerto Rico and the Virgin Islands had negative growth (- 2.2 and -2 percent respectively) (Mackun and Wilson 2011). States with the fastest growing populations on a percentage basis were mostly states that already had relatively large populations. This trend indicates widening differences in population density among states in the Southeast. Population growth likely will compound climate related risks for most sectors. Increasing competition for water resources (Chapter 10) will likely affect the energy (Chapter 4), agriculture (Chapter 7), fisheries and aquaculture (Chapter 9), natural ecosystems (Chapter 11), and built environment (Chapter 5) sectors.

The diversity of people, natural and managed ecosystems, and resources of the Southeast provide the region with great richness. With coastlines along the Gulf of Mexico and South Atlantic seaboard, the SE has a wealth of estuaries (Chapter 12) with associated fishing industry (Chapter 9), ports with associated transportation hubs

(Chapter 6), and beaches with associated tourism (Chapter 13). Inland forests constitute an important carbon sink (Chapter 8), which mitigate greenhouse gas effects on climate (Chapter 12). Its relatively humid, high rainfall environment provides the SE sufficient water resources (Chapter 10) to be a major exporter of energy (Chapter 4) to other regions at present, though future increases in competition for water resources might diminish the region's energy production capacity. Climate change threatens all of these natural resources and the industries that depend on them. Thus, it is not surprising that there are numerous efforts already underway in the SE to mitigate and adapt to climate change (Chapters 12 and 13). In addition there are ongoing programs to educate people about climate variability, climate change, and ways society can manage climate related risks (Chapter 14).

Table 1.1 Population of the Southeast USA and Puerto Rico in 2000 and 2010

State/Territory	2000	2010	Change (%)
Alabama	4,447,100	4,779,736	7.5
Arkansas	2,673,400	2,915,918	9.1
Florida	15,982,378	18,801,310	17.6
Georgia	8,186,453	9,687,653	18.3
Kentucky	4,041,769	4,339,376	7.4
Louisiana	4,468,976	4,533,372	1.4
Mississippi	2,844,658	2,967,297	4.3
North Carolina	8,049,313	9,535,483	18.5
South Carolina	4,012,012	4,625,364	15.3
Tennessee	5,689,283	6,346,105	11.5
Virginia	7,078,515	8,001,024	13.0
Puerto Rico	3,808,610	3,725,789	-2.2
US Virgin Islands	108,612	106,405	-2.0
Total	**67,473,856**	**76,350,620**	**13.2**

Source: Mackun and Wilson 2011, US Census Bureau 2000a, US Census Bureau 2000b, US Census Bureau 2010a, US Census Bureau 2010b.

1.2 Time-scales of Interest to Southeast Decision Makers

Decision makers in the SE have the greatest interest in seasonal and decadal time-scales (Bartels et al. 2011). Typically, the time-scale of interest matches the time-scale of investments and expenditures, most of which are 20 years or less. In order to engage decision makers in the use of climate information, it is important to provide information at time-scales that are relevant to the decisions for which they need information. If the science community can provide useful information at these shorter timescales, as decision makers use that information to manage seasonal and near term climate risks, they also begin to adapt to and mitigate climate change (Fraisse et al. 2009).

An advantage to providing climate information at shorter time-scales in the SE is that seasonal climates of the Florida peninsula and coastal plains from Louisiana to North Carolina are affected by sea surface temperatures in the equatorial Pacific, or El Niño-Southern Oscillation phenomenon (Chapter 2). For these areas, El Niño conditions typically result in cool, wet fall and winter conditions whereas La Niña conditions typically result in dry, warm fall and winter conditions. To the north of the coastal plains, seasonal climate does not typically exhibit an El Niño-Southern Oscillation signal.

1.3 Future Scenarios

In this report, we use the term "projection" to describe how future climate is expected to respond to various scenarios of population growth, greenhouse gas emissions, land development patterns, and other factors that might affect climate change. The report uses two of the Intergovernmental Panel on Climate Change (IPCC) scenarios for climate projections, A2 and B1. It is important to recognize that these scenarios describe potential situations for both greenhouse gas (GHG) emissions and societal development alternatives.

The A2 scenario is the most pessimistic in that it assumes that nations will have little or no response to anticipated adverse effects of climate change (EPA 2012). The A2 storyline and scenario describes a heterogeneous world with an underlying theme of self-reliance and preservation of local identities. Birth rates across regions converge slowly, which results in continuously increasing population. This scenario is often called "business as usual."

The B1 storyline and scenario describes a convergent world with the same global population as in the A1 storyline, but with rapid change in economic structures toward a service and information economy (EPA 2012). This scenario includes a reduction in material intensity and the introduction of clean and resource-efficient technologies. It emphasizes global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives. The B1 scenario is the most optimistic in that it generally reflects a concerted, global effort to mitigate human impacts that would further warm the planet.

An important feature of these scenarios is the difference in population growth for the region (Figure 1.2). In the A2 scenario the population of the SE nearly triples from 2010 through 2100 whereas in the B1 scenario, population increases about one-third over the same period. If population growth follows trends similar to those simulated in the A2 scenario, the SE will experience far more cross-sectoral competition for land and water resources, which will compound climate change impacts. On the other hand, the B1 scenario with its more modest population growth provides more opportunities for adaptation and mitigation.

Another important factor for the SE will be changes in land use and land cover. As population grows, development is inevitable. How that development proceeds, however, will have great impact on regional climate (Shin and Baigorria 2012).

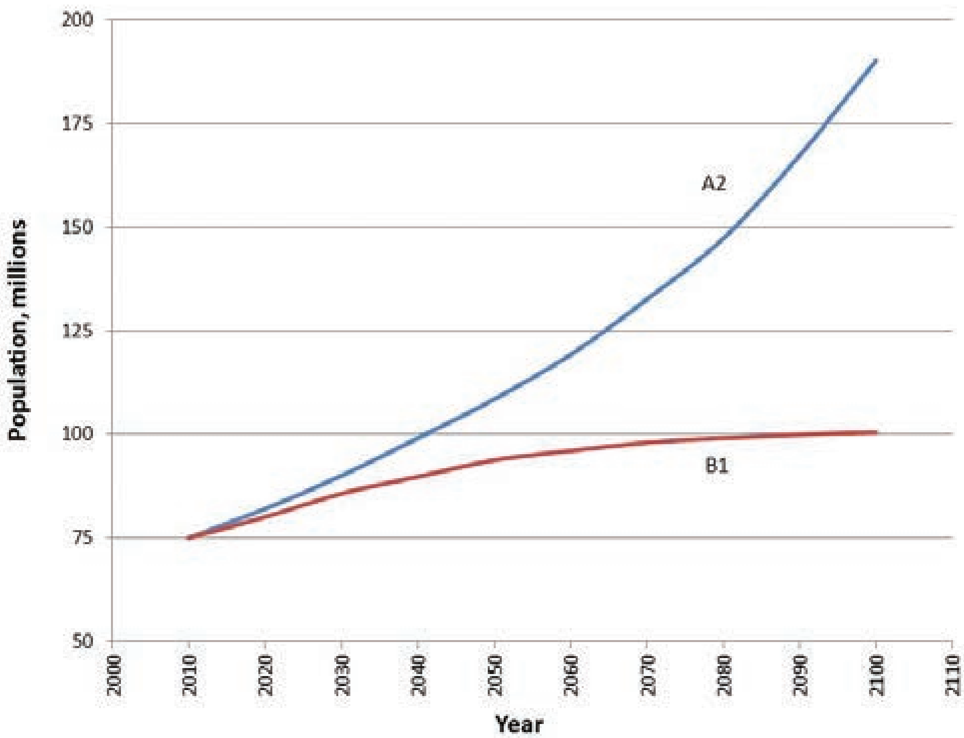


Figure 1.2 Population projections for the Southeast USA for the A2 (greatest climate change) and B1 (least climate change) scenarios.

1.4 Process for Developing this Book

This document has been produced through collaboration among three Regional Integrated Sciences and Assessments Centers (RISAs): the Southeast Climate Consortium; the Carolinas Regional Sciences and Assessments; and the Southern Climate Impacts Planning Program; and with contributions from numerous local, state, federal, and non-governmental individuals and agencies. We established a leadership committee that was charged with the design of the overall report and the organization of a two-day workshop with about 90 participants that was held in Atlanta, GA, in September

2011. From September 2011 through February 2012, more than 100 contributors provided information to lead authors, who drafted the chapters, which were reviewed and revised to the extent possible given the time constraints, and submitted as a draft to the NCA on March 1, 2012. Following this submission the report was fully reviewed, revised, and resubmitted to the NCA on July 23, 2012 (Ingram et al. 2012). Following submission of the final report to the NCA, the authors agreed to publish the report as a book through Island Press, which entailed another several rounds of edits and revisions that led to this book. Despite our best efforts to produce a comprehensive, fully documented assessment for the SE USA, we have likely missed some important documents, for which we apologize. If you are aware of such documents, please contact the NCA (engagement@usgcrp.gov) to learn how to submit documents for future reports.

1.5 Report Organization

Three sections of the report follow this introduction: (1) Climate of the SE, which has one chapter that reviews the historic climate, current climate, and projected future climate of the region; (2) Climate interactions with important sectors of the Southeast, which includes nine chapters loosely organized from most to least anthropocentric; and (3) Cross-sectoral issues, namely climate change mitigation, adaptation, and education and outreach.

1.6 References

Bartels, W., C.A. Furman, F. Royce, B. Ortiz, D. Zierden, C.W. Fraisse. 2012. Developing a learning community: Lessons from a climate working group for agriculture in the Southeast USA. SECC & FCI Technical Report 12-001: 1-56.

EPA (US Environmental Protection Agency). 2012. ICLUS data for southeast region. Integrated climate and land use scenarios. US Environmental Protection Agency. http://www.epa.gov/ncea/global/iclus/inclus_nca_southeast.htm

Fraisse, C.W., N.E. Breuer, D. Zierden, K.T. Ingram. 2009. From climate variability to climate change: Challenges and opportunities to extension. *Journal of Extension* 47 (2). http://www.joe.org/joe/2009april/a9.php

Ingram, K.T., K. Dow, L. Carter. 2012. Southeast region technical report to the national climate assessment. US Global Change Research Program. http://downloads.usgcrp.gov/NCA/Activities/NCA_SE_Technical_Report_FINAL_7-23-12.pdf.

Mackun, P. and S. Wilson. 2011. Population distribution and change: 2000 to 2010. US Census Bureau. http://www.census.gov/prod/cen2010/briefs/c2010br-01.pdf

Mitchum, G.T. 2011. Sea level changes in the southeastern United States: Past, present, and future. Florida Climate Institute and Southeast Climate Consortium. http://floridaclimateinstitute.org/images/reports/201108mitchum_sealevel.pdf

Shin, D.W. and G.A. Baigorria. 2012. Potential influence of land development patterns on regional climate: a summer case study in Central Florida. *Natural Hazards* 62 (3): 877-885.

Chapter 2

Climate of the Southeast USA: Past, Present, and Future

LEAD AUTHORS

Charles E. Konrad II (konrad@unc.edu; Southeast Regional Climate Center, University of North Carolina at Chapel Hill, North Carolina)

Christopher M. Fuhrmann (fuhrman1@email.unc.edu; Southeast Regional Climate Center, University of North Carolina at Chapel Hill, North Carolina)

CONTRIBUTING AUTHORS

Amanda Billiot (Louisiana State Climate Office, Louisiana State University, Baton Rouge, Louisiana)

Barry D. Keim (Louisiana State Climate Office, Louisiana State University, Southern Climate Impacts Planning Program, Baton Rouge, Louisiana)

Michael C. Kruk (NOAA National Climatic Data Center, Asheville, North Carolina)

Kenneth E. Kunkel (NOAA National Climatic Data Center, Asheville, North Carolina)

Hal Needham (Southern Climate Impacts Planning Program, Baton Rouge, Louisiana)

Mark Shafer (Southern Climate Impacts Planning Program, Norman, Oklahoma)

Laura Stevens (NOAA National Climatic Data Center, Asheville, North Carolina)

Acknowledgements

We thank Kevin Robbins, David Sathiaraj, and Luigi Romolo of the Southern Regional Climate Center, and Ryan Boyles and Ashley Frazier of the North Carolina State Climate Office, for producing many of the figures that accompany this document. We also thank those individuals who reviewed earlier versions of this document, including John Christy, Bill Murphey, Stu Foster, and Keith Ingram.

This chapter describes the climate of the Southeast USA, including past, present, and future conditions. In addition, it provides a historical perspective on extreme events and context for assessing future impacts of climate change.

Key Findings

- The Southeast USA experiences a wide range of extreme weather and climate events, including floods, droughts, heat waves, cold outbreaks, winter storms, severe thunderstorms, tornadoes, and tropical cyclones. These events have contributed to more billion-dollar weather disasters in the Southeast (SE) than in any other region of the USA during the past three decades.
- Historical records of precipitation and temperature reveal much interannual and interdecadal variability across the SE, with no long-term trends since the end of the 19th century. However, since the 1970s, temperatures have steadily increased, with the most recent decade (2001 to 2010) noted as the warmest on record. A portion of this warming may be due to increased nighttime temperatures resulting from human development of the earth's surface. Interannual precipitation variability has also increased across the SE region, with more exceptionally wet and dry summers compared to the middle of the 20th century.
- Mean annual precipitation is expected to decrease across the southern tier of the SE, including the Caribbean, and increase across the northern tier through the first half of the 21st century. The greatest changes are expected during the summer months. However, there is much uncertainty in projected precipitation by the end of the 21st century due to the overall lack of model agreement on the sign and magnitude of these changes (except across the Caribbean). There is better model agreement and overall confidence in temperature projections, which indicate an overall increase across the SE through the end of the 21st century. Increases in the length of the growing season, the number of cooling degree days, the number of consecutive hot days, and interannual temperature variability are projected through the end of the 21st century.
- There is much uncertainty regarding future projections of drought, severe thunderstorms tornadoes, and air quality. The frequency of major hurricanes is projected to increase in the Atlantic Basin, while the overall number of tropical cyclones is projected to decrease through the end of the 21st century. Mean relative sea level rise across the SE coast is generally consistent with the global trend and is expected to increase between 20 and 200 cm by the end of the 21st century. The exact rate will depend largely on the rate of ice sheet loss as well as local land motion (e.g., subsidence).

2.1 General Description

The climate of the Southeast (SE) is quite variable and influenced by a number of factors including latitude, topography, and proximity to large bodies of water. The topography of the region is diverse. In the southern and eastern portions of the region, extensive coastal plains stretch from Louisiana eastward to southeastern Virginia,

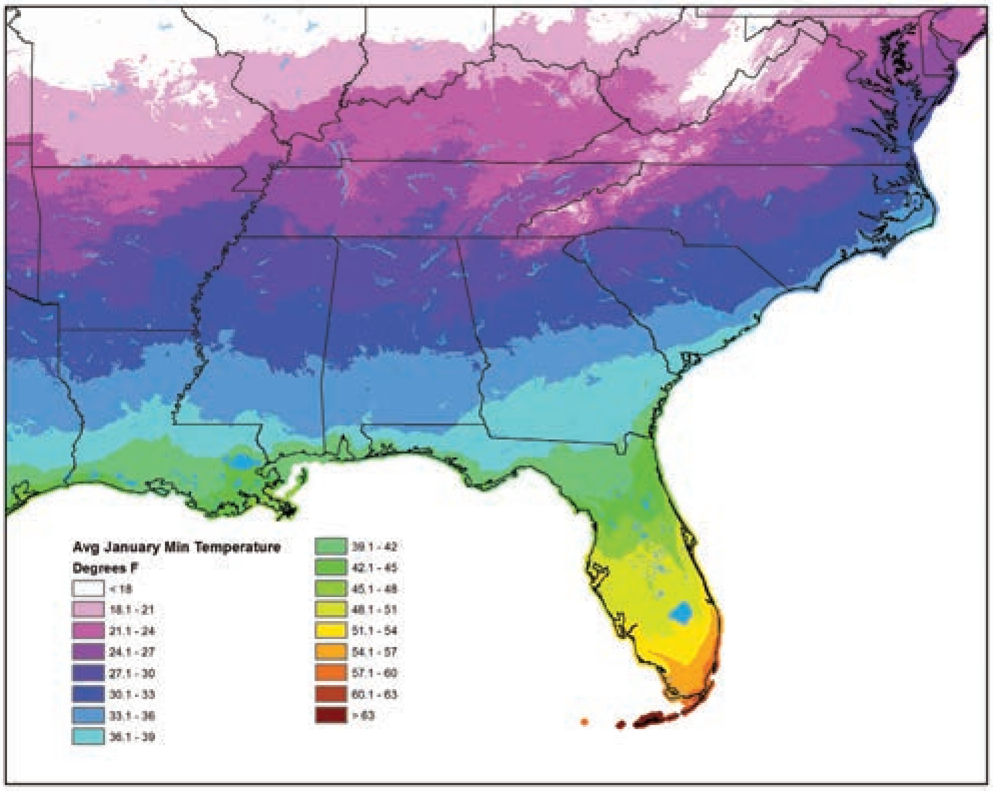


Figure 2.1 Map of average daily January minimum temperature. *Source*: *Parameter-elevation Regressions on Independent Slopes Model, or PRISM*; *http://www.prism.oregonstate.edu/.*

while rolling low plateaus, known as the Piedmont, are present from eastern Alabama to central Virginia. North and west of these areas, mountain ridges are found, including the Ozarks in Arkansas (1,500 to 3,000 ft) and the Appalachians, which stretch from Alabama to Virginia (2,000 to 6,600 ft). Finally, elevated, dissected plateaus lie from northern Alabama to Kentucky. Temperatures generally decrease with increasing latitude and elevation, while precipitation decreases away from the Gulf-Atlantic coasts, although rain is locally greater over portions of the Appalachian Mountains. Overall, the climate of the Southeast is generally mild and pleasant, which makes it a popular region for relocation and tourism.

A semi-permanent high pressure system, known as the Bermuda High, is typically situated off the Atlantic Coast. Depending on its position, the Bermuda High commonly draws moisture northward or westward from the Atlantic and Gulf of Mexico, especially during the warm season. As a result, summers across the SE are characteristically warm and moist with frequent thundershower activity in the afternoon and early evening hours. Day-to-day and week-to-week variations in the positioning of the Bermuda High can have a big influence on precipitation patterns. When the Bermuda High builds to the west over the region, hot and dry weather occurs, although humidity often remains relatively high. This pattern can cause heat waves and poor air quality, both of which negatively affect human health. When the Bermuda High persists over or immediately south of the area for extended periods, drought conditions typically develop. This places stress on water supplies and agricultural crops and can reduce hydroelectric energy production. Variations in the positioning of the Bermuda High also affect how hurricanes move across the region.

During cooler months of the year, the Bermuda High shifts southeastward as the jet stream expands southward. Accompanying the jet stream are extratropical cyclones and fronts that cause much day-to-day variability in the weather. As the jet stream dives southward, continental air can overspread the SE behind extratropical cyclones, leading to cold-air outbreaks. Sometimes subfreezing air reaches as far south as central Florida, causing major damage to citrus crops. Extratropical cyclones also draw warm and humid air from the Atlantic Ocean and Gulf of Mexico northward over frontal boundaries, and this can lead to potentially dangerous snowstorms or ice storms. These winter storms are generally confined to the northern tier of the region (35°N latitude and greater) where temperatures are cold enough to support frozen precipitation. In the spring, the sharp contrast in temperature and humidity in the vicinity of the jet stream can promote the development of severe thunderstorms that produce damaging winds, large hail, and tornadoes.

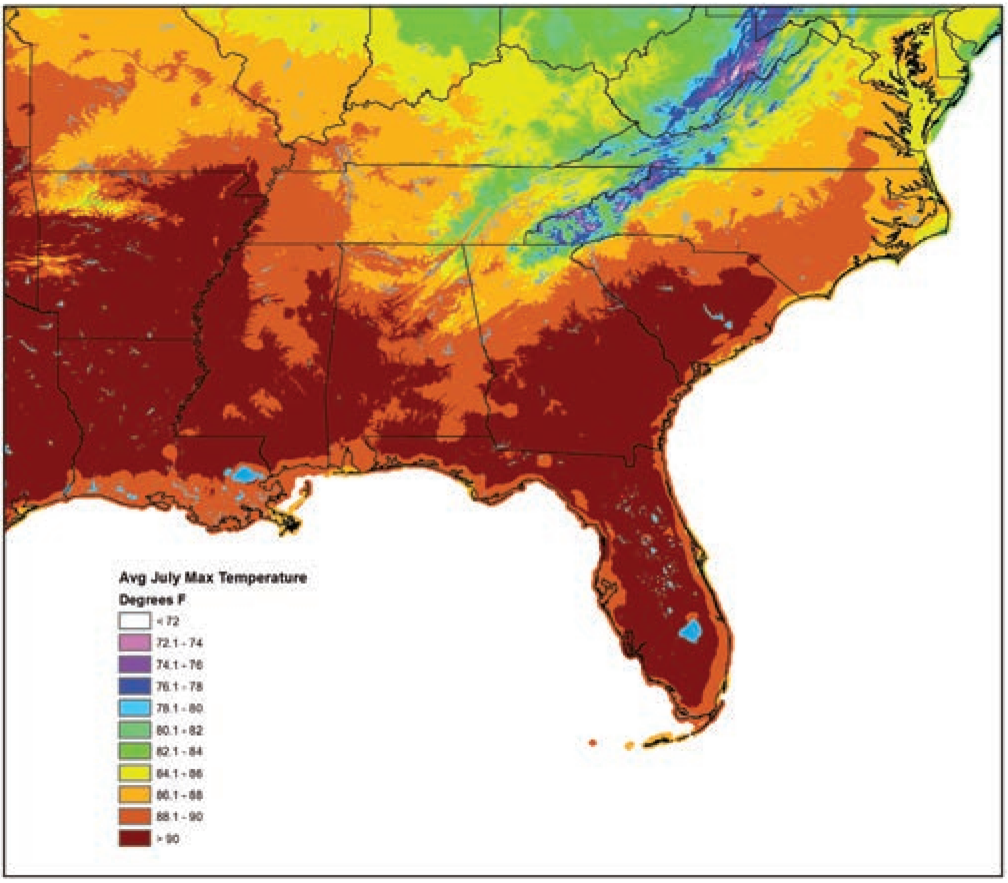


Figure 2.2 Map of average daily July maximum temperature. Source: Parameter-elevation Regressions on Independent Slopes Model, or PRISM; http://www.prism.oregonstate.edu/.

Temperature contrasts are especially great across the region in the wintertime. Average daily minimum temperatures in January range from 60°F in South Florida to 20°F across the southern Appalachians and northern Kentucky (Figure 2.1). In contrast, average daily maximum temperatures in July range from 95°F across the lower Mississippi River Valley and southeast Georgia to 75°F across the higher elevations of the southern Appalachians (Figure 2.2). Seasonal variations in temperature are relatively modest across the Caribbean due to its tropical climate. In Puerto Rico, these variations relate to both elevation and soil wetness. For example, minimum winter temperatures drop to as low as 50°F in the Cordillera Central mountain range (above 4,000 ft), while maximum summer temperatures reach 95°F across the drier southwestern part of the island.

Average annual precipitation across the region shows variations that relate both to the proximity to moisture sources (e.g., Gulf of Mexico and Atlantic Ocean) and the influences of topography, such as orographic lifting and rainshadows (dry areas on lee side of a mountain) (Figure 2.3). The Gulf Coast regions of Louisiana, Mississippi, Alabama, and the Florida Panhandle receive more than 60 in of precipitation, while much of Virginia, northern Kentucky, and central sections of the Carolinas and Georgia receive between 40 and 50 in of precipitation annually. Higher amounts of

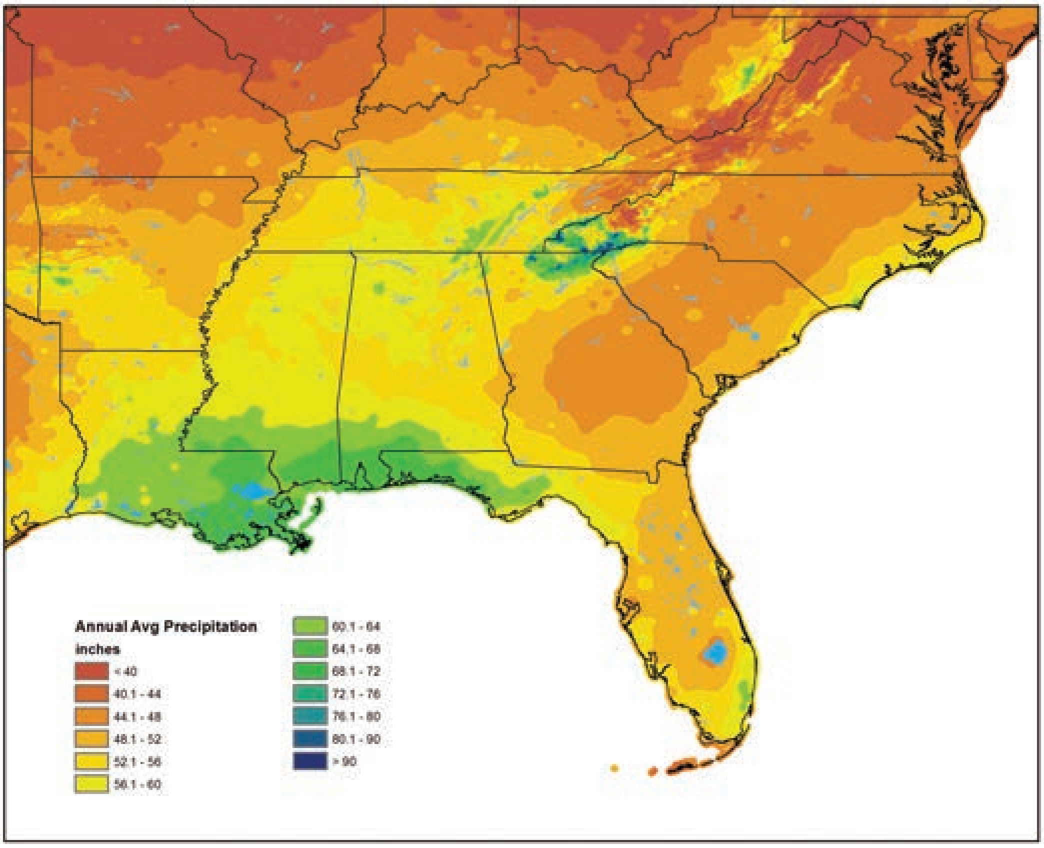


Figure 2.3 Map of annual average precipitation. *Source*: *Parameter-elevation Regressions on Independent Slopes Model, or PRISM; http://www.prism.oregonstate.edu/.*

precipitation are found along the Atlantic coast and across the Florida Peninsula due in part to the lifting of the air associated with sea breeze circulation. Tropical cyclones can also contribute significantly to annual precipitation totals in the region, especially over the Southeast Atlantic coast (Knight and Davis 2009). The wettest locations in the SE are found in southwestern North Carolina and across the eastern (i.e., windward) slope of Puerto Rico, where average annual totals exceed 100 in. Across the northern tier of the region, average annual snowfall ranges from 5 to 25 in, except at the higher elevations of the southern Appalachians in North Carolina and Tennessee (Figure 2.4). These locations can receive up to 100 in of snowfall annually, which is comparable to annual snowfall amounts experienced across portions of New England (Perry et al. 2010). The southern tier of the region (35°N latitude and lower) experiences little snowfall (i.e., less than 1 in per year) and may not record any measurable snowfall for several years.

Although the SE is mostly in a humid subtropical climate zone, the seasonality of precipitation varies considerably across the region (see Figure 6 in Kunkel et al. 2013). Along the coast, as well as some areas in the interior, a summer precipitation

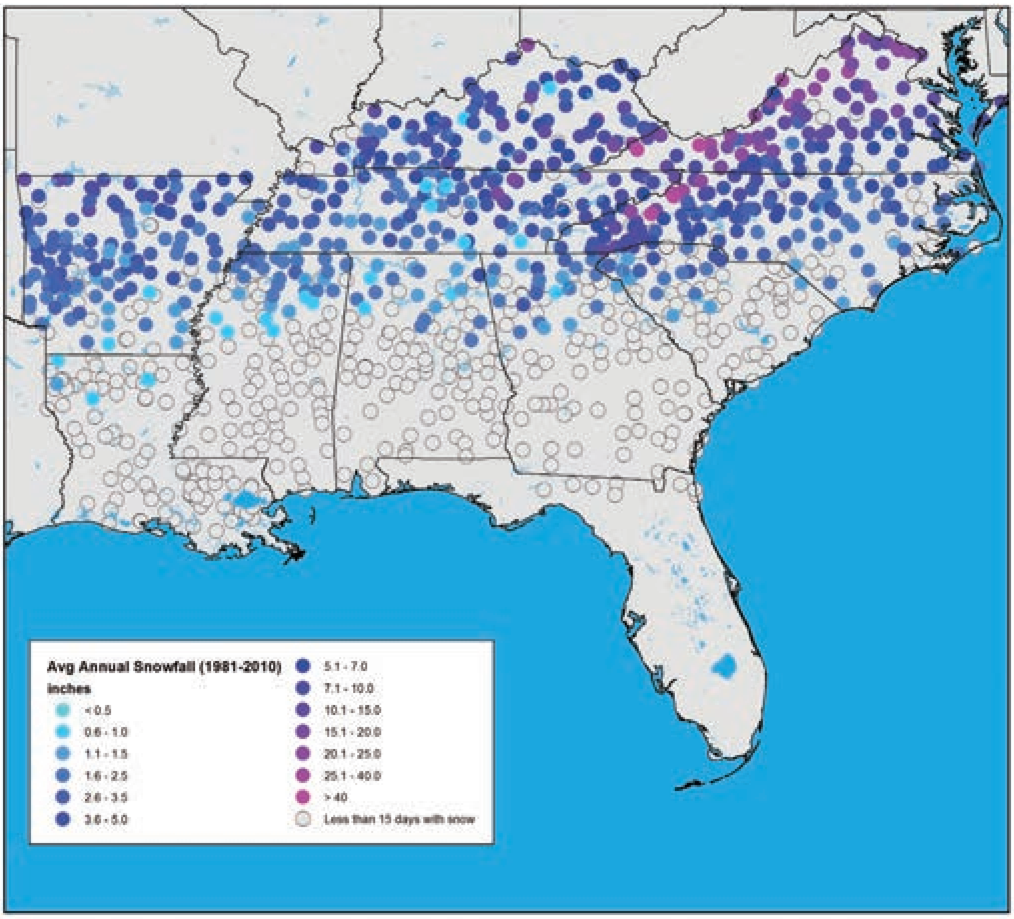


Figure 2.4 Annual average snowfall from 1981 to 2010. *Source*: *Global Historical Climatology Network, or GHCN*; *http://www.ncdc.noaa.gov/oa/climate/ghcn-daily/.*

maximum is found, especially across the Florida Peninsula. This can be related to the daytime thunderstorm activity associated with the heating of land surface and lifting of air along the sea breeze front. Many locations in the interior SE have nearly the same amount of precipitation in the cool season as in the warm season. In the cool season, extratropical cyclones and associated fronts frequently traverse much of the region and bring with them precipitation. Cool season precipitation totals, however, show much regional scale variability. The northern Gulf Coast is especially wet as mid-latitude cyclones frequently transport (advect) high levels of moisture northward from the Gulf of Mexico along frontal systems (Keim 1996). In contrast, the Florida Peninsula is often positioned south and east of cyclones and fronts and, therefore, displays a winter precipitation minimum (Trewartha 1981). Locations along the Atlantic Coast are situated in the path of mid-latitude cyclones in winter and spring. However, the fast motion of these systems frequently limits the deep transport of moisture and the duration of the associated precipitation (Keim 1996). Precipitation in the Caribbean is influenced primarily by the Bermuda High. In the winter, as the Bermuda High shifts southward, easterly trade winds increase while sea-surface temperatures (SSTs) and humidity decreases across the Caribbean, resulting in a winter precipitation minimum. The opposite occurs during the summer when the Bermuda High shifts northward, the easterly trade winds decrease, and summer precipitation maximizes (Taylor and Alfero 2005). A reduction in precipitation in July, known as the Caribbean midsummer drought, occurs when the Bermuda High temporarily expands southwestward across the Caribbean (Gamble et al. 2008). Tropical cyclones also contribute significantly to precipitation totals across the Caribbean in the summer and fall seasons.

2.2 Extreme Events

The southeastern region experiences a range of extreme weather and climate events that affect human society, ecosystems, and infrastructure. Since 1980, the SE has experienced more billion-dollar weather disasters than any other region in the USA (NCDC 2011). This section summarizes the climatology of these events across the region.

Heavy Rainfall and Floods

Heavy rainfall can produce short-lived flash floods and long-duration river floods that have enormous impacts on property and human life. These events result from a variety of weather systems that show much seasonality in their occurrence. In the winter and spring, slow-moving extratropical cyclones can produce large areas of very heavy rainfall, and during the late spring and summer slow-moving or training thunderstorms can generate excessive rainfalls over local areas. During the later summer and fall, tropical cyclones can produce extremely heavy rainfall, both locally and regionally, especially when they interact with frontal systems (Konrad and Perry 2010). Major rivers in the SE are susceptible to flooding, which can have a big impact on transportation and utility and industrial plants, as well as population interests along the major river basins (e.g., Mississippi and Ohio Rivers). Additional impacts include increased incidence of waterborne disease, contamination of water supplies, as well as property and agricultural losses. Most flood-related deaths result from flash floods associated with extratropical cyclones and tropical cyclones (Ashley and Ashley 2008). Of those deaths associated with tropical cyclones from 1970 to 1999, nearly 60% resulted from inland freshwater floods (Rappaport 2000). As air passes over mountains the very moist air in tropical cyclones rises quickly, which can produce extraordinary precipitation totals, resulting in flash and river flooding as well as landslides on the steeper slopes of the southern Appalachians (Fuhrmann et al. 2008).

Droughts

Despite the abundance of moisture, the SE is prone to drought as deficits of precipitation lead to a shortage of freshwater supplies. Rapid population growth and development has greatly increased the region's demand for water and vulnerability to drought. In the SE, droughts typically display a relatively shorter duration (i.e., one to three years) as compared to the multidecadal droughts experienced in the western and central parts of the USA (Seager et al. 2009). This may be due in part to the periodic occurrence of tropical cyclones, which can ameliorate the effects of drought during the peak water demand months of the late summer and fall (Maxwell et al. 2011). In contrast, the absence of tropical cyclones combined with high variability in warm season rainfall, increased evapotranspiration, and increased water usage can lead to the rapid development of drought conditions across the SE. Recent examples include the 1998-2002 drought, which resulted in record low lake, reservoir, and groundwater levels across parts of the Carolinas (Carbone et al. 2008), and the 2007-2008 drought, which resulted in over $1 billion in losses in Georgia alone and led to federal lawsuits over control of water releases from Lake Lanier in northern Georgia (Manuel 2008). In some cases, flooding and drought can occur simultaneously as was the case in early summer of 2011 (see Box 2.1). Severe droughts can also lead to forest fires and degraded air quality.

Extreme Heat and Cold

Due to its mid-latitude location, the SE often experiences extreme heat during the summer months and is occasionally prone to extreme cold during the winter months (see Figures 7 and 8 in Kunkel et al. 2013). Periods of extreme heat, particularly when combined with high humidity, can cause heat-related illness among vulnerable individuals as well as place stress on agriculture, water supplies, and energy production. Periods of extreme heat across the interior of the southeastern region have been tied to an upper-level ridge of high pressure centered over the Mississippi River Valley (Fuhrmann et al. 2011). There are significant local-scale variations in extreme heat and humidity related to adiabatic warming associated with downsloping winds off of the Appalachian Mountains, daytime mixing and draw-down of dry air from aloft, and the presence and strength of the sea-breeze circulation (Fuhrmann et al. 2011).

Outbreaks of extreme cold can have devastating effects on agriculture, particularly in the southern tier of the region. For example, a severe cold outbreak lasting more than a week in January 2010 resulted in more than $200 million in losses to the Florida citrus crop industry. Periods of extreme cold can also lead to cold-water anomalies that result in coral mortality. The cold outbreak of January 2010 resulted in the death of nearly 12% of corals along the Florida Reef Tract in the lower Florida Keys, marking the worst coral mortality on record for the region (Lirman et al. 2011). Outbreaks of extreme cold (e.g., deep freezes) in the SE are generally associated with a strong anticyclone moving southward from the Great Plains (Rogers and Rohli 1991). The most severe freezes

Box 2.1

Extreme Drought amongst a Record Flood

The complexities of climate variability may combine to produce a paradoxical mix of climate-related conditions. In the early summer of 2011, the lower Mississippi Valley experienced something unusual, the simultaneous occurrence of both flooding and drought. People were piling sandbags to hold back the floodwaters, and the Morganza Spillway in Louisiana was opened for the first time since 1973 to relieve pressure on the swollen river downstream in Baton Rouge and New Orleans. As the swollen river meandered across this region, however, much of the south Louisiana landscape was in extreme drought according to the USA. Drought Monitor (http://www.drought.gov).

The flood and the drought were tied to La Niña conditions in the equatorial Pacific Ocean. Las Niñas tend to dry out the Gulf Coast region by shifting storm tracks to the north across the Ohio River Valley. As storms tracked across the Central portion of the United States, they by-passed Texas, Oklahoma, Louisiana, and Missis-sippi, leaving them high and dry and producing drought conditions. However, excessive rainfall in the Midwest associated with the northward-displaced storm track, compounded by a large volume of spring snowmelt, produced a flood wave that moved downstream into drought stricken Tennessee, Arkansas, Mississippi and Louisiana.

On May 14, 2011, the US Army Corps of Engineers opened the first gate on the Morganza Floodway in Louisiana to relieve flooding on the Mississippi River. *Source*: *US Army Corps of Engineers*; *http://www.flickr.com/photos/30539067@N04/5722952407).*

occur when the anticyclone tracks into the Gulf Coast region, transporting cold polar air and promoting strong radiational cooling at night. Extreme cold can also have an adverse effect on river transportation, as was the case in January 1994 when sections of the Ohio River froze following a period of record cold temperatures across the eastern USA, including an all-time state record low temperature of -37°F in Kentucky.

Winter Storms

Winter storms, including snowstorms and ice storms, occur most frequently across the northern tier of the southeastern region. These storms have significant impacts on society, including property damage, disruption of utilities and transportation, power outages, school and business closings, injury, and loss of life. Snowstorms exceeding 6 in occur one or two times per year on average across Tennessee, Kentucky, and northern Virginia, and two or three times per year on average across the southern Appalachians (Changnon et al. 2006). In contrast, snowstorms exceeding 6 in occur only once every 100 years on average across the Gulf Coast region (Changnon et al. 2006).

Ice storms occur when a shallow dome of subfreezing air near the ground causes rain to freeze on surfaces. This cold air is sometimes supplied by a high pressure system located over New England. In this case, the Appalachian Mountains act as a dam by helping transport (advect) low-level cold and dry air from New England southward across Virginia and the Carolinas. The resulting glaze of ice can bring down tree limbs and power lines and cause widespread power outages. These events are most common across west-central portions of Virginia and North Carolina, which experience three to four days with freezing rain per year on average, and least common along the Gulf Coast (i.e., one day with freezing rain every 10 years on average) (Changnon and Karl 2003). Damaging ice storms can also occur across the mid-South from Arkansas to South Carolina. In February 1994, a major ice storm struck much of the southern tier of the USA, resulting in over $3 billion in damage as well as power outages exceeding one month in parts of Mississippi. The previous month, a major ice storm shut down the entire interstate highway system in Kentucky for nearly a week. A major ice storm in December 2002 produced more than 1 in of ice accretion across parts of the Carolinas. Though monetary losses from this event were lower than the 1994 storm, more than 1.8 million customers lost power, eclipsing the previous record for power outages in the region from a single storm set by Hurricane Hugo in 1989 (Jones et al. 2004).

Severe Thunderstorms and Tornadoes

Thunderstorms are frequent occurrences across the SE during the warmer months of the year. Severe thunderstorms, which are defined by the occurrence of winds in excess of 58 mph, hail at least 1 in diameter, or a tornado, occur most frequently in the late winter and spring months. Damaging winds and large hail occur most frequently across Alabama, Mississippi, Arkansas, western Tennessee, and northern Louisiana. These states also experience the highest number of strong tornadoes (F2 and greater) and experiences more killer tornadoes than the notorious "Tornado Alley" of the Great Plains (Ashley 2007) (see Figure 9 in Kunkel et al. 2013). The high death tolls can be attributed to increased mobile home density, longer path lengths, and a greater number of cool season and nocturnal tornadoes (Brooks et al. 2003, Ashley 2007, Ashley et al. 2008, Dixon et al. 2011). Cloud-to-ground lightning is also a significant hazard. The greatest frequencies of lightning strikes in the USA are found across the Gulf Coast and the Florida Peninsula. Moreover, eight of the eleven SE states rank in the top 20 for lightning-related fatalities from 1959 to 2006 (Ashley and Gilson 2009). Cloud-to-ground lightning also starts many house fires during the warm season and in rare instances can ignite wildfires.

Tropical Cyclones

Since 1980, tropical cyclones (tropical storms and hurricanes) have contributed to more billion-dollar weather disasters in the region than any other hazard (NOAA 2011). The Atlantic hurricane seasons of 2004 and 2005 were especially active and included seven of the top 10 costliest hurricanes to affect the USA since 1900 (Blake et al. 2011). Tropical cyclones produce a wide variety of impacts, including damaging winds, inland flooding, tornadoes, and storm surge (see Box 2.2). While their impacts are the greatest along the coast, significant effects are often observed several hundred miles inland. Wind gusts exceeding 75 mph occur every five to 10 years across portions of the coastal plain of the region and every 50 to 75 years across portions of the Carolina Piedmont, central Alabama, Mississippi, and northern Louisiana (Kruk et al. 2010). Tropical cyclones also contribute significantly to the rainfall climatology of the SE (Knight and Davis 2007) and relieve short-term droughts by providing a replenishing supply of soil moisture and rainfall for water supplies across the region. However, the heavy rainfall periodically results in deadly inland flooding, especially when the tropical cyclone is large or interacts with a stalled front (Konrad and Perry 2010).

Tropical cyclones make landfall most frequently along the Outer Banks of North Carolina (i.e., once every two years), southern Florida, and southeastern Louisiana (i.e., once every three years) (Keim et al. 2007). They are least frequent along concave portions of the coastline, including the western bend of Florida and the Georgia coast (Keim et al. 2007). Major hurricane landfalls (i.e., Categories 3 to 5) are most frequent in South Florida (once every 15 years) and along the northern Gulf Coast (once every 20 years) (Keim et al. 2007).

2.3 Trends

This section provides analyses of climatic trends for the SE region. These include trends in precipitation and temperature, which were calculated using data from the National Weather Service's Cooperative Observer Network since 1895, as well as trends in extreme events, sea level rise, and Atlantic sea surface temperatures.

Precipitation

No long-term trends are revealed in the time series of annual or summer season precipitation across the SE during the last 100 years, except along the northern Gulf Coast where precipitation has increased (Figure 2.5 and see Figures 14 and 15 in Kunkel et al. 2013). Inter-annual variability has increased during the last several decades across much of the region with more exceptionally wet and dry summers observed as compared to the middle part of the 20th century (Groisman and Knight 2008, Wang et al.

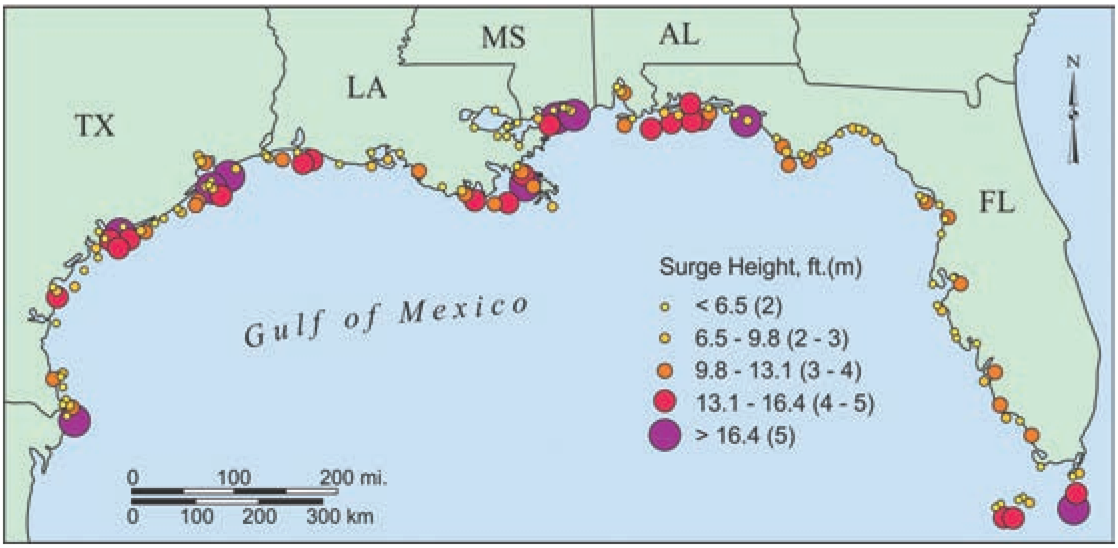
Box 2.2

Gulf Coast Storm Surge Database

SURGEDAT is the world's most comprehensive storm surge database. This dataset has identified the magnitude and location of peak storm surge for more than 550 tropical cyclone-generated surge events around the world since 1880. Prior to the creation of this dataset, such information was not archived in one central location. A recent expansion of this dataset includes all high water marks for each surge event, making it possible to visualize high-water profiles along the coast, which provides site-specific data on localized storm surge levels.

Analysis of storm surge activity along the USA Gulf of Mexico reveals that the greatest storm surge activity, in terms of both surge magnitudes and frequencies, generally occurs along the northern and western coast, as well as the Florida Keys. Florida's West Coast, from the eastern Panhandle to the Everglades, has generally observed less storm surge activity. Along the USA East Coast the largest surges have generally occurred in South Florida and the Carolinas, although several large surges have also impacted the Mid-Atlantic and Southern New England Coasts.

The complete dataset and map are hosted by the Southern Regional Climate Center at http://surge.srcc.lsu.edu. Points on the map are interactive, enabling users to click on a surge location and obtain information about that surge event. These data are supported by robust metadata files that provide documentation of all surge observations. This website also hosts a blog, which compares active and historic cyclones, incorporating historic surge observations into a discussion about surge potential in an active cyclone. Such discourse brings storm surge history to life, potentially enhancing surge forecasts, hurricane research, and public awareness.



This map depicts 195 peak storm surges along the U.S. Gulf Coast since 1880. Each circle represents a unique storm surge event. Larger, darker circles depict higher magnitude storm surge levels. *Source: Hal Needham and Barry Keim, Louisiana State University*

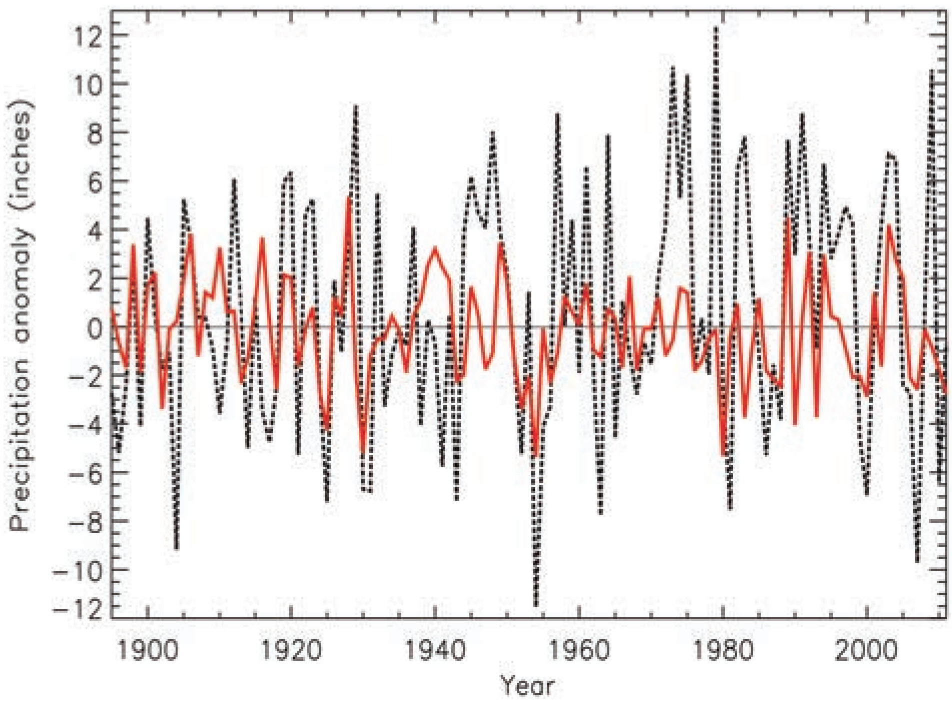


Figure 2.5 Annual (black/dotted line) and summer season (red/grey) precipitation anomalies for the SE. Source: Cooperative Observer data from the National Climatic Data Center.

2010). This precipitation variability is related at least partly to the mean positioning of the Bermuda High. For example, when the western ridge of the Bermuda High shifts to the southwest precipitation tends to increase in the southeastern region, and likewise when it shifts northwest, precipitation tends to decrease (Li et al. 2011). This broad scale relationship, however, is modulated in coastal areas by precipitation variations that relate to the strength of the sea breeze circulation. An intensification and westward expansion of the Bermuda High, for example, has been shown to correspond to a stronger sea breeze circulation and increased precipitation along the Florida Panhandle (Misra et al. 2011). Similar increases in precipitation are noted along much of the northern Gulf Coast (Keim et al. 2011). In addition, anthropogenic land-cover change may also be influencing the pattern and intensity of sea breeze-forced precipitation along the Florida Peninsula (Marshall et al. 2004).

The strength and position of the Bermuda High has been tied to sea surface temperature (SST) anomalies in the North Pacific (i.e., the Pacific Decadal Oscillation, Li et al. 2011) and subtropical western North Atlantic (i.e., Atlantic warm pool, Misra et al. 2011). Summer precipitation variability in the SE also shows some relationship with Atlantic SST anomalies and the Atlantic Multidecadal Oscillation (AMO). In general, warmer than average SSTs in the North Atlantic lead to increased warm-season precipitation across the southeastern region (Curtis 2008) and the Caribbean (Winter et al. 2011).

Sea-surface temperature anomalies in the equatorial Pacific such as El Niño-Southern Oscillation (ENSO) are correlated with precipitation totals across all seasons in

South Florida and the Caribbean (Jury et al. 2007, Mo et al. 2009). This influence extends across much of the rest of the SE during the winter and spring months. Specifically, a warm anomaly in the equatorial Pacific (El Niño) is associated with wetter and cooler than normal conditions across most of the SE, while a cold anomaly (La Niña) is tied to unseasonably dry and warm conditions (New et al. 2001), except across portions of the Appalachian plateau, including Kentucky and Tennessee (Budikova 2008). The influence of ENSO on precipitation diminishes during the warmer months and is restricted to southern portions of the region (e.g., Florida) where El Niño conditions typically lead to a dry weather pattern. The persistence of El Niño conditions can lead to significant impacts, as was the case during the unusually strong El Niño event of 1997-1998. For instance, numerous wildfires broke out across Florida in June, which were fueled by a dense growth of vegetation caused by heavy winter rainfall (Changnon 1999).

The severity of recent droughts across the southeastern region raises the possibility of a long-term shift in the precipitation regime. However, climate reconstructions using tree rings reveal significant multidecadal variability in precipitation and soil moisture across the SE over the past millennium with no discernible long-term trend (Stahle and Cleaveland 1992, 1994, Doublin and Grundstein 2008, Seager et al. 2009, Ortegren et al. 2011). In particular, the reconstructions suggest that the severity and duration of several prominent 20th and early 21st century droughts are not unusual in the longer-term context and that decade-long droughts have occurred periodically in the SE during the past 1,000 years. The disappearance of the Lost Colony of Roanoke in the late 16th century, as well as the abandonment of the Jamestown Colony in the early 17th century, were likely tied to food shortages and poor water quality resulting from severe and persistent drought that covered much of the southern tier of the USA—the 16th century "megadrought" (Stahle et al. 1998, Stahle et al. 2000, Stahle et al. 2007). In addition to this drought, prolonged dry periods are also evident in the middle 18th century (Stahle and Cleaveland 1994) and early-to-middle 19th century (Seager et al. 2009), after which conditions transitioned to a persistent wet regime that is largely unmatched in the region over the past millennium (Fye et al. 2003, Kangas and Brown 2007, Seager et al. 2009).

Both instrumental and proxy records indicate significant multidecadal variability in Caribbean precipitation dating back over 800 years that appears to be linked to variations in the North Atlantic Oscillation (NAO) (Malmgren et al. 1998) and the AMO (Winter et al. 2011), as well as variations in the character of the Intertropical Convergence Zone (Kilbourne et al. 2010). Trends beginning in the early 20th century indicate a drying of the Caribbean over time associated with an accelerated Hadley circulation (Jury and Winter 2009). The drying trend is more pronounced over tropical landmasses than over water and is presumed to be the result of land-surface interactions modulated by large-scale circulation patterns (Kumar et al. 2004).

Heavy Rainfall and Floods

The frequency of extreme precipitation events has been increasing across the southeastern region, particularly over the past two decades (Figure 2.6). Increases in extreme precipitation events are most pronounced across the lower Mississippi River Valley and along the northern Gulf Coast (see Figures 22 and 23 in Kunkel et al. 2013). Despite a long-term increase in extreme precipitation events, there is no discernible trend in the magnitude of floods along ex-urban, unregulated streams across the region (Hirsch and Ryberg 2011). The increase in extreme precipitation, coupled with increased runoff due to the expansion of impervious surfaces and urbanization, has led to an increased risk of flooding in the region's urban areas (e.g., the record-breaking Atlanta, GA flood in 2009) (Shepherd et al. 2011). Time series of extreme precipitation events are available at the climate division level from the following website: http://charts.srcc.lsu.edu/ghcn/.

Temperature

The southeastern USA is one of the few regions globally that did not exhibit an overall warming trend in surface temperature during the 20th century (IPCC 2007). Annual and summer season temperatures across the region exhibited much variability during the first half of the 20th century, though most years were above the long-term average (Figure 2.7). This was followed by a cool period in the 1960s and 1970s. Since then, temperatures have steadily increased, with the most recent decade (2001 to 2010) being the warmest on record. The recent increase in temperature is most pronounced during the summer season, particularly along the Gulf and Atlantic coasts, while winter season temperatures have generally cooled over the same areas (see Figures 16 and 17 in Kunkel et al. 2013). The overall increase in temperatures over the past several decades is also related at least partially to increasing daily minimum temperatures due to human development of the surface, including urbanization and irrigation (Christy 2002, Christy et al. 2006).

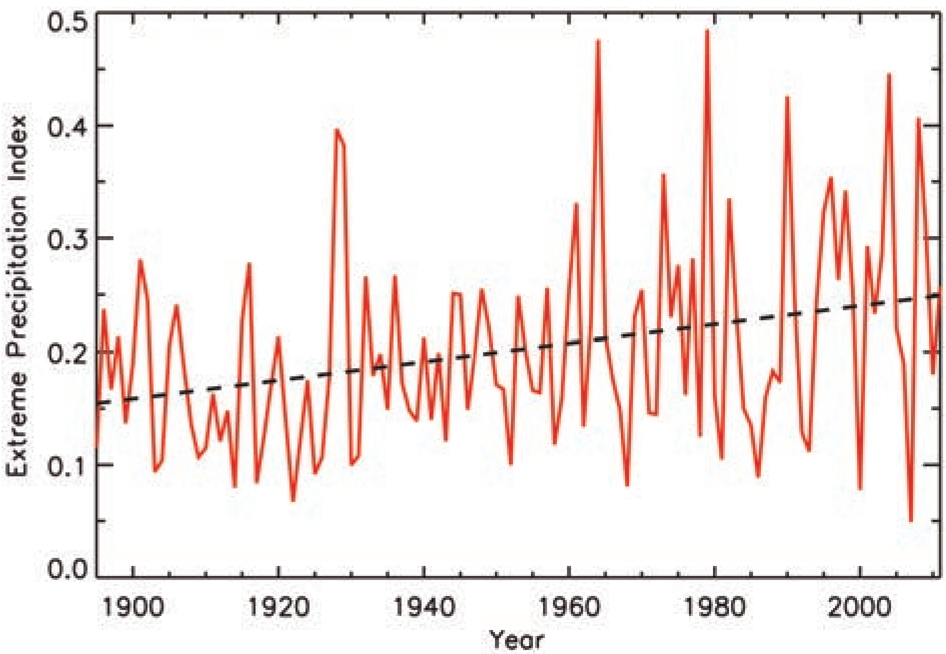


Figure 2.6 Time series of the extreme precipitation index (using a 5-year running average) for the SE for the occurrence of 1-day, 1 in 5 year extreme precipitation events (red/grey line) and 5-day, 1 in 5 year events (black/dashed line). Source: Cooperative observer data from the National Climatic Data Center and updated from Kunkel et al. (2003).

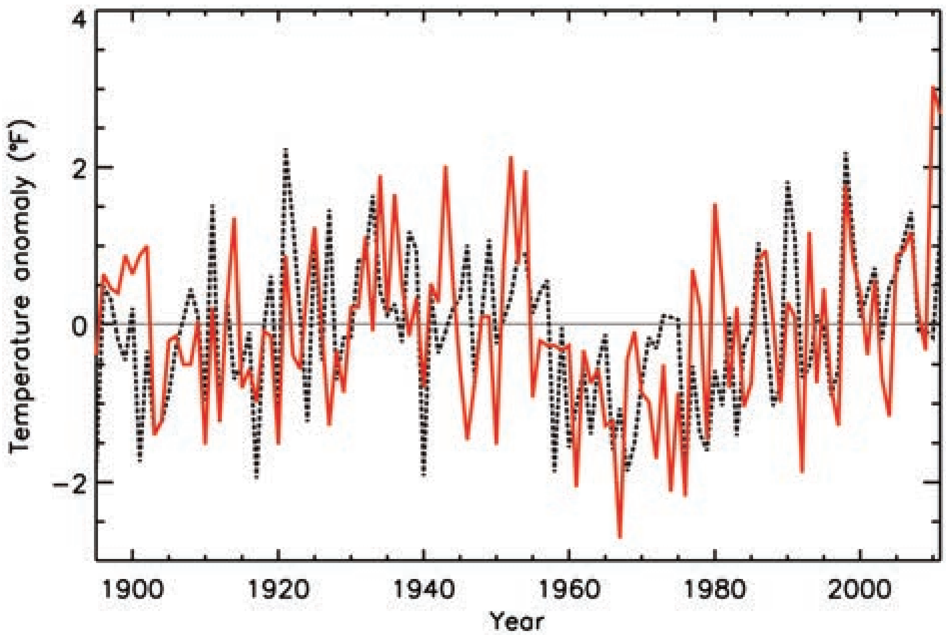


Figure 2.7 Annual (black/dotted line) and summer season (red/grey) temperature anomalies for the SE. Source: Cooperative observer data from the National Climatic Data Center.

The observed lack of warming during the 20th century (i.e., "warming hole," Pan et al. 2004) also includes parts of the Great Plains and Midwest regions, and several hypotheses have been put forward to explain it, including increased cloud cover and precipitation (Pan et al. 2004), increased aerosols and biogenic production from forest re-growth (Portmann et al. 2009), decreased sensible heat flux due to irrigation (Puma and Cook 2010), and multidecadal variability in both North Atlantic SSTs (Kunkel et al. 2006) and tropical Pacific SSTs (Robinson et al. 2002).

In the Caribbean, no long-term trend has been identified in temperatures from the mid-18th to the mid-20th centuries (Kilbourne et al. 2008) but significant multidecadal variability is evident in the time series. Since then, a significant warming trend has occurred, which is consistent with the overall global trend (Campbell et al. 2011) and is positively correlated with both the AMO and ENSO (i.e., warmer Atlantic SSTs, more El Niño events) (Malmgren et al. 1998).

Extreme Heat and Cold

The frequency of maximum temperatures exceeding 95°F has been declining across much of the SE since the early 20th century, particularly across the lower Mississippi River Valley (see Figure 13 in Kunkel et al. 2013). Higher frequencies of extreme maximum temperatures are noted in the 1930s and 1950s and correspond to periods of exceptionally dry weather. Following a period of relatively few extreme maximum temperatures in the 1960s and 1970s, there has been an upward trend over the last three decades, particularly across the northern Gulf Coast, Florida Peninsula, and northern Virginia. The frequency of minimum temperatures exceeding 75°F has generally been increasing across most of the SE region. This increase is most pronounced over the past few decades (see Figure 14 in Kunkel et al. 2013) and has been attributed largely to human development of the surface (Christy 2002, DeGaetano and Allen 2002). Time series of extreme heat and cold are available at the climate division level from the following website: http://charts.srcc.lsu.edu/ghcn/.

Similar to trends in extreme heat, the number of days with extreme cold has generally been declining across most locations in the SE, though there is much decadal and intraregional variability (see Figures 19 and 20 in Kunkel et al. 2013). For example, major Florida freezes tend to be clustered in time, particularly in the late 19th and early 20th centuries and from the late 1970s to the late 1980s (Rogers and Rohli 1991). These clusters are tied to decadal-scale periods in which the PNA (NAO) pattern was predominantly positive (negative) (Downton and Miller 1993) and ENSO neutral conditions prevailed across the equatorial Pacific (Goto-Maeda et al. 2008). Recent cold winters across the eastern USA have also been associated with a persistent negative phase of the NAO (Seager et al. 2010). The occurrence of several strong freezes beginning in the 19th century have gradually forced the citrus industry and other industries, for example, winter vegetables and sugarcane, to migrate from northern Florida into South Florida. To accommodate this shift, substantial areas of wetlands were drained and converted to agricultural land, reducing the moisture in the atmosphere above these former wetlands, which increased the risk of freezes (Marshall et al. 2004).

Winter Storms

Average annual snowfall totals across the northern tier of the southeastern region have declined at a rate of approximately 1% per year since the late 1930s (Kunkel et al. 2009). Additionally, snowstorms exceeding 6 in have been declining in frequency since the start of the 20th century (Changnon et al. 2006). This trend, however, is punctuated by an increase in frequency of snowstorms in the 1960s (Changnon et al. 2006). Snowfall trends across the SE southern tier are less certain due to the relative lack of snowfall (see Figure 2.4) and possible inconsistencies in the snowfall data. The decline in snowfall and snowstorms across the northern tier of the region corresponds to low-frequency variability in the NAO, which reveals a positive trend (i.e., warmer winters) over the latter half of the 20th century (Durkee et al. 2007). It is worth noting that this decline stands in contrast to a positive trend in snowfall and snowstorms over much of the 20th century (Changnon et al. 2006, Kunkel et al. 2009) across the northeastern and Midwest regions of the USA. The frequency of days with freezing rain has shown little overall change since the middle of the 20th century but more interdecadal variability relative to snowstorms (Changnon and Karl 2003).

Severe Thunderstorms and Tornadoes

There has been a marked increase in the number of severe thunderstorm reports, including tornadoes over the last 50 years; however, this increase is associated with a much-improved ability to identify and record storm damage. In the case of tornadoes, improved radar technology (Doppler) has allowed meteorologists to resolve storm circulations and identify where to anticipate storm damage (Verbout et al. 2006). The annual frequencies of strong tornadoes (F1 and greater) have remained relatively constant nationally over the last 50 years (Brooks and Doswell 2001). Preliminary statistics suggest that the 2011 storm season was one of the most active and deadliest on record; however, this is not part of an upward trend. Due to increased public awareness as well as improved weather forecasting and technology, tornado fatalities have declined dramatically since the 1930s (Ashley 2007) in spite of the fact that the population has increased in tornado-prone areas.

Hurricanes

Many of the hurricanes that affect the United States make landfall in the SE. The decadal frequencies of both hurricane and major hurricane (category 3 and greater) landfalls have declined slightly over the last 100 years (Blake et al 2011); however, there is much inter-decadal variability in the record that relates to the AMO (Keim et al. 2007, Klotzbach 2011) and ENSO (Klotzbach 2011). The AMO was most positive between 1930 and 1950, and 27 major hurricanes made landfall. In contrast, only 13 major hurricanes made landfall during the AMO negative phase between 1970 and 2000. During the last 10 years, there has been an increase in hurricanes as the AMO has shifted back to a positive phase. Tropical cyclone activity and landfall frequencies are typically lower during El Niño years, though this relationship is somewhat weaker during AMO positive phases (Klotzbach 2011).

Analyses of hurricanes and tropical cyclones over the entire Atlantic Basin provide differing perspectives regarding secular trends in activity. Holland and Webster (2007) and Mann and Emmanuel (2006) found increasing trends in tropical cyclone activity in the Atlantic basin extending back to 1900 and 1880, respectively. Landsea (2007), however, points out that the pre-satellite era (prior to the late 1960s) record of tropical activity is likely missing numerous storms and that the record may be worse before airplane reconnaissance began in the mid-1940s. Prior to the 1940s, storms were largely detected through landfalls and/or encounters with ships at sea. Even when a ship route intersected a hurricane, the intensity of the storm was likely underestimated (Landsea et al. 2004). Landsea et al. (2010) also suggest that there has been a significant increase in the number of short-lived storms detected since the introduction of satellites that were likely missed in the earlier portions of the hurricane records.

When adjusted for these reporting and monitoring biases, the time series of Atlantic basin tropical cyclone frequency shows only a slight upward trend from 1878 to 2008 (Landsea et al. 2010). Examination of the accumulated cyclone energy (ACE) index, a metric that incorporates cyclone intensity (wind speed) and duration, reveals that, while global hurricane activity since 2006 has been at its lowest level since the 1970s, hurricane activity across the Atlantic basin has remained high over the past two decades (Maue 2011). Klotzbach (2011) examined the ACE index across the Atlantic basin and found an increasing trend from 1900 to 2009. Earlier work by Webster et al. (2005) and Klotzbach (2006) showed that the frequency of Category 4 and 5 hurricanes has increased across the Atlantic basin during the satellite era. These studies attribute increasing trends in ACE and major Atlantic basin hurricanes to anthropogenic global warming, multidecadal climate variability, and improved monitoring technology.

Trends in Atlantic basin tropical cyclone frequency and landfalls dating back 1,500 years have been estimated using various proxy reconstructions that include the use of sediment records of storm surge over-wash (Mann et al. 2009). Results indicate a peak in tropical cyclone activity during the Medieval Period more than 1,000 years ago with an overall declining trend into the mid-20th century. This result is also supported by Nyberg et al. (2007), who used coral and marine sediment cores in the Atlantic basin and found a declining trend in tropical cyclone frequencies from the mid-18th century to the early 1990s.

Sea Level Rise and Sea Surface Temperatures

Sea levels have slowly risen across the extensive coastline of the southeastern region. Satellite altimetry records, however, reveal spatial and temporal variations in the rates of sea level rise that relate to land motion (e.g., subsidence) as well as short-term climate variability (e.g., ENSO) (Mitchum et al. 2010). Trends in global sea level dating back nearly 500,000 years have been assessed using coastal sediment cores. These records indicate variations in global sea level of as much as 100 meters that correspond with glacial and inter-glacial cycles (Church et al. 2010). Variations in sea level since the mid-19th century have been assessed using tidal gauge records, which indicate a rate rise of approximately 1.7 mm per year (+/- 0.2 mm per year) over most of the 20th century (Church et al. 2010, Church and White 2011). However, satellite altimetry data indicate a rate rise of between 3.0 and 3.5 mm per year since the early 1990s, or nearly double the average rate experienced over the 20th century (Prandi et al. 2009, Church et al. 2010). It is unclear whether this shorter-term increase is due to natural, multidecadal variability in sea levels or is a response to recent global warming trends. Nevertheless, higher mean sea levels threaten the security of critical infrastructure and coastal ecosystems, and they increase the frequency and magnitude of flooding associated with coastal storms. Overall rates of sea level rise across the SE are generally consistent with the mean global rate, though some locations in the northern Gulf of Mexico and along the East Coast exhibit slightly greater rates due to land subsidence (Mitchum 2011). Variations in sea level rise are driven primarily by thermal expansion due to the warming of ocean waters and glacial melt (Domingues et al. 2008, Pritchard et al. 2009). Recent analysis of glacial melting on Greenland shows that the melt rate from 1996 to 2011 was above the long-term average (1973 to 2007), with five of the six highest melt rates on record occurring since 2000 (Tedesco et al. 2012).

Trends in SSTs during the 20th century reveal a cooling over the North Atlantic near Greenland. This cooling may be related to an infusion of melt water as well as an increase in wind speed and heat loss from the ocean surface connected with the upward trend in the NAO circulation during the latter half of the century (Deser et al. 2010). A marked warming trend in SST (1.6°C per century) has been noted off of the East Coast of North America; globally only the east coast of China exhibits a comparable trend (Deser et al. 2010).

2.4 Future Projections

This section provides a summary of future climate projections for the southeastern USA based on recently published studies and an independent analysis of model output from statistically and dynamically downscaled datasets. These include global climate model output and statistically downscaled monthly and daily climate projections from phase 3 of the Coupled Model Inter-comparison Project (CMIP3) as well as dynamically downscaled output from the North American Regional Climate Change Assessment Program (NARCCAP). The reader is directed to Kunkel et al. (2013) for a detailed description of the model datasets and methods used as well as measures of model uncertainty and agreement.

Precipitation

Model simulations of future precipitation patterns using the A2 and B1 emissions scenarios from the IPCC AR4 reveal both increases and decreases in precipitation across the SE by the mid-21st century. Average annual precipitation is projected to decrease by 2% to 4% in Louisiana and South Florida, while increases in precipitation of up to 6% are projected across North Carolina and Virginia (Figure 2.8). Precipitation is expected to increase across most of the SE in all seasons except summer, where a decrease of as much as 15% is noted across parts of Arkansas, Louisiana, and South Florida (see also Keim et al. 2011). An increase in interannual precipitation variability is noted across the region through the first half of the 21st century, with the greatest variability projected during the summer season and in line with recent trends in the observational record. The continued intensification and westward expansion of the Bermuda High will likely increase summer season precipitation variability across most of the SE and is a robust feature in several of the IPCC AR4 models (Li et al. 2011).

Short-range projections (i.e., by 2035) reveal changes in annual precipitation across the SE that are smaller than typical year-to-year variations seen in the observed record (see Figure 37 in Kunkel et al. 2013). In contrast, by the end of the 21st century, annual precipitation is projected to decrease by as much as 12% across Louisiana and Arkansas, with increases of up to 6% noted across the far northeastern part of the region. These changes are significantly larger than the year-to-year variations seen over most of the 20th century. Moreover, individual model ranges by 2085 are rather large compared to the multimodel mean difference in precipitation from the 1971-2000 baseline period, indicating much uncertainty in precipitation projections by the end of the 21st century (Kunkel et al. 2013).

The annual number of days with extreme precipitation is expected to increase across most of the region by the mid-21st century, particularly along the southern Appalachians as well as parts of Tennessee and Kentucky (Figure 2.9). Little change in the annual frequency of extreme precipitation is projected across the southern tier of the region, with more consecutive dry days expected across the northern Gulf Coast (see also Keim et al. 2011). These trends are projected to continue throughout the 21st century. The projected drying across the southern tier of the region extends into the northern Caribbean and is a robust feature in all of the IPCC AR4 models (Rauscher et al. 2008, Biasutti et al. 2009). This drying trend across the Caribbean, which is most pronounced during the summer and winter months (Campbell et al. 2011), may be associated with projected increases in atmospheric stability and decreases in convection. These trends are tied to a mean warming of the tropical atmosphere (Lee et al. 2011, Rauscher et al. 2011), as well as variations in the strength of the trade winds and Caribbean low-level jet stream (Gamble et al. 2008, Campbell et al. 2011). This broad drying pattern may

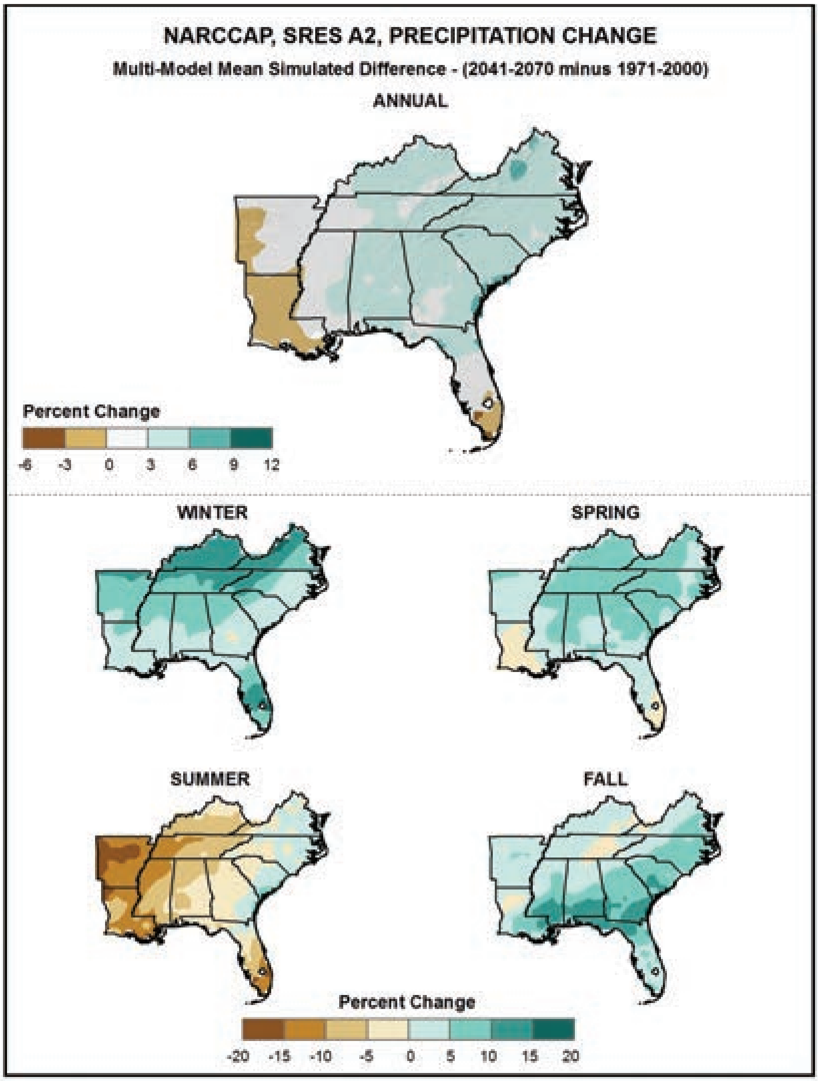


Figure 2.8 Annual and seasonal difference in precipitation (percent) between projections for 2041–2070 and the baseline of 1971–2000. *Source*: *North American Regional Climate Change Assessment Program (NARCCAP).*

lead to an increase in the frequency and severity of hydrologic drought (Biasutti et al. 2009). Overall, there is much uncertainty in these projections because of inadequacies in model resolution, which is often too coarse to resolve regional and local-scale processes (e.g., sea-breeze circulation), and internal variability in the climate system (e.g., AMO, NAO, ENSO), which is also less successfully simulated by climate models (Ting et al. 2009, Stefanova et al. 2011, Kunkel et al. 2013).

Another measure of model uncertainty involves the comparison between model simulations and observations of 20th century climate conditions. Figure 2.10 shows the observed and simulated mean decadal average precipitation changes for the SE from

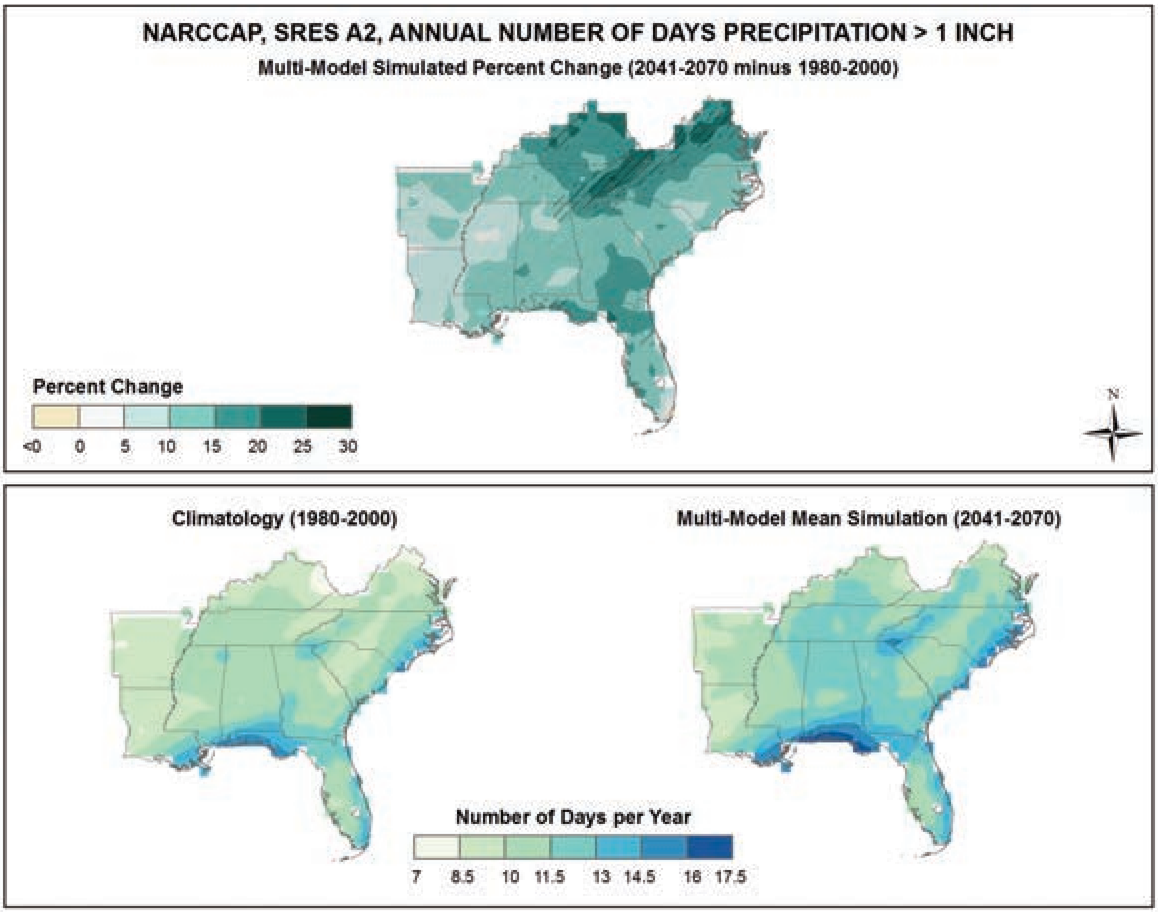


Figure 2.9 Mean change in annual number of days with precipitation exceeding 1 inch (projections for 2041–2070 minus the baseline of 1971–2000). *Source*: *North American Regional Climate Change Assessment Program (NARCCAP).*

1900 to 2100, expressed as deviations from the 1901 to 2000 average. Observed precipitation was derived from the National Weather Service's Cooperative Observer Network, while model simulated precipitation was derived from 15 different CMIP3 simulations for the high (A2) emissions scenario (see Kunkel et al. 2013). Simulation of 20th century conditions were based on estimated historical forcings of the climate system, including greenhouse gas emissions, solar variations, and aerosols. As seen in Figure 2.10, the observed trends and variations in decadal average precipitation are small and are within the envelopes of the model simulations. However, model projections into the 21st century indicate increased decadal variability in precipitation compared to the 20th century observations. Moreover, there is significant spread in projected precipitation among individual model simulations and an overall lack of agreement on the sign (i.e., an increase or decrease) of the projected change. When examined by season, the 21st century portions of the time series indicate an overall increase in precipitation in all seasons except summer (see Figure 46 in Kunkel et al. 2013).

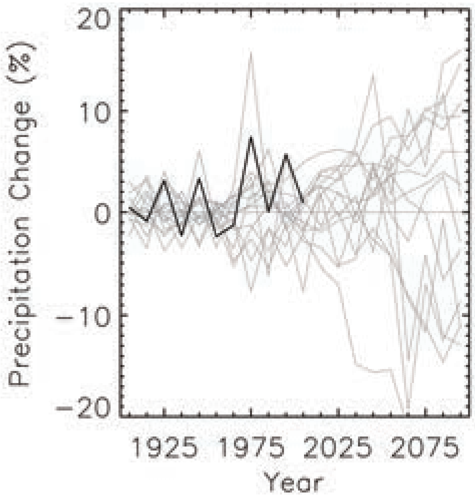


Figure 2.10 Observed decadal mean annual precipitation change (percent change from the 1901 to 2000 average) for the southeastern US (black lines) and the 20th and 21st century simulations from 15 CMIP3 models for the high (A2) emissions scenario (gray lines). *Source*: *Kunkel et al. (2013), Figure 45.*

Temperature

Mean annual temperatures are projected to increase across the SE through the 21st century. By 2050, the largest increases (3°F to 5°F) are projected over the interior of the region with the smallest increases observed over South Florida (Figure 2.11). By the end of the 21st century, the interior of the region is projected to warm by as much as 9°F while temperatures across the Caribbean are projected to be between 2°F and 4°F warmer than the late 20th century average (Biasutti et al. 2009, Campbell et al. 2011). These changes are generally consistent between the CMIP3 and NARCCAP simulations (see Figures 26 and 27 in Kunkel et al. 2013). The greatest warming is projected to take place during the summer months, while the winter months exhibit the least amount of warming (Figure 2.11). Additionally, the seasonal changes exhibit more spatial variability than the mean annual temperature change. It is important to note that the range of temperatures across the model simulations is large, particularly through the middle of the 21st century as internal climate variability contributes significantly to the temperature uncertainties in each model simulation over shorter time scales (Hawkins and Sutton 2009). Therefore, these projections should not be interpreted as precise quantitative predictions, but instead as broadly indicative of the kinds of changes that are likely to occur in the SE as the global climate warms.

Maximum temperatures exceeding 95°F are expected to increase across the SE, with the greatest increases (35 additional days annually) found across the southern half of Florida by the mid-21st century (Figure 2.12). In general, more warm temperature extremes are predicted in the southwest part of the region, which has seen an increasing trend in such temperatures during the 20th and early 21st centuries (Diffenbaugh and Ashfaq 2010). In addition, the number of consecutive days exceeding 95°F, a metric used as a measure of heat waves, is expected to increase between 97% and 207%, depending on the model and emissions scenario (see Table 5 in Kunkel et al. 2013). An increase in the number of warm nighttime temperatures is projected across the Caribbean, with the warmest nights over the 20th century becoming four times more frequent by the end of the 21st century (Biasutti et al. 2009). Minimum temperatures

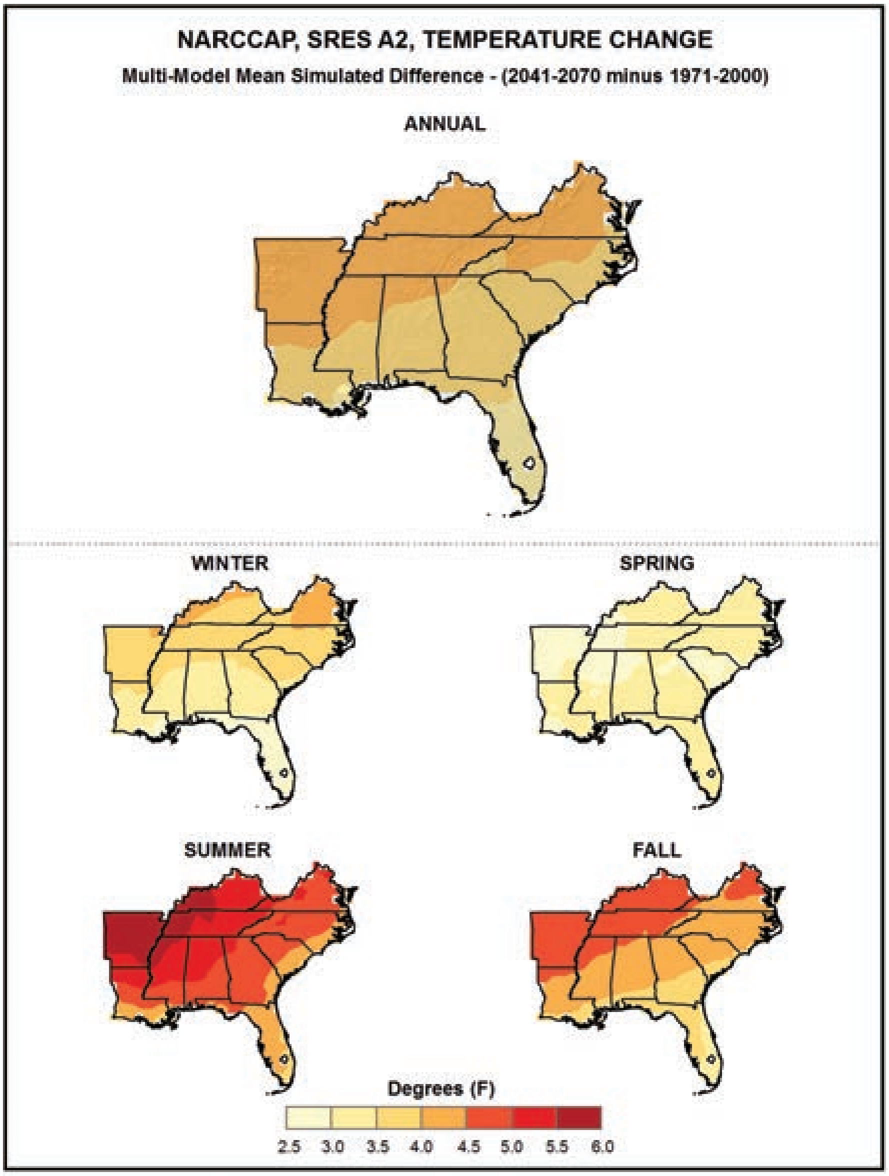


Figure 2.11 Annual and seasonal difference in temperature (°F) (projections for 2041–2070 minus the baseline of 1971–2000). *Source: North American Regional Climate Change Assessment Program (NARCCAP).*

below 10°F are expected to decrease in frequency by as much as 10 days in the northern tier of the region by the mid-21st century (Figure 2.13). Overall warming in the northern tier of the region is projected to increase the length of the freeze-free season by as much as 30 days in the mid-21st century. The length of the freeze-free season is defined as the period of time between the last spring frost, or daily minimum temperature less than 32°F, and first fall frost. In addition, the number of growing degree days (with a

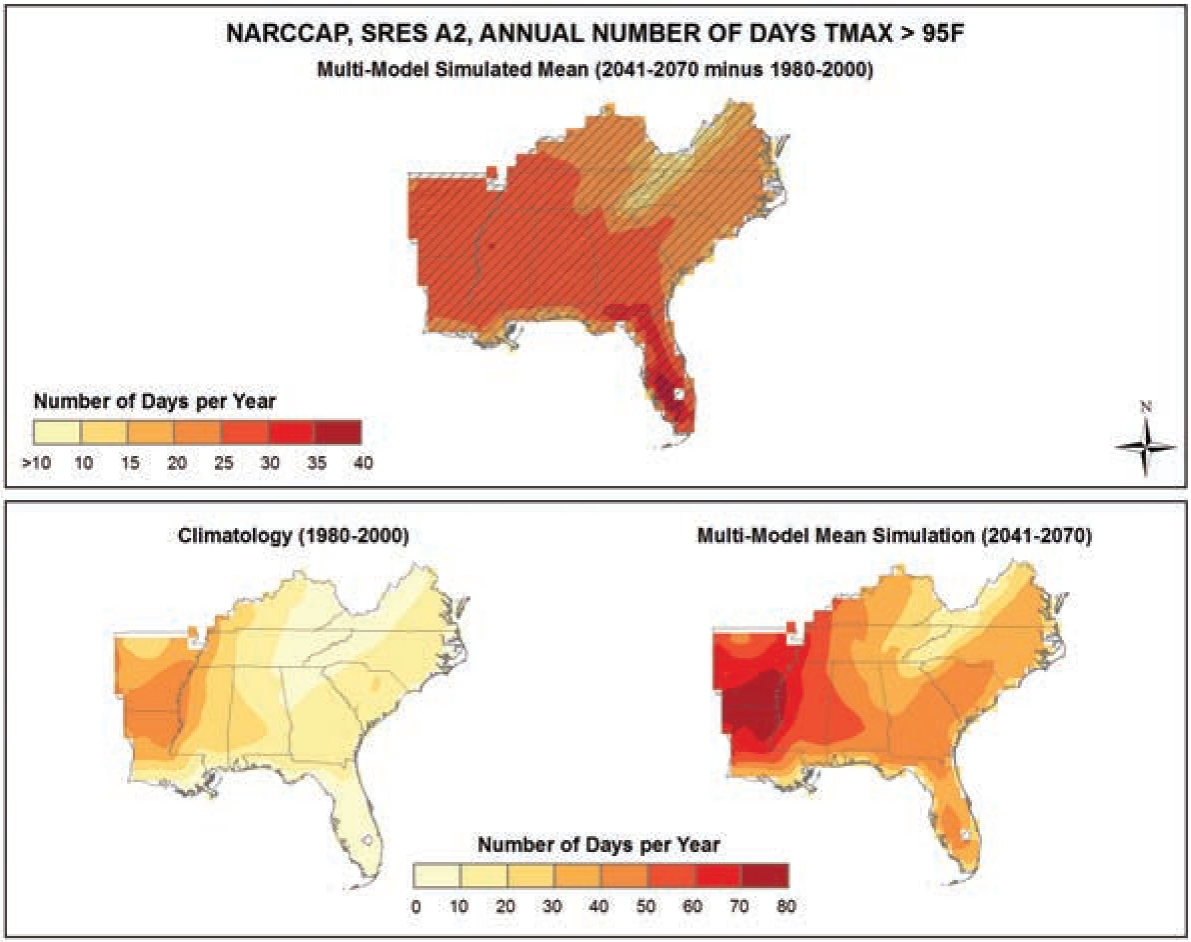


Figure 2.12 Mean change in annual number of days with a maximum temperature exceeding 95°F (projections for 2041–2070 and baseline of 1980–2000). Areas with hatching indicate more than 50% of the models show a statistically significant change in the number of days with a maximum temperature exceeding 95°F, and more than 67% of the models agree on the sign of the change (see Kunkel et al. 2013). Source: North American Regional Climate Change Assessment Program (NARCCAP).

base of 50°F) is expected to increase by nearly 25%. Depending on the model and emissions scenario, the number of heating degree days in expected to decrease by 19% to 23%, while the number of cooling degree days is expected to increase by 42% to 49% by the mid-21st century (see Table 5 in Kunkel et al. 2013). The areas expected to have a larger increase in cooling degree days (e.g., south Florida and the northern Gulf Coast) will have a smaller increase in heating degree days, and vice versa.

Projections of mean annual and seasonal temperature variability across the SE were calculated for each future period (2035, 2055, and 2085) using monthly data from CMIP3 for the high (A2) emissions scenario (see Kunkel et al. 2012). Variability in these projections is defined as the standard deviation of mean annual or seasonal temperature. Secular changes in the temperature variability are calculated as a percent change

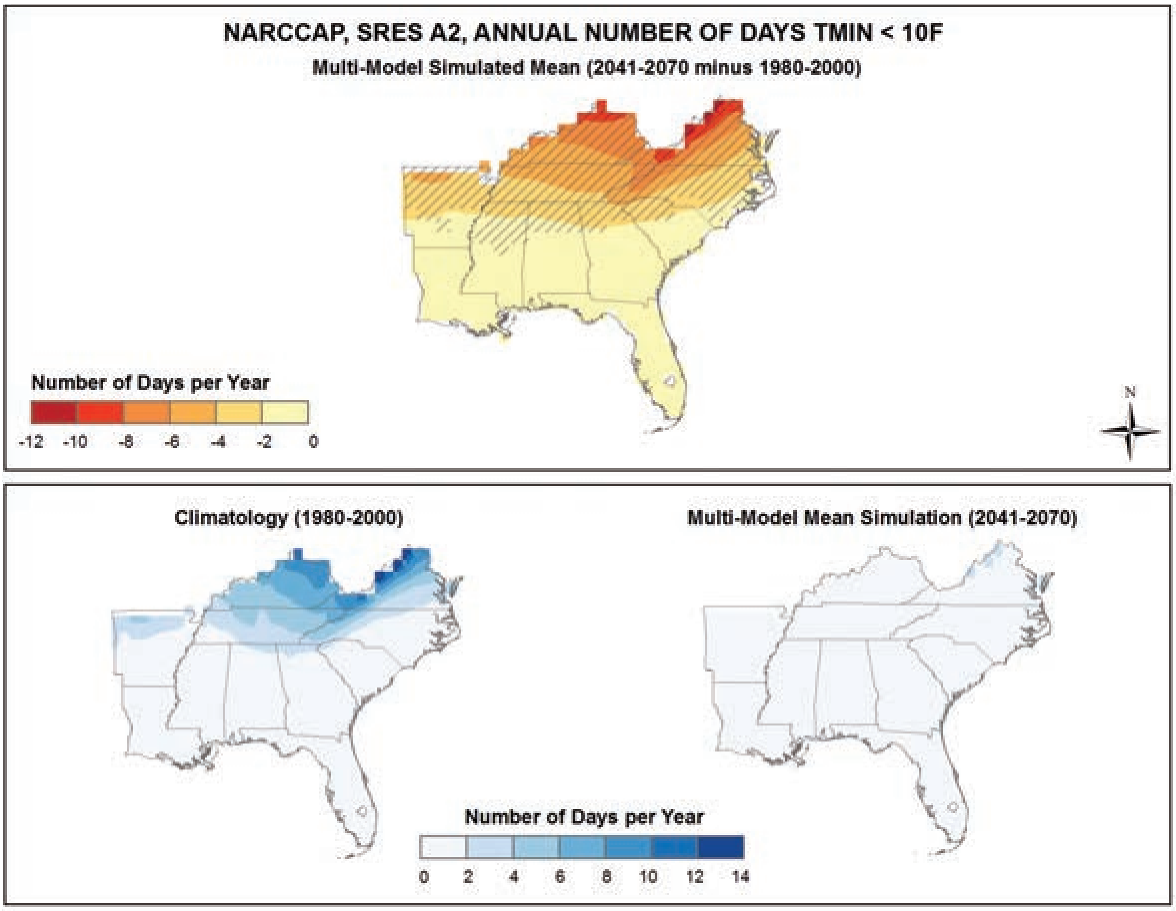


Figure 2.13 Mean change in annual number of days with minimum temperatures below 10°F (projections for 2041–2070 and baseline of 1980–2000). Areas with hatching indicate more than 50% of the models show a statistically significant change in the number of days with a maximum temperature exceeding 95°F, and more than 67% of the models agree on the sign of the change (see Kunkel et al. 2013). Source: North American Regional Climate Change Assessment Program (NARCCAP).

in standard deviation between the future periods and a 1971 to 2000 baseline period. The models reveal a trend of increasing annual variability of temperature across all periods in the future, especially the latter 21st century. Projections of temperature variability at the seasonal scale, however, are more varied. Small changes of less than 5% are seen during winter and spring, while summer exhibits the greatest increase in variability of 24% by the end of the 21st century.

A comparison between model simulations and observations of 20th century mean annual temperatures across the SE shows that the models do capture the observed rate of warming since the 1960s. However, the models currently do not simulate interdecadal variability, which is a key aspect of the observed temperature record across the SE region. Specifically, the rate of warming from 1900 to the 1930s as well as the rate of cooling from the 1930s to the 1960s was not simulated by any of the CMIP3 models

(Figure 2.14). Moreover, while the rate of warming since the 1960s was captured by the models, the observed decadal temperatures during this period were slightly cooler than those reproduced by the models. For the winter and summer seasons, observed temperatures in the 1930s are higher than any model simulation, while observed temperatures in the 1960s and 1970s are lower than any model simulation. Observed spring and fall temperatures generally fall within the envelope of the model simulations and do not show a marked change in temperature over the 20th century.

Droughts

Hydrological drought is expected to increase in frequency and intensity across most of the country through the end of the 21st century (Strzepek et al. 2010, Wehner et al. 2011, Dai 2011). Across the Southeast, some models project a greater likelihood of increased drought across the lower Mississippi River Valley and Gulf Coast, with fewer droughts across the northern tier of the region and in the mid-Atlantic (Strzepek et al. 2010). While this is shown across a range of higher greenhouse gas emissions scenarios, there is much uncertainty because of variations in the projections of future precipitation patterns and evaporation rates across the region (Seager et al. 2009), as well as model deficiencies in simulating many of the atmospheric processes that contribute to drought, particularly ENSO (Dai 2011).

Severe Thunderstorms and Tornadoes

Future projections in the frequency and intensity of severe thunderstorms and tornadoes are uncertain. This is especially the case for tornadoes, which cannot be resolved by global or regional climate models (Diffenbaugh et al. 2008). Severe thunderstorms, including those that produce tornadoes, require large amounts of convective available potential energy (CAPE), which is tied to atmospheric warming and moistening. CAPE is projected to increase throughout the 21st century, thereby providing additional energy for severe thunderstorms (Trapp et al. 2007). However, global climate model simulations indicate significant inter-annual variability in CAPE due to internal climate dynamics, such as ENSO (Marsh et al. 2007). Tornadoes also require strong vertical

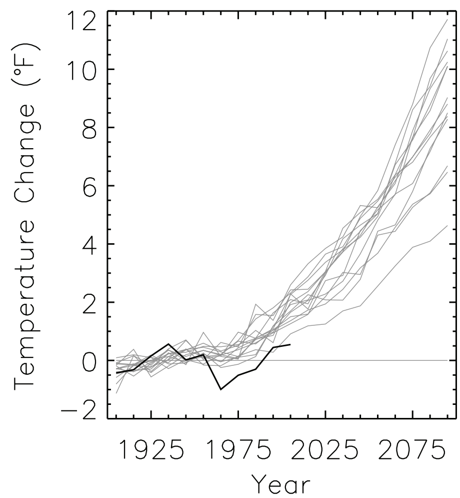


Figure 2.14 Observed decadal mean annual temperature change (percent change from the 1901 to 2000 average) for the southeastern USA (black lines) and the 20th and 21st century simulations from 15 CMIP3 models for the high (A2) emissions scenario (gray lines). *Kunkel et al. (2013), Figure 43.*

wind shear, but this is projected to decrease over much of the mid-latitudes due to a weakening of the pole-to-equator temperature gradient (Diffenbaugh et al. 2008).

Hurricanes

Recent modeling studies suggest that the frequency of major hurricanes (Categories 3 to 5) likely will increase in the future, while the overall number of tropical cyclones will likely decrease (Bender et al. 2010, Knutson et al. 2010). These studies project the greatest increase in major hurricanes over the western Atlantic basin, where increases in SSTs and decreases in vertical wind shear are expected (Wu and Tao 2011). Conversely, hurricane frequency is projected to decrease in the Caribbean and Gulf of Mexico sub-basins due to increased vertical wind shear (Biasutti et al. 2009, Bender et al. 2010). The observed positive trend in sea surface temperatures (Trenberth 2005), which may be partly attributed to anthropogenic forcings (Mann and Emanuel 2006), has been strongly correlated with hurricane intensity in the Atlantic basin (Emanuel 2005, Webster et al. 2005). However, no definitive connections have been established between greenhouse gas emissions and hurricane activity (Pielke et al. 2005).

Sea Level Rise and Sea Surface Temperatures

The southeastern region displays an extensive and complex coastline that is especially vulnerable to sea level rise. As the sea level rises, storm surge and coastal erosion from tropical cyclones and other extreme events will likely increase in magnitude. A recent report on sea level rise describes several global scenarios that project a mean rise of between 20 and 200 cm by the end of the 21st century (Parris et al. 2012). The high scenarios (120 to 200 cm) were based on recent trends of sea level rise revealed from tidal gauge and satellite records as well as revised assumptions and projections of rapid ice sheet loss. The low scenarios (20 to 60 cm) are in line with past projections from the IPCC AR4 and are based on an extrapolation of the trend over the tidal gauge record without additional sea level rises from a rapid ice sheet loss. Any additional rise from a rapid dynamic melting episode of the Greenland or West Antarctic ice could result in complete inundation of various low-lying areas in the Caribbean and the SE coast, including the northern Gulf Coast and southeastern Florida (Heimlich et al. 2009, Milliken et al. 2008, Mitchum et al. 2010). Of particular importance to coastal communities and ecosystems is the rise in relative sea level, which accounts for changes in ocean volume and land motion. For example, coastal areas currently subsiding due to natural and human-induced processes (e.g., groundwater extraction, sediment redistribution), including portions of the northern Gulf Coast, will be most affected by sea level rise (Ericson et al. 2006). Since the historical mean rate of sea level rise across the SE is generally consistent with the mean global rate, the projected global sea level rise scenarios in Parris et al. (2012) may apply across the SE. However, relative changes in contributions from land motion and ice sheet melting may alter this relationship (Mitchum 2011).

North Atlantic sea surface temperatures are expected to increase by the end of the 21st century, with the greatest increases (3°C) noted in a region extending eastward across the subtropics from South Florida and the Bahamas. Smaller increases are projected across the higher latitudes of the North Atlantic as well as the Caribbean Sea and Gulf of Mexico (Biasutti et al. 2009, Leloup and Clement 2009). However, there is significant uncertainty in SST projections in these regions, as recent studies indicate significant model errors and biases in the IPCC AR4 projections, for instance, a cold bias in sea surface temperatures across the Gulf of Mexico (Richer and Xie 2008, Misra et al. 2009).

Air Quality

Poor air quality, especially high ozone levels, is known to be harmful to ecosystems, agriculture, and human health. Atmospheric conditions that promote poor air quality—such as increased temperatures, increased solar radiation, reduced precipitation, increased air stagnation, and decreased atmospheric ventilation—are expected to become more frequent across the western and southern USA by the mid-21st century (Leung and Gustafson 2005). By the mid-21st century, average summer season ground-level ozone concentrations are projected to increase by 4.5 to 7.5 ppb across the northern tier of the region, with locations along the Ohio River and in the vicinity of Atlanta, GA, exhibiting increases of as much as 12 ppb (Hogrefe et al. 2004). Conversely, projections of summer season ozone concentrations in the southern tier of the region are projected to show little change (Hogrefe et al. 2004). However, it is probable that future changes in ozone concentrations may be driven as much or more by mitigation practices than by changes in atmospheric conditions.

2.5 References

Ashley, W.S. 2007. Spatial and temporal analysis of tornado fatalities in the United States: 1880-2005. *Weather and Forecasting* 22 (6): 1214-1228.

Ashley, S.T. and W.S. Ashley. 2008. Flood fatalities in the United States. *Journal of Applied Meteorology and Climatology* 47 (3): 805-818.

Ashley, W.S. and C.W. Gilson. 2009. A reassessment of U.S. lightning mortality. *Bulletin of the American Meteorological Society* 90 (10): 1501-1518.

Ashley, W.S., A.J. Krmenec, R. Schwantes. 2008. Vulnerability due to nocturnal tornadoes. *Weather and Forecasting* 23 (5): 795-807.

Bender, M.A., T.R. Knutson, R.E. Tuleya, J.J. Sirutis, G.A. Vecchi, S.T. Garner, I.M. Held. 2010. Modeled impact of anthropogenic warming on the frequency of intense Atlantic hurricanes. *Science* 327 (5964): 454-458.

Biasutti, M., A.H. Sobel, S.J. Camargo, T.T. Creyts. 2009. Projected changes in the physicalclimate of the Gulf Coast and Caribbean. *Climatic Change* 112: 819-845.Blake, E.S., C.W. Landsea, E.J. Gibney. 2011. The deadliest, costliest, and most intense United States tropical cyclones from 1851 to 2010. NOAA Technical Memorandum NWS NHC-6. http://www.nhc.noaa.gov/pdf/nws-nhc-6.pdf

Brooks, H. E. and C. A. Doswell III. 2001. Some aspects of the international climatology of tornadoes by damage classification. *Atmospheric Research* 56 (January): 191-201.

Brooks, H.E., C.A. Doswell, M.P. Kay. 2003. Climatological estimates of local daily tornado probability for the United States. *Weather and Forecasting* 18 (4): 626-640.

Budikova, D. 2008. Effect of the Arctic Oscillation on precipitation in the Eastern USA during ENSO winters. *Climate Research* 37 (1): 3-16.

Campbell, J.D., M.A. Taylor, T.S. Stephenson, R.A. Watson, F.S. Whyte. 2011. Future climate of the Caribbean from a regional climate model. *International Journal of Climatology* 31 (12): 1866-1878.

Carbone, G., J. Rhee, H. Mizzell, R. Boyles. 2008. A regional-scale drought monitoring tool for the Carolinas. *Bulletin of the American Meteorological Society* 89 (1): 20-28.

Changnon, S.A. 1999. Impacts of 1997-98 El Nino-generated weather in the United States. *Bulletin of the American Meteorological Society* 80 (9): 1819-1828.

Changnon, S.A. and T.R. Karl. 2003. Temporal and spatial variations of freezing rain in the contiguous United States: 1948-2000. *Journal of Applied Meteorology and Climatology* 42 (9): 1302-1315.

Changnon, S.A., D. Changnon, T.R. Karl. 2006. Temporal and spatial characteristics of snowstorms in the contiguous United States. *Journal of Applied Meteorology and Climatology* 45 (8): 1141-1155.

Chen, Q., L. Wang, R. Tawes. 2008. Hydrodynamic response of Northeastern Gulf of Mexico to hurricanes. *Estuaries and Coasts* 31 (6): 1098-1116.

Christy, J.R. 2002. When was the hottest summer? A state climatologist struggles for an answer. *Bulletin of the American Meteorological Society* 83 (5): 723-734.

Christy, J.R., W.B. Norris, K. Redmond, K.P. Gallo. 2006. Methodology and results of calculating Central California surface temperature trends: Evidence of human-induced climate change? *Journal of Climate* 19 (4): 548-563.

Church, J., T. Aarup, P.L. Woodworth, W.S. Wilson, R.J. Nicholls, R. Rayner, K. Lambeck, G.T. Mitchum, K. Steffen, A. Cazenave, G. Blewitt, J.X. Mitrovica, J.A. Lowe. 2010. Sea-level rise and Variability: Synthesis and Outlook for the Future. In *Understanding Sea-level Rise and Variability*, ed. J.A. Church, P.L. Woodworth, T. Aarup and W.S. Wilson, 402-419. London: Wiley-Blackwells Publishing.

Church, J. A. and N.J. White. 2011. Sea-level rise from the late 19th to the early 21st century. *Surveys in Geophysics*, doi:10.1007/s10712-011-9119-1.

Curtis, S. 2008. The Atlantic multidecadal oscillation and extreme daily precipitation over the U.S. and Mexico during the hurricane season. *Climate Dynamics* 30 (4): 343-351.

Dai, A. 2011. Drought under global warming: A review. *Wiley Interdisciplinary Reviews: Climate Change* 2(1): 45-65.

DeGaetano, A.T. and R.J. Allen. 2002. Trends in twentieth-century temperature extremes across the United States. *Journal of Climate* 15 (22): 3188-3205.

Deser, C., A.S. Phillips, M.A. Alexander. 2010. Twentieth century tropical sea surface temperature trends revisited. *Geophysical Research Letters* 37, L10701; doi:10.1029/2010GL043321.

Diffenbaugh, N.S., and M. Ashfaq. 2010. Intensification of hot extremes in the United States. *Geophysical Research Letters* 37, L15701; doi:10.1029/2010GL043888.

Diffenbaugh, N.S., R.J. Trapp, H. Brooks. 2008. Does global warming influence tornado activity? EOS, *Transactions, American Geophysical Union* 89 (53): 553-560.

Dixon, P.G., A.E. Mercer, J. Choi, J.S. Allen. 2011. Tornado risk analysis – Is Dixie Alley an extension of Tornado Alley? *Bulletin of the American Meteorological Society* 92 (4): 433-441.

Domingues, C.M., J.A. Church, N.J. White, P.J. Glecker, S.E. Wijffels, P.M. Barker, J.R. Dunn. 2008. Improved estimates of upper-ocean warming and multi-decadal sea-level rise. *Nature* 453 (7198): 1090-1093.

Doublin, J. and A. Grundstein. 2008. Warm season soil moisture deficits in the Southern United States. *Physical Geography* 29 (1): 3-18.

Downton, M.W. and K.A. Miller. 1993. The freeze risk to Florida citrus. Part II: Temperature variability and circulation patterns. *Journal of Climate* 6 (2): 364-372.

Durkee, J.D., J.D. Frye, C.M. Fuhrmann, M.C. Lacke, H.G. Jeong, T.L. Mote. 2007. Effects of the North Atlantic Oscillation on precipitation-type frequency and distribution in the Eastern United States. *Theoretical and Applied Climatology* 94 (1-2): 51-65.

Ericson, J.P., C.J. Vorosmarty, S.L. Dingman, L.G Ward, M. Meybeck. 2006. Effective sea-level rise and deltas: Causes of change and human dimension implications. *Global and Planetary Change* 50 (1-2): 63-82.

Fuhrmann, C.M., C.E. Konrad II, L.E. Band. 2008. Climatological perspectives on the rainfall characteristics associated with landslides in Western North Carolina. *Physical Geography* 29 (4): 289-305.

Fuhrmann, C.M., C.E. Konrad II, M.M. Kovach, D.J. Perkins. 2011. The August 2007 heat wave in North Carolina: Meteorological factors and local variability. *Physical Geography* 32 (3): 217-240.

Fye, F.K., D.W. Stahle, E.R. Cook. 2003. Paleoclimatic analogs to twentieth-century moisture regimes across the United States. *Bulletin of the American Meteorological Society* 84 (7): 901-909.

Gamble, D.W., D.B. Parnell, S. Curtis. 2008. Spatial variability of the Caribbean mid-summer drought and relation to the North Atlantic high circulation. *International Journal of Climatology* 28 (3): 343-350.

Goto-Maeda, Y., D.W. Shin, J.J. O'Brien. 2008. Freeze probability of Florida in a regional climate model and climate indices. *Geophysical Research Letters* 35, L11703; doi:10.1029/2008GL033720.

Groisman, P.Y. and R.W. Knight. 2008. Prolonged dry episodes over the conterminous United States: New tendencies emerging during the last 40 years. *Journal of Climate* 21 (9): 1850-1862.

Hawkins, E. and R. Sutton. 2009. The potential to narrow uncertainty in regional climate predictions. *Bulletin of the American Meteorological Society* 90 (8): 1095-1107.

Heimlich, B.N., F. Bloetscher, D.E. Meeroff, and J. Murley. 2009. Southeast Florida's resilient water resources: adaptation to sea level rise and other climate change impacts. Florida Atlantic University, Center for Urban and Environmental Solutions. Fort Lauderdale, FL. http://www.ces.fau.edu/files/projects/climate_change/SE_Florida_Resilient_Water_Resources.pdf

Hirsch, R.M. and K.R. Ryberg. 2011. Has the magnitude of floods across the USA changed with global CO2 levels? *Hydrological Sciences Journal* 57 (1): 1-9.

Hogrefe, C., B. Lynn, K. Civerolo, J.Y. Ku, J. Rosenthal, C. Rosenzweig, R. Goldberg, S. Gaffin, K. Knowlton, P.L. Kinney. 2004. Simulating changes in regional air quality over the Eastern United States due to changes in global and regional climate and emissions. *Journal of Geophysical Research* 109, D22301; doi:10.1029/2004JD004690.

Holland, G.J., and P.J. Webster. 2007. Heightened tropical cyclone activity in the North Atlantic: Natural variability or climate trend? *Philosophical Transactions of the Royal Society-Mathematical, Physical, and Engineering Sciences* 365 (1860): 2695-2716.

IPCC. 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Ed. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller. New York and United Kingdom: Cambridge University Press.

Irish, J.L., D.T. Resio, J.J. Ratcliff. 2008. The influence of storm size on hurricane surge. *Journal of Physical Oceanography* 38 (9): 2003-2013.

Jones, K.F., A.C. Ramsay, J.N. Lott. 2004. Icing severity in the December 2002 freezing-rain storm from ASOS data. *Monthly Weather Review* 132 (7): 1630-1644.

Jury, M.R. and A. Winter. 2009. Warming of an elevated layer over the Caribbean. *Climatic Change* 99 (1-2): 247-259.

Jury, M.R., B.A. Malmgren, A. Winter. 2007. Subregional precipitation climate of the Caribbean and relationships with ENSO and NAO. *Journal of Geophysical Research* 112, D16107; doi:10.1029/2006JD007541.

Kangas, R.S. and T.J. Brown. 2007. Characteristics of U.S. drought and pluvials from a high-resolution spatial dataset. *International Journal of Climatology* 27 (10): 1303-1325.

Keim, B.D. 1996. Spatial, synoptic, and seasonal patterns of heavy rainfall in the Southeastern United States. *Physical Geography* 17 (4): 313-328.

Keim, B.D., R.A. Muller, G.W. Stone. 2007. Spatiotemporal patterns and return periods of tropical storms and hurricane strikes from Texas to Maine. *Journal of Climate* 20 (14): 3498-3509.

Keim, B.D., R. Fontenot, C. Tebaldi, D. Shankman. 2011. Hydroclimatology of the U.S. Gulf Coast under global climate change scenarios. *Physical Geography* 32 (6): 561-582.

Kilbourne, K.H., T.M. Quinn, R. Webb, T. Guilderson, J. Nyberg, A. Winter. 2008. Paleoclimate proxy perspective on Caribbean climate since the year 1751: Evidence of cooler temperatures and multidecadal variability. *Paleoceanography* 23, PA3220; doi:10.1029/2008PA001598.

Kilbourne, K.H., T.M. Quinn, R. Webb, T. Guilderson, J. Nyberg, A. Winter. 2010. Coral windows onto seasonal climate variability in the northern Caribbean since 1479. *Geochemistry, Geophysics, Geosystems* 11 (10): doi:10.1029/2010GC003171.

Klotzbach, P.J. 2006: Trends in global tropical cyclone activity over the past twenty years (1986-2005). *Geophysical Research Letters* 33; doi:10.1029/2006GL025881.

Klotzbach, P.J. 2011. El Nino-Southern Oscillation's impact on Atlantic basin hurricanes and U.S. landfalls. *Journal of Climate* 24 (4): 1252-1263.

Knight, D.B. and R.E. Davis. 2007. Climatology of tropical cyclone rainfall in the southeastern United States. *Physical Geography* 28 (2): 126-147.

Knight, D.B. and R.E. Davis. 2009. Contribution of tropical cyclones to extreme rainfall events in the Southeastern United States. *Journal of Geophysical Research-Atmospheres* 114, D23102.

Knutson, T.R., J.L. McBride, J. Chan, K. Emanuel, G. Holland, C. Landsea, I. Held, J.P. Kossin, A.K. Srivastava, M. Sugi. 2010. Tropical cyclones and climate change. *Nature Geoscience* 3 (February): 157-163.

Konrad, C.E. and L.B. Perry. 2010. Relationships between tropical cyclones and heavy rainfall in the Carolina region of the United States. *International Journal of Climatology* 30 (4): 522-534.

Kruk, M.C., E.J. Gibney, D.H. Levinson, M. Squires. 2010. A climatology of inland winds from tropical cyclones for the Eastern United States. *Journal of Applied Meteorology and Climatology* 49 (7): 1538-1547.

Kumar, A., F. Yang, L. Goddard, S. Schubert. 2004. Differing trends in the tropical surface temperatures and precipitation over land and oceans. *Journal of Climate* 17 (3): 653-664.

Kunkel, K.E., D.R. Easterling, K. Redmond, K. Hubbard. 2003. Temporal variations of extreme precipitation events in the United States: 1895-2000. *Geophysical Research Letters* 30; doi: 10.1029/2003GL018052.

Kunkel, K.E., X.Z. Liang, J. Zhu, Y. Lin. 2006. Can GCMs simulate the twentieth-century "warming hole" in the Central United States? *Journal of Climate* 19 (17): 4137-4153.

Kunkel, K.E., M. Palecki, L. Ensor, K.G. Hubbard, D. Robinson, K. Redmond, D. Easterling. 2009. Trends in twentieth-century U.S. snowfall using a quality-controlled dataset. *Journal of Atmospheric and Oceanic Technology* 26 (1): 33-44.

Kunkel, K.E., L.E. Stevens, S.E. Stevens, L. Sun, E. Janssen, D. Weubbles, C.E. Konrad, C.M. Fuhrmann, B.D. Keim, M.C. Kruk, A. Billot, H. Needham, M. Shafer, and J.G. Dobson. 2013. Regional Climate Trends and Scenarios for the U.S. National Climate Assessment. Part 2: Climate of the Southeast United States. NOAA Technical Report NESDIS 142-2.

Landsea, C.W. 2007. Counting Atlantic tropical cyclones back to 1900. EOS, *Transactions, American Geophysical Union* 88 (18): 197-208.

Landsea, C.W., C. Anderson, N. Charles, G. Clark, J. Dunion, J. Fernandez-Partagas, P. Hungerford, C. Neumann, M. Zimmer. 2004. The Atlantic Hurricane Database Re-analysis Project: Documentation for 1851-1910 Alterations and Additions to the HURDAT Database. In *Hurricanes and Typhoons: Past, Present and Future*, ed. R.J. Murnane and K-B Liu. New York: Columbia University Press.

Landsea, C.W., G.A. Vecchi, L. Bengtsson, T.R. Knutson. 2010. Impact of duration thresholds on Atlantic tropical cyclone counts. *Journal of Climate* 23 (10): 2508-2519.

Lee, S-K, D.B. Enfield, C. Wang. 2011. Future impact of differential interbasin ocean warming on Atlantic hurricanes. *Journal of Climate* 24 (4): 1264-1275.

Leloup, J. and A. Clement. 2009. Why is there a minimum in projected warming in the tropical North Atlantic Ocean? *Geophysical Research Letters* 36, L14802; doi:10.1029/2009GL038609.

Leung, L.R. and W.I. Gustafson. 2005. Potential regional climate change and implications to USA air quality. *Geophysical Research Letters* 32, L16711; doi:10.1029/2005GL022911.

Li, L., L. Wenhong, Y. Kushnir. 2011. Variation of the North Atlantic subtropical high western ridge and its implication to Southeastern U.S. summer precipitation. *Climate Dynamics* doi:10.1007/s00382-011-1214-y.

Lirman, D., S. Schopmeyer, D. Manzello, L.J. Gramer, W.F. Precht, F. Muller-Karger, K. Banks, B. Barnes, E. Bartels, A. Bourque, J. Byrne, S. Donahue, J. Duquesnel, L. Fisher, D. Gilliam, J. Hendee, M. Johnson, K. Maxwell, E. McDevitt, K. Monty, D. Rueda, R. Ruzicka, S. Thanner. 2011. Severe 2010 cold-water event caused unprecedented mortality to corals of the Florida Reef Tract and reversed previous survivorship patterns. *PLoS ONE* 6 (8)

Malmgren, B.A., A. Winter, D. Chen. 1998. El Nino-Southern Oscillation and North Atlantic Oscillation control of climate in Puerto Rico. *Journal of Climate* 11 (10): 2713-2717.

Mann, M.E. and K.A. Emanuel. 2006. Atlantic hurricane trends linked to climate change. *EOS, Transactions, American Geophysical Union* 87 (24): 197-208.

Mann, M.E., J.D. Woodruff, J.P. Donnelly, Z. Zhang. 2009. Atlantic hurricanes and climate over the past 1,500 years. *Nature* 460 (7257): 880-885.

Manuel, J. 2008. Drought in the Southeast: Lessons for water management. *Environmental Health Perspectives* 116 (4): A168-A171.

Marsh, P.T., H.E. Brooks, D.J. Karoly. 2007. Assessment of the severe weather environment in North America simulated by a global climate model. *Atmospheric Science Letters* 8 (4): 100-106.

Marshall, C.H., R.A. Pielke, L.T. Stewart. 2004. Has the conversion of natural wetlands to agricultural land increased the incidence and severity of damaging freezes in South Florida? *Monthly Weather Review* 132 (9): 2243-2258.

Marshall, C.H., R.A. Pielke, L.T. Steyaert, D.A. Willard. 2004. The impact of anthropogenic land-cover change on the Florida Peninsula sea breezes and warm season sensible weather. *Monthly Weather Review* 132 (1): 28-52.

Maue, R.N. 2011. Recent historically low global tropical cyclone activity. *Geophysical Research Letters* 38, L14803; doi:10.1029/2011GL047711.

Maxwell, J.T., P.T. Soule, J.T. Ortegren, P.A. Knapp. 2011. Drought-busting tropical cyclones in the Southeastern Atlantic United States: 1950-2008. *Annals of the Association of American Geographers* 102 (2): 1-17.

Milliken, K.T., J.B. Anderson, A.B. Rodriguez. 2008. A new composite Holocene sea-level curve for the northern Gulf of Mexico. In *Response of Upper Gulf Coast Estuaries to Holocene Climate Change and Sea-level Rise*, ed. Anderson, J.B. and A.B. Rodriguez, Special Paper 443, 1-11. Colorado: Geological Society of America.

Misra, V., S. Chan, R. Wu, E. Chassignet. 2009. Air-sea interaction over the Atlantic warm pool in the NCEP CFS. *Geophysical Research Letters* 36, L15702; doi:10.1029/2009GL038525.

Misra, V., L. Moeller, L. Stefanova, S. Chan, J.J. O'Brien, T.J. Smith, N. Plant. 2011. The influence of the Atlantic warm pool on the Florida panhandle sea breeze. *Journal of Geophysical Research* 116; doi:10.1029/2010JD015367.

Mitchum, G. (2011). Sea level changes in the southeastern United States – Past, present and future. Florida Climate Institute and the Southeast Climate Consortium. www.seclimate.org/pdfpubs/201108mitchum_sealevel.pdf

Mitchum, G.T., R.S. Nerem, M.A. Merrifield, R. Gehrels. 2010. 20th Century sea level change estimates from tide gauges and altimeters. In *Understanding Sea-level Rise and Variability*, ed. J.A. Church, P.L. Woodworth, T. Aarup and W.S. Wilson. London: Wiley-Blackwells Publishing.

Mo, K.C., K.E. Schemm, S.H. Yoo. 2009. Influence of ENSO and the Atlantic Multidecadal Oscillation on drought over the United States. *Journal of Climate* 22 (22): 5962-5982.

National Climatic Data Center (NCDC). 2011. Billion dollar USA Weather/Climate Disasters http://www.ncdc.noaa.gov/oa/reports/billionz.html

Needham, H.F. and B.D. Keim. 2011. A storm surge database for the US Gulf Coast. *International Journal of Climatology*, doi:10.1002/joc.2425.

New, M., M. Todd, M. Hulme, P. Jones. 2001. Precipitation measurements and trends in the twentieth century. *International Journal of Climatology* 21 (15): 1889-1922.

Nyberg, J., B.A. Malmgren, A. Winter, M.R. Jury, K.H. Kilbourne, T.M. Quinn. 2007. Low Atlantic hurricane activity in the 1970s and 1980s compared to the past 270 years. *Nature* 447 (7145): 698-701.

Ortegren, J.T., P.A. Knapp, J.T. Maxwell, W.P. Tyminski, P.T. Soule. 2011. Ocean-atmosphere influences on low-frequency warm-season drought variability in the Gulf Coast and Southeastern United States. *Journal of Applied Meteorology and Climatology* 50 (6): 1177-1186.

Pan, Z., R.W. Arritt, E.S. Takle, W.J. Gutowski, C.J. Anderson, M. Segal. 2004. Altered hydrologic feedback in a warming climate introduces a "warming hole". *Geophysical Research Letters* 31, L17109; doi:10.1029/2004GL020528.

Parris, A., P. Bromirski, V. Burkett, D. R. Cayan, M. Culver, J. Hall, R. Horton, K. Knuuti, R. Moss, J. Obeysekera, A. Sallenger, J. Weiss. 2012. Global Sea Level Rise Scenarios for the United States National Climate Assessment. NOAA, U.S. National Oceanic and Atmospheric Administration, Silver Spring, MD. (in press).

Perry, L.B., C.E. Konrad, D.G. Hotz, L.G. Lee. 2010. Synoptic classification of snowfall events in the Great Smoky Mountains, USA. *Physical Geography* 31 (2): 156-171.

Pielke, R.A., C. Landsea, M. Mayfield, J. Laver, R. Pasch. 2005. Hurricanes and global warming. *Bulletin of the American Meteorological Society* 86 (11): 1571-1575.

Portmann, R.W., S. Solomon, G.C. Hegerl. 2009. Spatial and seasonal patterns in climate change, temperatures, and precipitation across the United States. *Proceedings of the National Academies of Science* 106 (18): 7324-7329.

Prandi, P., A. Cazenave, M. Becker. 2009. Is coastal mean sea level rising faster than the global mean? A comparison between tide gauges and satellite altimetry over 1993-2007. *Geophysical Research Letters* 36, L05602; doi:10.1029/2009GL036564

Pritchard, H.D., R.J. Arthern, D.G. Vaughan, L.A. Edwards. 2009. Extensive dynamic thinning on the margins of the Greenland and Antarctic ice sheets. *Nature* 461 (7266): 971-975.

Puma, M.J. and B.I. Cook. 2010. Effects of irrigation on global climate during the 20th century. *Journal of Geophysical Research–Atmospheres* 115; doi:10.1029/2010JD014122.

Rappaport, E.N. 2000. Loss of life in the United States associated with recent Atlantic tropical cyclones. *Bulletin of the American Meteorological Society* 81 (9): 2065-2074.

Rauscher, S.A., F. Giorgi, N. Diffenbaugh, A. Seth. 2008. Extension and intensification of the Meso-American mid-summer drought in the twenty-first century. *Climate Dynamics* 31 (5): 551-571.

Rauscher, S.A., F. Kucharski, D.B. Enfield. 2011. The role of regional SST warming variations in the drying of Meso-America in future climate projections. *Journal of Climate* 24 (7): 2003-2016.

Richer, I. and S.P. Xie. 2008. On the origin of equatorial Atlantic biases in coupled general circulation models. *Climate Dynamics* 31 (5): 587-598.

Robinson, W.A., R. Reudy, J.E. Hansen. 2002. General circulation model simulations of recent cooling in the east-central United States. *Journal of Geophysical Research–Atmospheres* 107 (4748); doi:10.1029/2001JD001577.

Rogers, J.C. and R.V. Rohli. 1991. Florida citrus freezes and polar anticyclones in the Great Plains. *Journal of Climate* 4 (11): 1103-1113.

Seager, R., Y. Kushnir, J. Nakamura, M. Ting, N. Naik. 2010. Northern hemisphere winter snow anomalies: ENSO, NAO, and the winter of 2009/10. *Geophysical Research Letters* 37, L14703; doi:10.1029/2010GL043830.

Seager, R., A. Tzanova, J. Nakamura. 2009. Drought in the southeastern United States: Causes, variability over the last millennium, and the potential for future hydroclimate change. *Journal of Climate* 22 (19): 5021-5045.

Shepherd, J.M., T.L. Mote, S. Nelson, S. McCutcheon, P. Knox, M. Roden, J. Dowd. 2011. An overview of synoptic and mesoscale factors contributing to the disastrous Atlanta flood of 2009. *Bulletin of the American Meteorological Society* 92 (7): 861-870.

Stahle, W.D. and M.K. Cleaveland. 1992. Reconstruction and analysis of spring rainfall over the Southeastern U.S. for the past 1000 years. *Bulletin of the American Meteorological Society* 73 (12): 1947-1961.

Stahle, D.W. and M.K. Cleaveland. 1994. Tree-ring reconstructed rainfall over the Southeastern USA during the Medieval warm period and Little Ice Age. *Climatic Change* 26 (2): 199-212.

Stahle, D.W., M.K. Cleaveland, D.B. Blanton, M.D. Therrell, D.A. Gay. 1998. The Lost Colony and Jamestown droughts. *Science* 280 (5363): 564-567.

Stahle, R.W., E.R. Cook, M.K. Cleaveland, M.D. Therrell, D.M. Meko, H.D. Grissino-Mayer, E. Watson, B.H. Luckman. 2000. Tree-ring data document 16th century megadrought over North America. *EOS, Transactions, American Geophysical Union* 81 (12): 121.

Stahle, R.W., F.K. Fye, E.R. Cook, R.D. Griffin. 2007. Tree-ring reconstructed megadroughts over North America since A.D. 1300. *Climatic Change* 83 (1-2): 133-149.

Stefanova, L., V. Misra, S. Chan, M. Griffin, J.J. O'Brien, T.J. Smith. 2011. A proxy for high-resolution regional reanalysis for the Southeast United States: Assessment of precipitation variability in dynamically downscaled reanalysis. *Climate Dynamics* 38 (11-12): 2449-2466.

Strzepek, K., G. Yohe, J. Neumann, B. Boehlert. 2010. Characterizing changes in drought risk for the United States from climate change. *Environmental Research Letters* 5 (4); doi:10.1088/1748-9326/5/4/044012.

Taylor, M.A. and E.J. Alfero. 2005. Climate of Central America and the Caribbean. In *Encyclopedia of World Climatology*, ed. J.E. Oliver. Springer Publishing.

Tedesco, M., J.E. Box, J. Cappellen, T. Mote, R.S.W. van de Wal, J. Wahr. 2012. (The Arctic) Greenland ice sheet. In State of the Climate in 2011. *Bulletin of the American. Meteorological Society* 93 (7): S134-S137.

Ting, M., Y. Kushnir, R. Seager, C. Li. 2009. Forced and internal 20th century SST trends in the North Atlantic. *Journal of Climate* 22 (6): 1469-1481.

Trapp, R.J., N.S. Diffenbaugh, H.E. Brooks, M.E. Baldwin, E.D. Robinson, J.S. Pal. 2007. Changes in severe thunderstorm environment frequency during the 21st century caused by anthropogenically enhanced global radiative forcing. *Proceedings of the National Academy of Sciences* 104 (5): 19719-19723.

Trenberth, K.E. 2005. Uncertainty in hurricanes and global warming. *Science* 308 (5729): 1753-1754.

Verbout, S.M., H.E. Brooks, L.M. Leslie, D.M. Schultz. 2006. Evolution of the USA tornado database: 1954-2003. *Weather and Forecasting* 21 (1): 86-93.

Wang, H., R. Fu, A. Kumar, W. Li. 2010. Intensification of summer rainfall variability in the southeastern United States during recent decades. *Journal of Hydrometeorology* 11 (4): 1007-1018.

Webster, P.J., G.J. Holland, J.A. Curry, H-R Chang. 2005. Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science* 309 (5742): 1844-1846.

Wehner, M., D.R. Easterling, J.H. Lawrimore, , R.R. Heim, , R.S. Vose, , B.D. Santer. 2011. Projections of future drought in the continental United States and Mexico. *Journal of Hydrometeorology* 12: 1359-1377.

Winter, A., T. Miller, Y. Kushnir, A. Sinha, A. Timmermann, M.R. Jury, C. Gallup, H. Cheng, R.L. Edwards. 2011. Evidence for 800 years of North Atlantic multidecadal variability from a Puerto Rican speleothem. *Earth and Planetary Science Letters* 308 (1-2): 23-28.

Wu, L.G. and L. Tao. 2011. A mechanism for long-term changes in Atlantic tropical cyclone intensity. *Climate Dynamics* 36 (9-10): 1851-1864.

Chapter 3

Human Health and Climate Change in the Southeast USA

COORDINATING AUTHOR

Paul J. Schramm (pschramm@cdc.gov; Climate and Health Program, National Center for Environmental Health, Centers for Disease Control and Prevention, Atlanta, Georgia)

CONTRIBUTING AUTHORS

Carina G.M. Blackmore (Department of Environmental and Global Health, University of Florida, Gainesville, Florida)

William Crosson (Universities Space Research Association, Huntsville, Alabama)

Christopher T. Emrich (Hazards and Vulnerability Research Institute, Department of Geography, University of South Carolina, Columbia, South Carolina)

Maury Estes (NASA, Huntsville, Alabama)

Michael Goodman (NASA, Huntsville, Alabama)

Erin K. Lipp (Department of Environmental Health Science, University of Georgia, Athens, Georgia)

Yang Liu (Rollins School of Public Health, Emory University, Atlanta, Georgia)

Glenn Morris (Emerging Pathogens Institute, University of Florida, Gainesville, Florida)

Richard P. Stumpf (National Ocean Service, NOAA, Silver Spring, Maryland)

Lauren Thie (Occupational and Environmental Epidemiology Branch, Division of Public Health, North Carolina Department of Health and Human Services, Raleigh, North Carolina)

Michelle C. Tomlinson (National Ocean Service, NOAA, Silver Spring, Maryland)

Acknowledgements

Thanks to Janet Gamble, Winston Liao, John Thayer, and Karin Yeatts for providing review comments.

Climate change is expected to have a broad impact on human health. This chapter discusses current and potential regional human health effects from climate change in seven major categories affecting the Southeast (SE): heat and cold; air quality and respiratory/airway diseases; storms, extreme weather, and sea-level rise; harmful algal blooms and marine toxins; vector-borne and zoonotic disease; water quality and quantity; and human migration/displacement and healthcare disruption. Health impacts in other areas, such as mental health and food security may also occur, but more research is needed to determine the potential effects in the SE.

Key Findings

- Higher ocean temperatures have already contributed to several outbreaks of harmful algal blooms and outbreaks of food-borne illnesses from marine toxins in shellfish.
- Rising air temperatures will worsen heat waves and increase levels of harmful pollutants such as ozone.
- Shifts in precipitation are expected to lead to more extreme precipitation events that can cause direct injury and other related health effects.
- Sea-level rise could impact human health by increasing storm surges and disrupting infrastructure and ecosystems.
- Vector-borne disease like dengue and malaria could be affected by rising temperatures and shifting precipitation patterns
- Water quality and quantity, which is already stressed, could be degraded

3.1 Climate Change and Human Health

Climate change is projected to affect human health in the Southeast (SE) USA in a variety of ways, both directly and indirectly. Increasing temperatures, shifts in weather patterns, and variations in sea level and water composition have the potential to exacerbate existing public health problems in the region while also leading to the introduction of novel diseases. The SE has a wide variety of ecosystems, ranging from the subtropical wetlands of the Everglades to the temperate forests of the Smoky Mountains, as well as diverse human development patterns including rural farmlands and large, dense cities. In addition, the SE experiences a wide range of weather events that can affect health and could be influenced by climate change. These factors complicate the assessment of climate-related health issues in the region.

Identifying the underlying health risks and vulnerabilities from climate change to the population of the SE is essential. By taking steps to reduce vulnerability to these events through improved monitoring, prediction, education, communication, engagement, and planning, the southeastern US can become more resilient to climate-related health impacts. Developing tools and products that translate weather and climate information into a form that is useful for public health can also help in managing and reducing vulnerability. There exists a dense network of weather stations in the SE, as well as a significant amount of health data from sources such as the North Carolina Disease

Event Tracking and Epidemiologic Collection Tool (NC DETECT), various Centers for Disease Control (CDC) tracking programs, and other federal, local, state, citizen-based and academic research programs. Opportunities to link disease surveillance systems with available climate and environmental data should be explored.

3.2 Heat and Cold

As a result of global climate change, global mean temperatures have been rising and are projected to continue rising. In the southeastern USA, average temperatures have already risen by 2°F since 1970, some areas more than others. Climate models project continued warming, with average annual temperatures rising by 4.5°F to as much as 9°F by the 2080s, depending on the emissions scenario used. Climate models project continued warming in all seasons across the SE and an increase in the rate of warming through the end of this century. Summer temperatures alone could rise by as much as 10.5°F on average (Karl et al. 2009). In addition, according to the 2000 National Climate Assessment the SE is expected to experience a greater increase in heat index than any other region of the country by 2100 (Burkett et al. 2001).

The negative relationship between increasing high temperatures and human health is well established, particularly the stresses on the cardiovascular, cerebral, and respiratory systems (Kovats and Hajat 2008, O'Neill and Ebi 2009). Extreme heat events cause more deaths annually in the US than all other extreme weather events combined (Luber 2008). In addition to the direct health effects from heat exposure, increasing temperatures can also exacerbate preexisting chronic conditions, like asthma, and contribute to formation of harmful air pollution and allergens (Portier et al. 2010). As with other USA regions, higher temperatures in the Southeast are expected to have an increasingly negative impact on human health.

Despite the increase in average temperatures in the SE over the past several decades, heat-related mortality overall has been decreasing. Improvements in health care and the prevalence of air-conditioning are likely the two main factors affecting the relationship between heat and mortality (Sheridan et al. 2009). Human biophysical acclimatization to higher temperatures in the region could also reduce mortality rates (Davis et al. 2003). However, the declining trend in heat-related mortality appeared to stabilize from the mid-1990s to the mid-2000s. Vulnerable and high-exposure populations such as the elderly, athletes, and outdoor laborers could be particularly at risk from increasing heat (Luber and McGeehin 2008), and population increase and demographic shifts in the SE could expand the vulnerable population in the future. For example, of 68 heat-related deaths among crop workers from 1992 to 2006 in the USA just under 30% occurred in the SE with 13 in North Carolina and 6 in Florida (MMWR 2008). Urban areas are also at risk, as several of the largest cities in the SE (Atlanta, Tampa, Miami, and New Orleans) have already seen significant increases in the number of hot days per year in which mean mortality is significantly above the summer baseline (Sheridan et al. 2009). Rising spring heat vulnerability was seen in Atlanta (Sheridan 2010). Increasing temperatures in the SE are projected to lead to increased ozone concentrations in the 19 largest urban areas in the region, causing an increase in mortality from exposure to harmful ozone levels and exacerbation of respiratory disease (Chang et al. 2010).

Expanding and improving the tracking and surveillance of heat-related illness can help to classify cases and allow planning for interventions to reduce the overall burden on the public health system. Improving education and communication, particularly among at-risk groups and communities, may best be accomplished through collaborative efforts between meteorologists and public health officials. Nationally, such efforts are underway between National Oceanic and Atmospheric Administration (NOAA) and the CDC, which recently signed a Memorandum of Understanding to help foster collaboration and connect climate data to health data. Moreover, designing and utilizing collaborative models for engaging at-risk citizens in building resilience to heat waves may prove an effective tool for reducing vulnerability and raising awareness to heat-related threats.

Rising temperatures could also affect food quality and security. Expanding population and land use changes have already reduced the existing land available for agriculture in the SE more rapidly than any other area of the country (Drummond and Loveland 2010). In addition, summer average temperatures are already at or above the optimal temperature range for major crops including corn, peanuts, soy, rice, and wheat (Hatfield et al., 2008). Moderate temperature increases may result in lower crop yields (Boote et al. 2005).

One benefit of increased temperatures is the potential for a reduction in cold-related deaths in the SE, although this has not been fully explored in the literature. Since the mid-1970s, the average number of freezing days in the SE has declined from four to seven days per year for much of the region, with some specific locations experiencing more and some fewer days (USGCRP 2009). However, the human health response to cold temperatures is much less pronounced than the response to high temperatures, making direct relationships between cold weather and mortality more difficult to predict (Laschewski and Jendritzky 2002).

3.3 Air Quality Effects on Respiratory and Airway Diseases

Climate changes impact air quality via several mechanisms, including increases in ozone production due to higher temperatures or a shift in cloud cover; changes in rates of precipitation scavenging, the process by which precipitation removes particulates from the atmosphere; shifts in vertical mixing due to changes in stability and wind speeds; and changes in the intensity or duration of tropical and extra-tropical cyclones and cold fronts which can remove pollutants. Impacts on air quality can also result from variation in vegetation type and amount, which affects biogenic emissions, and higher temperatures leading to higher fossil fuel consumption. In turn, atmospheric chemistry impacts climate, primarily via radiative effects of aerosols. The many feedbacks are not yet fully understood or simulated by current models (Denman et al. 2007). Changes in particulate matter, ozone, and other air pollutants have a direct impact on human respiratory and airway diseases.

Studies of climate change impacts on air quality in the southeastern USA have focused on ozone and small particulate matter ($PM_{2.5}$). In estimating future ozone and $PM_{2.5}$ levels, both air quality modeling simulations driven by downscaled global-climate model projections and empirical models linking future meteorological parameters with pollution levels have been reported in the literature. Although daily maximum

8-hour ozone levels in the SE have been generally estimated to rise in the 2040s and 2050s as compared to early 2000s, the magnitude of change varies among different studies, from less than 1 ppbv (Chang et al. 2010) to as much as 3 ppbv (Avise et al. 2009). The uncertainty in estimated daily maximum 8-hour ozone concentrations has been found to be approximately 2.5 ppbv in the SE (Liao et al. 2009). The resulting estimate of premature deaths that are attributable to climate change in the region ranges from a few dozen to a few hundred per year. Less research has been done on projected ozone-related morbidity, although a rise in outcomes such as hospital admissions due to respiratory illnesses, emergency room visits for asthma, and lost school days is expected (Tagaris et al. 2009). The relationships between pollutants and health outcomes are different under different air masses. Projections for North Carolina indicate moister air mass patterns and increased ozone, which likely would trigger asthma attacks and result in more emergency room visits (Hanna 2011).

There is less consensus in the estimated $PM_{2.5}$ concentration trends in the SE. A small increase of 1 mcg/m^3 has been reported in one study, as increased future emissions under the business-as-usual scenarios offset the air pollution reduction effects of increased precipitation and wet deposition (Avise et al. 2009). Another study projects a slight decrease of $PM_{2.5}$ levels by 2050, resulting in fewer cases of related premature mortality as well as morbidity outcomes (Tagaris et al. 2009). In addition, current air quality models such as Congestion Mitigation and Air Quality (CMAQ) can underestimate $PM_{2.5}$ by as much as 30% (Tagaris et al. 2007). Another study found that uncertainty in estimated $PM_{2.5}$ concentrations is moderate in the SE (< 1 mcg/m^3) (Liao et al. 2009).

Wildfires reduce air quality and therefore also affect human health. Projected temperature increases coupled with anticipated precipitation changes in the SE could lead to increased evapotranspiration and lower vegetation water content. Lightning, a frequent initiator of wildfires, is expected to increase (Wu et al. 2008). Together, these factors indicate an increasing risk of wildfires, which continues a recent trend (Ebi et al. 2008). Particulate matter (PM) emitted by wildfires poses a serious health risk and specifically increases asthma. Studies have demonstrated that PM is associated with increases in hospital admissions and occurrences of acute asthma exacerbations (Zanobetti and Schwartz 2006). In the Carolinas, peat bog wildfires pose a health hazard, and even brief exposure to smoke associated with these types of wildfires has been associated with negative respiratory and cardiovascular outcomes (Rappold et al. 2011).

Climate change can also affect human health through shifts in airborne allergens. Recent changes in both carbon dioxide concentrations and temperature may be responsible for the observed trend of the earlier onset of the spring pollen season in the USA (Confalonieri et al. 2007). It is reasonable to expect that this trend will continue, and that the incidence of allergies and other respiratory illnesses related to airborne pollens will continue to increase.

3.4 Storms, Extreme Weather, and Sea Level Rise

Climate change may increase the probability of extreme weather events such as heat waves, floods, drought, and the intensity of tropical cyclones in the SE. Greenough et al. (2001) and the IPCC note that extreme weather events will be more frequent, costly, and likely raise the morbidity and mortality rate across the USA. The country's aging population will be more vulnerable to extreme heat events especially in cities where the urban heat island effect can raise temperatures by 2°F to 10°F (Luber and McGeehin 2008; IPCC 2007). In addition, by 2030, several southeastern states, such as Florida, North Carolina, and Georgia are projected to have some of the largest numbers of older Americans (Administration on Aging 2011).

Tropical cyclones that make landfall will also impact public health systems in the southeastern USA, especially in populated coastal areas. The incidence of longer-lived tropical cyclones in the North Atlantic is correlated with increased sea-surface temperatures consistent with a warming climate (Mann and Emanuel 2006). The destructive potential of tropical cyclones in the North Atlantic basin, based on longer storm lifetimes and greater storm intensities, has been increasing since the mid-1970s (Emmanuel 2005, Wu et al. 2008).

In the aftermath of Hurricanes Katrina and Rita in 2005, coastal and inland populations along the SE USA suffered from breakdowns of various societal and infrastructure systems including governance and public health systems. Storm surge, high winds and falling trees, and rising and receding floodwaters led directly to deaths and injuries and also impeded transportation and prevented many people from obtaining emergency medical services. The lack of potable water was a major concern, as people require water for hydration, food preparation, and washing. Raw sewage and industrial contaminated waters disrupted the water distribution system and became a major environmental and health issue (IOM 2007). Survivors showed a higher prevalence of serious mental illness (Kessler et al. 2006), and a study by the CDC seven weeks after Hurricane Katrina indicated that half of returning residents in Orleans and Jefferson Parishes had a possible need for mental health assistance while 33% had probable need for mental health assistance (MMWR 2006). The havoc that these storms wreaked is emblematic of the potential public health impacts from future powerful storms in the SE.

Sea level rise is another potential consequence of the Earth's warming. Changes in Mean Sea Level (MSL) are of major interest to public health in the northern Gulf of Mexico (nGOM) due to the large extent of coastal wetlands, productive fisheries, and large resident populations. The major impacts from MSL rise cited in the IPCC 2007 report are inundation, flood and storm damage, erosion, saltwater intrusion, rising water tables, impeded drainage, and wetland loss, all of which could have an impact on human health. Barrier islands and other low lying areas are subject to increased frequency and levels of flooding, which has human health implications from direct injury and disruption of emergency response. MSL rise and coastal erosion may affect nearshore ecosystems including seagrasses and oyster reefs, which degrade habitats essential for commercial fisheries, possibly leading to shellfish contamination (Hagen et al. 2011, also see Chapter 11). Adaptation strategies that protect critical infrastructure from sea level rise have the potential to protect public health by supporting emergency response during flood events and protecting marine food supplies.

3.5 Harmful Algal Blooms and Marine Toxins

Harmful algal blooms (HABs) are toxin-producing blooms of algae including cyanobacteria that can endanger human health (Landsberg 2002, Backer et al. 2008). HABs have caused mass mortalities of fish and marine mammals in the ocean, killed domestic animals on land, and sickened people through exposure to the toxins by consumption of contaminated seafood or through recreational exposure (Backer and McGillicuddy 2006). In the eastern USA, the major toxin producers are dinoflagellates and cyanobacteria. These organisms have life cycles that can be influenced by climatic patterns; changes in climate may increase the effects of HABs and consequently increase concern for food safety and public health (Tirado et al. 2010).

A variety of climate changes can be expected to cause changes in the frequency, distribution, and intensity of toxic algal blooms in inland and coastal waters (see Table 3.1). These include warmer temperatures and changes in the timing of lake warming, changes in the duration of calm winds, as well as changes in the intensity and duration of hurricanes. Over the past decade significant strides have been made in understanding how climate affects HABs (Moore et al. 2008, Tester et al. 2010, Hallegraeff 2010), which should improve predictions of these blooms in the future.

Table 3.1 Summary of Potential Climate Impacts on Marine Toxins in the Southeast.

Organism	**Location**	**Trend**	**Citation(s)**
Cylindrospermopsis raciborskii	Established in Florida in the 1990s	Moving up the Eastern seaboard; early onset of warm season encourages growth	Wiedner et al. 2007
Karenia brevis	Florida	Northward movement to North Carolina; appearance in Mississippi and Louisiana	Tester et al. 1991, Maier Brown et al. 2006
Dinophysis	Gulf of Mexico	First appearance in the US occurred in 2008	Campbell et al. 2010
Pyrodinium sp	Florida	Established in Florida from the mid-1990s	Landsberg et al. 2006
Gambierdiscus sp	South Carolina, Texas, Louisiana	First appearances in the US occurred in the 2000s; northward movement observed	Villareal et al. 2007, Litaker et al. 2010

In the SE and Caribbean the most common coastal hazards from HABs are ciguatera fish poisoning (CFP) and neurotoxic shellfish poisoning (NSP), although potential risks of diarrhetic shellfish poisoning (DSP) and paralytic shellfish poisoning (PSP) exist (Landsberg 2002). CFP results from eating fish carrying ciguatoxin, a neurotoxin produced by species of the tropical dinoflagellate *Gambierdiscus*. With the exception of scombroid fish poisoning (associated with mishandling of fish after harvest), ciguatoxin is the most common foodborne illness associated with fish, affecting an estimated 50,000 to 500,000 people per year globally. In the USA, CFP illness is concentrated in the Virgin Islands, Puerto Rico, south Florida, and Hawaii. A subset of patients develops chronic symptoms, which may be associated with long-term disability (Litaker et al. 2010). NSP results from brevetoxin, produced by the dinoflagellate *Karenia brevis* and some related species. *K. brevis* produces the well-known "red tide" in Florida. Brevetoxin is unusual in that it can become aerosolized, leading to respiratory distress in humans. During a bloom, hospital admissions for respiratory illness increase, and asthmatics are especially at risk (Kirkpatrick et al. 2006, Fleming et al. 2009). An economic byproduct of red tide is changes in tourism plans that can lead to millions of dollars in losses to coastal communities (Larkin and Adams 2007; see Chapter 5).

Cyanobacteria also produce a variety of health risks (Backer 2002) including the hepatotoxin *Microcystin*. In addition, cyanobacteria produce several other toxins that pose health risks. Dermatitis as a result of recreational exposure is an additional risk to humans. *Cylindrospermopsis raciborskii* is a cyanobacterium of subtropical origin that appeared in Florida in the early 1990s and has established itself in the eastern USA and has also bloomed in the Midwest. The cause of the spread is uncertain but earlier onset of the warm season favors its growth (Wiedner et al. 2007). Changes in climate that affect the timing of the warm season in these areas may favor development of *Cylindrospermopsis* blooms.

As climate change affects water temperature and rainfall, shifts in phytoplankton populations are expected (Moore et al. 2008; Hallegraeff 2010). As a particular water body changes with climate, a niche shift is likely to provide the opportunity for new species to populate. Changes in rainfall and the subsequent nutrient shifts likely will alter the dynamics of the population. In October 1987, *Karenia brevis* (Florida "red tide") was transported in the Gulf Stream to North Carolina, resulting in closures of shellfisheries in both Carolinas from October until late winter 1988 (Tester et al. 1991). *Dinophysis*, which has not been a problem in the USA, appeared in the Gulf of Mexico in March 2008, causing a closure of shellfish beds, as well as a recall of oysters. Blooms of tropical *Pyrodinium* sp. have appeared in Florida in the last decade, and have caused PSP through consumption of fish containing saxitoxin (Landsberg et al. 2006).

Climate change may lead to the expansion of ciguatera fish poisoning (CFP) in tropical areas as well as more temperate zones. While higher sea surface temperatures are associated with higher rates of CFP (Hales et al. 1999, Tester et al. 2010), studies also have suggested that there may be a maximum temperature at which the toxin responsible for CFP can grow, with risk declining above this temperature (Leewellyn 2010). The preferred substrate of *Gambierdiscus* is macroalgae, which may spread as a result of coral bleaching (Tester et al. 2010). In the Caribbean, longer duration of warm temperatures favors development of *Gambierdiscus* spp. potentially allowing ciguatera to bio-accumulate in reef fish over a longer period of time (Tester et al. 2010). This will also cause a decrease in the amount of time available for the toxin to depurate. In the past decade, CFP has been documented from fish caught in South Carolina and in the Flower Garden Banks National Marine Sanctuary on the Texas/Louisiana border. These observations suggest that the disease is moving northward, possibly in association with increasing sea surface temperatures (Villareal et al. 2007, Litaker et al. 2010).

The frequency and intensity of other events, such as hurricanes, may result from climate change and may play a role in the spreading of blooms. The first documented *K. brevis* bloom in Mississippi and Louisiana occurred in 1996 when Tropical Storm Josephine transported a Florida bloom westward (Brown et al. 2006). Hurricane Katrina in 2005 transported a *K. brevis* bloom from southwest Florida to the north Florida coast (Carlson and Clarke 2008). While the full effect of hurricanes on HABs is not clear, these storms have contributed to the spread or relocation of blooms in the past and it is likely this trend will continue in the future.

3.6 Vector-borne and Zoonotic Disease

The subtropical climate in Florida and parts of the SE is attractive to mosquitoes, including vectors for the most important mosquito-borne diseases. These diseases include malaria, vectored by *Anopheles* sp. mosquitoes; and yellow fever, chikungunya, and dengue fever vectored by *Aedes aegypti* and *Aedes albopictus*. Outbreaks of dengue occurred regularly in Florida before the 1950s, when mosquito control efforts were implemented across the state. The vector, *A. aegypti*, also called the Yellow Fever mosquito, lives in close proximity to people, in and around homes. Mosquitoes prefer warm environments with high humidity. Modern homes with air conditioning and screens help interrupt transmission by separating the vectors from susceptible hosts. Local transmission of dengue and malaria in the southeastern USA is now rare, partially due to the actions of the Centers for Disease Control and Prevention, which was created to help with the control and prevention of malaria and related diseases. However, as the 2003 malaria outbreak in West Palm Beach (MMWR 2004) and the 2009 and 2010 dengue fever outbreak in Key West (2010b) showed that disease transmission is still possible when pathogens are introduced by travelers.

How climate change will impact vector-borne and zoonotic disease transmission in the southeastern USA is still uncertain. Vector-borne disease transmission cycles are complex and influenced by many factors. An increase in temperature is likely to shorten the development time of immature vectors to adults and also shorten the extrinsic incubation period of the pathogen in an infected vector (Watts et al. 1987). However, vectors also require access to water to breed, vegetation and humidity to disperse, and susceptible vertebrate hosts to propagate the disease transmission cycle. Regardless of the complexity of these transmission cycles, it is important to note that with climate change, it is likely the SE tropical wet-dry climate zone will expand. This is the climate zone where the most intense vector borne disease transmission occurs around the world. It is possible that the expansion of the wet-dry tropical climate zone in the SE USA will result in more favorable ecologic conditions for vector-borne disease transmission; however, lifestyle and socioeconomic patterns have a great effect on limiting these diseases in the region.

The greatest climate change related vector-borne disease concerns are associated with the expansion of habitats or accessible hosts for the mosquito *A. aegypti*. The human population in the SE is growing fast and the demand for drinking and irrigation water is increasing. *A. aegypti* is known to readily adapt to urban environments with high host densities. As energy prices increase, the cost of running air-conditioning may result in increased disease transmission due to higher prevalence of open windows. In addition, climate change is predicted to increase the severity of tropical storms and hurricanes. During the many months required to repair homes damaged by such storms, residents are potentially vulnerable to mosquitos. In addition, debris from the storms creates mosquito-breeding habitats, potentially increasing mosquito populations.

Zoonotic disease transmission is dependent on contact between infected animals and susceptible human hosts, and it is possible that any climate-associated ecological changes that facilitate such contact will result in an increased risk for zoonotic diseases. For example, the anticipated water shortages during periods of drought may facilitate zoonotic disease transmission by attracting raccoons, a rabies vector species, and other wildlife to human water supplies. By 2055, changing temperature and precipitation patterns could shift the zoonotic disease tularemia northward, resulting in reduced infections in the central-south area of the USA (Nakazawa et al. 2007).

3.7 Water Quality and Quantity

Worldwide, climate change is expected to increase diarrheal incidence by 10% by 2030 (Shuman et al. 2010), much of which will be associated with the waterborne disease transmission route. In the USA, while widely underreported (Blackburn et al. 2004), waterborne diseases continue to cause significant morbidity; exposure patterns and illness rates may change alongside climate and weather patterns (Semenza et al. 2012).

Human exposure to climate-sensitive pathogens occurs by ingestion of water intended for drinking; incidental ingestion during swimming; or direct contact with eyes, ears, or open wounds. Bivalve shellfish, such as oysters, also can concentrate pathogens in water or pathogens in irrigation water can be deposited on produce; both food sources can then serve as vehicles for water-associated bacteria and viruses. Pathogens of concern for waterborne exposure could be either enteric and transmitted by the fecal-oral route (enteric viruses, bacteria and protozoa) or can occur naturally in aquatic systems (bacteria and protozoa), where they could cause a range of diseases. Climate can act on these pathogens directly by influencing growth, survival, persistence, transmission, or virulence. Changing climate or environments could alter or facilitate transmission of the pathogens or affect the ecology and/or habitat of zoonotic reservoirs.

Climatological drivers, especially those affecting the hydrologic cycle, can influence how contaminants are introduced, transported, and processed in coastal ecosystems. Climate change in the SE has affected the regional hydrologic cycle (Portmann et al. 2009). In particular, there has been a significant shift in summer precipitation patterns over the SE, with a move toward higher variability in recent years (Wang et al. 2008). Exceptionally dry and wet summers will be more likely during the 21st century (Li et al. 2011). Recent summer precipitation patterns show multiple shifts from drought to extreme precipitation. This severe combination of more frequent drought with episodes of intense rainfall alters overland and groundwater flow, changing mobilization patterns of inorganic and organic nutrients and contaminants (Boxall et al. 2009). There is also current evidence for the role of climate change and variability on water quality and waterborne disease in the SE including (1) expansion in temporal (seasonal) ranges of certain disease and pathogens related to moderate changes in temperature, (2) increased loading of enteric pathogens due to intense precipitation events, and (3) periodic exposure to multiple pathogens during hurricanes and extreme events.

There is a commonly noted correlation between general diarrheal disease (irrespective of agent) and ambient temperatures. This phenomenon has been documented in both the northern and southern hemispheres and across geographical areas (Hall et al. 2005, Singh et al. 2001). Infections with *Salmonella enterica* serovars continue to be among the top sources of foodborne disease in the USA, and the SE reports the highest rates in the nation (CDC 2010a). Worldwide, including the USA, *Salmonella* cases peak with the highest annual temperatures (D'Souza et al. 2004, Kovats et al. 2004, Fleury et al. 2006, Naumova et al. 2006), although the specific mechanism for this trend is not clear. One study in southern Georgia showed that maximum waterborne prevalence of *Salmonella* and diversity of serovars, especially those associated with human clinical cases, are most common in summer months (Haley et al. 2009). Increased risk of waterborne exposure may be driving many of the sporadic cases of *Salmonella* infections that are currently driving regional and national trends in increasing disease incidence (Clarkson et al. 2009).

Naturally occurring pathogens, including the marine bacteria *Vibrio* spp., are directly associated with warm temperatures. While the genus is commonly found in coastal waters worldwide, four species are commonly associated with human disease: *V. parahaemolyticus*, *V. vulnificus*, *V. cholerae* non-O1 and *V. alginolyticus*. *Vibrio* spp. are the most common bacteria associated with shellfish disease in the USA and a common cause of wound, eye, and ear infections. *Vibrio* illnesses are common in the coastal states of the SE, especially along the Gulf coast, where most cases of *V. vulnificus* arise (Yoder et al. 2008).

Pathogenic *Vibrio* spp. are well adapted to coastal waters and proliferate at warm temperatures, particularly above 15°C (Martinez-Urtaza et al. 2010), and human infections are more frequently observed in warm climates (Dechet et al. 2008, Iwamoto et al. 2010, Weis et al. 2011). Reported human cases also peak during summer months, corresponding with warm temperatures and increased human exposures through seafood and recreational water use (Dechet et al. 2008, Dziuban et al. 2006, Iwamoto et al. 2010, Yoder et al. 2008). Additionally, in the USA, human reports from Gulf Coast states and southeastern Atlantic states include a greater overall diversity of *Vibrio* spp. associated with infections (Dechet et al. 2008). Recent analyses on *Vibrio* infections associated with consumption of Gulf Coast shellfish indicates that cases are expanding temporally, with cases now frequently reported in April, one month earlier and in November, one month later than traditionally observed (Martinez-Urtaza et al. 2010). This trend is associated with an increase in the number of days in each month when water temperature is greater than 20°C. From the decade between 1997 and 2007 compared to the decade between 1987 and 1997, there were water temperatures reaching more than 20°C for five days in April with a 300% increase in the number of *V. vulnificus* illnesses (Martinez-Urtaza et al. 2010). Across the USA, rates of *Vibrio* spp. infections have grown by more than 115% since 1996 (CDC 2011).

Changes in precipitation leading to increased flooding may have the greatest potential impact on food and waterborne disease, especially those associated with the fecal-oral route. A retrospective analysis of waterborne outbreaks associated with drinking water in the USA between 1948 and 1994 revealed that 51% of outbreaks occurred following a daily precipitation event in the 90th percentile and 68% occurred when precipitation levels reached the 80th percentile (Curriero et al. 2001). Waterborne pathogens associated with point and nonpoint sources of pollution include *Cryptosporidium* spp., *Giardia* spp., *Salmonella* spp., *Campylobacter* spp., and a range of enteric viruses, such as noroviruses, hepatitis A viruses, and enteric viruses.

High levels of precipitation may cause the spread of pathogens in a number of ways: overloading of wastewater treatment plants leading to diversion of waste water to combined sewer overflows, increased runoff of pesticides and other contaminants from agricultural or urban lands, or the failure of septic systems. Such events may expose people to significant quantities of enteric pathogens as has been documented with storm events in the SE (Lipp et al. 2001a, Shehane et al. 2005, Vereen et al. 2007, Stumpf et al. 2010, Parker et al. 2010).

The specific effects of climate variability on water quality in the SE have been determined using El Niño-Southern Oscillation (ENSO) events as a model for interannual variability in retrospective studies. Tidally influenced rivers in the SE respond to increased precipitation and streamflow associated with El Niño events with significantly higher levels of fecal contamination that are measured using fecal coliform bacteria (Lipp et al. 2001b, Chigbu et al. 2004). Moreover, specific enteric pathogens, such as enteric viruses, are also more likely to occur with high precipitation and streamflow associated with El Niño winters (Lipp et al. 2001a).

Water quality is also impaired during extreme events, specifically hurricanes, which are projected to increase in strength under various climate change scenarios. Hurricanes associated with large storm surges and tidal inundation may increase exposure for *Vibrio* spp. in affected populations as was seen in Gulf Coast states following the 2005 hurricanes, Katrina and Rita. The incidence of *Vibrio* spp. infection increased relative to previous periods, with 22 wound infections and five deaths in slightly more than a one-month period (Heilpern 2005). Flooding can also result in contamination from fecal sources and associated increase in enteric illnesses. In 1999, Hurricane Floyd flooded much of eastern North Carolina, including farm and livestock operations. This massive flooding event resulted in high levels of fecal contamination (Bales et al. 2000). The number of people seeking treatment for gastrointestinal illness doubled (Setzer and Domino 2004).

3.8 Human Migration and Displacement and Healthcare Disruption

Past disasters have identified problems associated with medical surge capacities during disaster events. Not only are the medical services within a disaster area often overtaxed (Franco et al. 2006), but, in many instances populations evacuating from impact zones to safe areas can overwhelm medical services in the safe zone (Sheppa et al. 1993, Gagnon et al. 2005, Gavagan et al. 2006, Stratton and Tyler 2006, Allen et al. 2007). Figure 3.1 shows the displacement pattern of Mississippians to other parts of the nation after Hurricane Katrina. These disaster diaspora populations often need more than food, water, and shelter during the transition from victims to survivors. One of the least understood aspects of this additional need is related to medical surge and the need to create accurate plans for the accommodation of increased patient volumes both inside and outside of the disaster impact zone (Hick et al. 2004, Bonnett et al. 2006, Barbisch and Koeing 2008). With climate change likely to increase extreme weather events in the SE, including storm intensity, increased health implications associated with this type of migration will be expected to increase in the future. Mental health impacts could result from traumatic stress and deterioration of community wellbeing (Berry at al. 2010), especially for the disadvantaged communities in the SE (Wilson et al. 2010). The severity of mental health impacts such as anxiety and emotional stress following an extreme climate event will depend on the resiliency and capacity of the public health and emergency response system, both during and following the event (Portier et al. 2010).

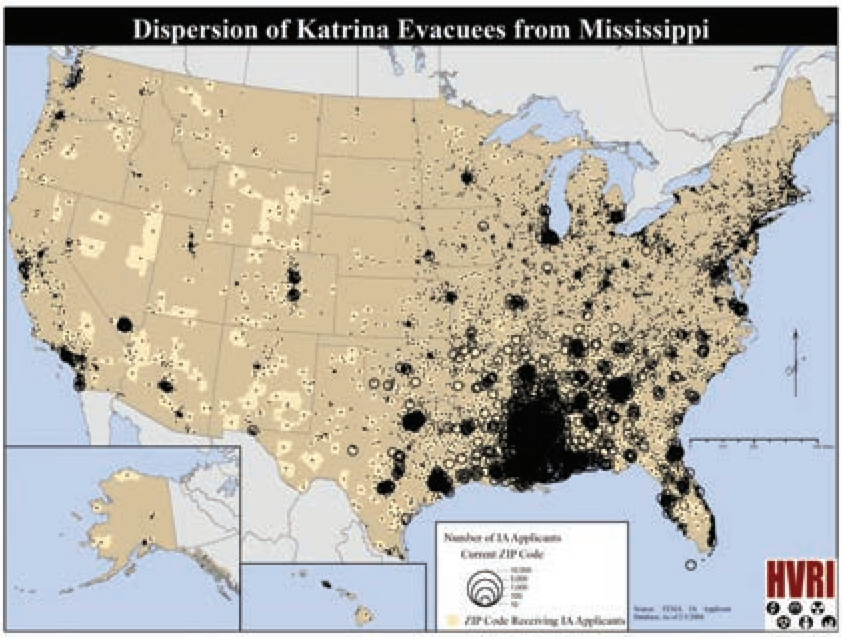


Figure 3.1 Disaster diaspora populations from Mississippi by evacuation location.

3.9 References

AoA (Administration on Aging). 2010. Projected Future Growth of the Older Population. http://www.aoa.gov/AoARoot/Aging_Statistics/future_growth/future_growth.aspx#age.

Allen, A.T., A.M. Flinn, W.F. Moore. 2007. The 81st Medical Group obstetrics and gynecology flight's role during Hurricane Katrina. *Military Medicine* 172 (2): 199-201.

Avise, J., J. Chen, B. Lamb, C. Wiedinmyer, A. Guenther, E. Salathe, C. Mass. 2009. Attribution of projected changes in summertime U.S. ozone and $PM_{2.5}$ concentrations to global changes. *Atmospheric Chemistry and Physics* 9 (4): 1111-1124.

Backer, L.C. 2002. Cyanobacterial harmful algal blooms (CyanoHABs): Developing a public health response. *Lake and Reservoir Management* 18 (1): 20-31.

Backer, L.C. and L.E. Fleming. 2008. Background epidemiology. In oceans and human health: risks and remedies from the sea, ed. P.J. Walsh, S.L. Smith, L.E. Fleming, H. Solo-Gabriele, W.H. Gerwick. New York: Elsevier Science Publishers, 201-218 (Chapter 10).

Backer, L.C., D.J. McGillicuddy, Jr. 2006. Harmful algal blooms at the interface between coastal oceanography and human health. *Oceanography* 19 (2): 94-106.

Bales, J.D., C.J. Oblinger, A.H. Sallenger. 2000. Two months of flooding in Eastern North Carolina, September-October 1999: Hydrological water quality, and geologic effects of Hurricanes Dennis, Floyd and Irene. 00-4093. USGS Water Resources Investigation Report. http://pubs.usgs.gov/wri/wri004093/

Barbisch, D.F. and K.L. Koenig. 2008. Understanding surge capacity: Essential elements. *Academic Emergency Medicine* 13 (11): 1098-1102.

Berry, H.L., K. Bowen, T. Kjellstrom. 2010. Climate change and mental health: A causal pathways framework. *International Journal of Public Health* 55 (2): 23-132.

Blackburn, B.G., G.F. Craun, J.S. Yoder, V. Hill, R.L. Calderon, N. Chen, S.H. Lee, D.A. Levy, M.J. Beach. 2004. Surveillance for waterborne-disease outbreaks associated with drinking water—United States, 2001-2002. *Morbidity and Mortality Weekly Report* 53 (8): 23–45.

Bonnett, C.J., B.N. Peery, S.V. Cantrill, P.T. Ponns, J.S. Haukoons, K.E. McVaney, C.B. Colwell. 2006. Surge capacity: A proposed conceptual framework. *The American Journal of Emergency Medicine,* 25 (3): 297-306.

Boote, K. J., L.H. Allen, P.V.V. Prasad, J.T. Baker, R.W. Gesch, A.M. Snyder, D. Pan, J.M.G. Thomas. 2005. Elevated temperature and CO_2 impacts on pollination, reproductive growth, and yield of several globally important crops. *Journal of Agricultural Meteorology of Japan* 60 (5): 469-474.

Boxall, A.B.A., A. Hardy, S. Beulke, T. Boucard, L. Burgin, P.D. Falloon, P.M. Haygarth, T. Hutchinson, R.S. Kovats, G. Leonardi, L.S. Levy, G. Nichols, S.A. Parsons, L. Potts, D. Stone, E. Topp, D.B. Turley, K. Walsh, E.M.H. Wellington, R.J. Williams. 2009. Impacts of climate change on indirect human exposure to pathogens and chemicals from agriculture. *Environmental Health Perspectives* 117 (4): 508-514.

Brown, A.F.M., Q. Dortch, F.M. Van Dolah, T.A. Leighfield. 2006. Effect of salinity on the distribution, growth, and toxicity of Karenia spp. *Harmful Algae* 5 (2): 199-212.

Burkett, V., R. Ritschard, S. McNulty, J.J. O'Brien, R. Abt, J. Jones, U. Hatch, B. Murray, S. Jagtap, J. Cruise. 2000. Potential consequences of climate variability and change for the Southeastern United States. In *Climate Change Impacts on the United States: The potential consequences of climate variability and change*, ed. National Assessment Synthesis Team, 137-165. Cambridge: Cambridge University Press.

Campbell, L., R.J. Olson, H.M. Sosik, A. Abraham, D.W. Henrichs, C.J. Hyatt, E.J. Buskey. 2010. First harmful dinophysis (dinophyceae, dinophysiales) bloom in the U.S. is revealed by automated imaging flow cytometry. *Journal of Phycology* 46(1): 66-75.

Carlson, D.F. and A.J. Clarke. 2009. Seasonal along-isobath geostrophic flows on the West Florida Shelf with application to *Karenia brevis* red tide blooms in Florida's Big Bend. *Continental Shelf Research* 29 (2): 445-455.

CDC (Centers for Disease Control and Prevention). 2010a. Preliminary FoodNet data on the incidence of infection with pathogens transmitted commonly through food—10 states, 2009. *Morbidity and Mortality Weekly Report* 59 (14): 418-422.

CDC (Centers for Disease Control and Prevention). 2010b. Locally acquired dengue—Key West, Florida, 2009–2010. *Morbidity and Mortality Weekly Report* 59: 77–81.

CDC (Centers for Disease Control and Prevention). 2011. Vital Signs: Incidence and trends of infection with pathogens transmitted commonly through food—foodborne diseases active surveillance network, 10 U.S. sites, 1996-2010. *Morbidity and Mortality Weekly Report* 60 (22): 749-755.

Chang, H.H., J.W. Zhou, M. Fuentes. 2010. Impact of climate change on ambient ozone level and mortality in Southeastern United States. *International Journal of Environmental Research and Public Health* 7 (7): 2866-2880.

Chigbu, P., S. Gordon, T. Strange. 2004. Influence of inter-annual variations in climatic factors on fecal coliform levels in Mississippi Sound. *Water Research* 38 (20): 4341-4352.

Clarkson, L.S., M. Tobin-D'Angelo, C. Shuler, S. Hanna, J. Benson, A.C. Voetsch. 2009. Sporadic *Salmonella enterica* serotype Javiana infections in Georgia and Tennessee: A hypothesis-generating study. *Epidemiology and Infection* 138 (3): 340-346.

Confalonieri, U., B. Menne, R. Akhtar, K.L. Ebi, M. Hauengue, R.S. Kovats, B. Revich, A. Woodward. 2007. Human health. In *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,* ed. M.L. Perry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson, 391-431. New York and United Kingdom: Cambridge University Press.

Curriero, F.C., J.A. Patz, J.B. Rose, S. Lele. 2001. The association between extreme precipitation and waterborne disease outbreaks in the United States, 1948-1994. *American Journal of Public Health* 91 (8): 1194-1199.

Davis, R.E., P.C. Knappenberger, P.J. Michaels, W.M. Novicoff. 2003. Changing heat-related mortality in the United States. *Environmental Health Perspectives* 111 (14): 1712-1718.

Dechet, A.M., P.A. Yu, N. Koram, J. Painter. 2008. Non-foodborne *Vibrio* infections: An important cause of morbidity and mortality in the United States, 1997-2006. *Clinical Infectious Disease* 46 (7): 970-976.

Denman, K.L., G. Brasseur, A. Chidthaisong, P. Ciais, P.M. Cox, R.E. Dickinson, D. Hauglustaine, et al. 2007. Couplings between changes in the climate system and biogeochemistry. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller, 499-587. New York and United Kingdom: Cambridge University Press.

Drummond, M.A. and T.R. Loveland. 2010. Land-use pressure and a transition to forest-cover loss in the eastern United States. *Bioscience* 60 (4): 286-298.

D'Souza, R.M., N.G. Becker, G. Hall, K.B.A. Moodie. 2004. Does ambient temperature affect foodborne disease? *Epidemiology* 15 (1): 86-92.

Ebi, K.L., J. Balbus, P.L. Kinney, E. Lipp, D. Mills, M.S. O'Neill, M. Wilson. 2008. Effects of Global Change on Human Health. In *Analyses of the Effects of Global Change on Human Health and Welfare and Human Systems,* ed. J.L. Gamble, K.L. Ebi, F.G. Sussman and T.J. Wilbanks, 39-87. US Environmental Protection Agency, Washington, DC.

Fleury, M., D.F. Charron, J.D. Holt, O.B. Allen, A.R. Maarouf. 2006. A time series analysis of the relationship of ambient temperature and common bacterial enteric infections in two Canadian provinces. *International Journal of Biometeorology* 50 (6): 385-391.

Fleming L.E., J.A. Bean, B. Kirkpatrick, Y.S. Cheng, R. Pierce, J. Naar, K. Nierenberg, et al. 2009. Exposure and effect assessment of aerosolized red tide toxins (Brevetoxins) and asthma. *Environmental Health Perspectives* 117:1095-1100.

Gagnon, E.B., M.B. Aboutanos, A.K. Malhotra, D. Dompkowski, T.M. Duane, R.R. Ivantury. 2005. In the wake of Hurricane Isabel: A prospective study of postevent trauma and injury control strategies. *The American Surgeon* 71 (3): 194-197.

Gavagan, T.F., K. Smart, H. Palacio, C. Dyer, S. Greenberg, P. Sirbaugh, A. Fishkind, D. Hamilton, U. Shah, G. Masi, R.T. Ivey, J. Jones, F.Y. Chiou-Tan, D. Bloodworth, D. Hyman, C. Whigham, V. Pavlik, R.D. Feigin, K. Mattox. 2006. Hurricane Katrina: Medical response at the Houston Astrodome/Reliant Center Complex. *Southern Medical Journal* 99 (9): 933-939.

Greenough, G., M. McGeehin, S.M. Bernard, J. Trtanj, J. Riad, D. Engelberg. 2001. The potential impacts of climate variability and change on health impacts of extreme weather events in the United States. *Environmental Health Perspectives* 109 (Suppl 2): 191-198.

Groisman, P.Y., R.W. Knight, D.R. Easterling, T.R. Karl, G.C. Hegerl, V.N. Razuvaev. 2004. Trends in intense precipitation in the climate record. *Journal of Climate* 18 (9): 1326-1350.

Hagen, S., D. Passeri, D. DeLorme, W. Huang, G. Lewis, J.T. Morris, D. N. Slinn, L. Walters, D. Wang, J. Weishampel. 2011. Ecological Effects of Sea Level Rise in the Northern Gulf of Mexico. American Geophysical Union, Fall Meeting 2011, abstract #GC24A-03.

Hales, S., P. Weinstein, A. Woodward. 1999. Ciguatera (fish poisoning), El Niño, and Pacific Sea surface temperatures. *Ecosystem Health* 5 (1): 20-25.

Haley, B.J., D. Cole, E.K. Lipp. 2009. Distribution, diversity and seasonality of waterborne salmonellae in a rural watershed. *Applied and Environmental Microbiology* 75 (5): 1248-1255.

Hall, G.V., K.R. Ashbolt, R. Stafford, K. Lalor. 2005. Frequency of infectious gastrointestinal illness in Australia, 2002: Regional, seasonal and demographic variation. *Epidemiology and Infection* 134 (1): 111-118.

Hallegraeff, G.M. 2010. Ocean climate change, phytoplankton community responses, and harmful algal blooms: A formidable predictive challenge. *Journal of Phycology* 46 (2): 220-235.

Hanna, A.F., K.B. Yeatts, A. Xiu, Z. Zhu, R.L. Smith, N.N. Davis, K.D. Talgo, G. Arora, P.J. Robinson, Q. Meng, J.P. Pinto. 2011. Associations between ozone and morbidity using the Spatial Synoptic Classification System. *Environmental Health* 10 (49): 1-15.

Hatfield, J., K. Boote, P. Fay, L. Hahn, C. Izaurralde, B.A. Kimball, T. Mader, J. Morgan, D. Ort, W. Polley, A. Thompson, D. Wolfe. 2008. Agriculture. In *The effects of climate change on agriculture, land resources, water resources, and biodiversity*, ed. P. Backlund, A. Janetos, and D. Schimel, 21-74. US Environmental Protection Agency, Washington, DC.

Heilpern, K.L. and K. Borg. 2005. *Vibrio* illnesses after Hurricane Katrina–Multiple States, August–September 2005. *Morbidity and Mortality Weekly Report* 54 (37): 928-931.

Hick, J.L., D. Hanfling, J.L. Burstein, C. DeAtley, D. Barbisch, G.M. Bogdan, S. Cantrill. 2004. Health care facility and community strategies for patient care surge capacity. *Annals of Emergency Medicine* 44 (3): 253-261.

IOM (Institute of Medicine). 2007. *Environmental Public Health Impacts of Disaster: Hurricane Katrina Workshop Summary*. Washington, DC: The National Academies Press.

IPCC (Intergovernmental Panel on Climate Change). 2007. AR4 synthesis report: Contribution of working groups I, II and III to the fourth assessment report of the Intergovernmental Panel on Climate Change, ed. R.K. Pachauri and A. Reisinger. http://www.ipcc.ch/publications_and_data/publications_and_data_reports.shtml#1

Iwamoto, M., T. Ayers, B.E. Mahon, D.L. Swerdlow. 2010. Epidemiology of seafood-associated infections in the United States. *Clinical Microbiology Reviews* 23 (2): 399-411.

Karl, T.R., J.M. Melillo, T.C. Peterson. 2009. *Global Climate Change Impacts in the United States*. Washington, DC: Cambridge University Press.

Kirkpatrick, B., L. Fleming, L.C. Backer. 2006. Environmental exposures to Florida red tides: Effects on emergency room respiratory diagnoses admissions. *Harmful Algae* 5 (5): 526-533.

Kovats, R.S. and S. Hajat. 2008. Heat stress and public health: A critical review. *Annual Review of Public Health* 29: 41-55.

Kovats, R.S., S.J. Edwards, S. Hajat, B. Armstrong, K.L. Ebi, B. Menne. 2004. The effect of temperature on food poisoning: A time-series analysis of salmonellosis in ten European countries. *Epidemiology and Infection* 132 (3): 443-453.

Landsberg, J.H., S. Hall, J.N. Johannessen. 2006. Saxitoxin puffer fish poisoning in the United States, with the first report of Pyrodinium Bahamense as the putative toxin source. *Environmental Health Perspectives* 114 (10): 1502-1507.

Landsberg, J.H. 2002. The effects of harmful algal blooms on aquatic organisms. *Reviews in Fisheries Science* 10 (2): 113-390.

Larkin, S.L. and C.M. Adams. 2007. Harmful algal blooms and coastal business: Economic consequences in Florida. *Society and Natural Resources* 20 (9): 849-859.

Laschewski, G. and G. Jendritzky. 2002. Effects of the thermal environment on human health: An investigation of 30 years of daily mortality data from SW Germany. *Climate Research* 21 (1): 91-103.

Li, W., l. Li, F. Rong, Y. Deng, H. Wang. 2011. Changes to the North Atlantic subtropical high and its role in the intensification of summer rainfall variability in the Southeastern United States. *Journal of Climate* 24 (5): 1499-1506.

Liao, K.J., E. Tagaris, K. Manomaiphiboon, C. Wang, J.H. Woo, P. Amar, S. He, A.G. Russell. 2009. Quantification of the impact of climate uncertainty on regional air quality. *Atmospheric Chemistry and Physics* 9 (3): 865-878.

Lipp, E.K., R. Kurz, R. Vincent, C. Rodriguez-Palacios, S.R. Farrah, J.B. Rose. 2001. The effects of seasonal variability and weather on microbial fecal pollution and enteric pathogens in a subtropical estuary. *Estuaries* 24 (2): 266-276.

Lipp, E.K., N. Schmidt, M.E. Luther, J.B. Rose. 2001. Determining the effects of El Niño-Southern oscillation events on coastal water quality. *Estuaries* 24 (4): 491-497.

Litaker, R.W., M.W. Vandersea, M.A. Faust, S.R. Kibler, A.W. Nau, W.C. Holland, M. Chinain, M.J. Holmes, P.A. Tester. 2010. Global distribution of ciguatera causing dinoflagellates in the genus Gambierdiscus. *Toxicon* 56 (5): 711-730.

Llewellyn, L.E. 2010. Revisiting the association between sea surface temperature and the epidemiology of fish poisoning in the South Pacific: Reassessing the link between ciguatera and climate change. *Toxicon* 56 (5): 691-697.

Luber, G. and M. McGeehin. 2008. Climate change and extreme heat events. *American Journal of Preventative Medicine* 35 (5): 429-435.

Mann, M.E. and K. Emanuel. 2006. Atlantic hurricane trends linked to climate change. *EOS, Transactions, American Geophysical Union* 87 (24): 233-244.

Martinez-Urtaza, J., J.C. Bowers, J. Trinanes, A. DePaola. 2010. Climate anomalies and the increasing risk of *Vibrio*. *Food Research International* 43 (7): 1780-1790.

Mississippi Department of Marine Resources. 2011. Assessment of sea level rise in coastal Mississippi. http://www.dmr.ms.gov/images/cmp/2011-slr-final.pdf

MMWR (Morbidity and Mortality Weekly Report). 2004. Multifocal Autochthonous Transmission of Malaria—Florida, 2003. *Morbidity and Mortality Weekly Report* 2004; 53 (19): 412-413.

MMWR (Morbidity and Mortality Weekly Report). 2006. Assessment of health-related needs after Hurricanes Katrina and Rita: Orleans and Jefferson Parishes, New Orleans area, Louisiana, October 17-22, 2005. *Morbidity and Mortality Weekly Report* 2006; 5538-41

MMWR (Morbidity and Mortality Weekly Report). 2008. Heat related deaths among crop workers—United States, 1992-2006. *Morbidity and Mortality Weekly Report* 57 (24): 694-653.

MMWR (Morbidity and Mortality Weekly Report). 2011. Vital signs: incidence and trends of infection with pathogens transmitted commonly through food: Foodborne diseases active surveillance network, 10 U.S. sites, 1996–2010. *Morbidity and Mortality Weekly Report* 60 (22): 749-755. http://www.cdc.gov/mmwr/preview/mmwrhtml/mm6022a5.htm?s_cid=mm6022a5_w

Moore, S.K., V.L. Trainer, N.J. Mantua, M.S. Parkder, E.A. Laws, L.C. Backer, L.E. Fleming. 2008. Impacts of climate variability and future climate change on harmful algal blooms and human health. *Environmental Health* 7 (Suppl 2): S4.

Nakazawa, Y., R. Williams, T. Peterson, P. Mead, E. Staples, K.L. Gage. 2007. Climate change effects on plague and tularemia in the United States. *Vector-borne and Zoonotic Diseases* 7 (4): 529-540.

Naumova, E.N., J.S. Jjagai, B. Matyas, A. DeMaria, I.B. MacNeill, J.K. Griffiths. 2006. Seasonality in six enterically transmitted diseases and ambient temperature. *Epidemiology and Infection* 135 (2): 281-292.

NC Coastal Resources Commission: Science Panel on Coastal Hazards. 2010. Sea level rise assessment report. http://dcm2.enr.state.nc.us/slr/NC%20Sea-Level%20Rise%20Assessment%20Report%202010%20-%20CRC%20Science%20Panel.pdf

O'Neill, M.S. and K.L. Ebi. 2009. Temperature extremes and health: impacts of climate variability and change in the United States. *Journal of Occupational and Environmental Medicine* 51 (1): 13-25

Parker, J.K., D. McIntyre, R.T. Noble. 2010. Characterizing fecal contamination in stormwater runoff in coastal North Carolina, USA. *Water Research* 44 (14): 4186-4194.

Portier, C.J., T.K. Thigpen, S.R. Carter, C.H. Dilworth, A.E. Grambsch, J. Gohlke. 2010. *A Human Health Perspective on Climate Change: A Report Outlining the Research Needs on the Human Health Effects of Climate Change*. Research Triangle Park, NC: Environmental Health Perspectives and National Institute of Environmental Health Sciences.

Portmann, R.W., S. Solomon, G.C. Hegerl. 2009. Spatial and seasonal patterns in climate change, temperatures, and precipitation across the United States. *Proceedings of the National Academy of Sciences* 106 (18): 7324-7329.

Rappold, A.G., S.L. Stone, W.E. Cascio, L.M. Neas, V.J. Kilaru, M.S. Carraway, J.J. Szykman, A. Ising, W.E. Cleve, J.T. Meredith, H. Vaughan-Batten, L. Deyneka, R.B. Devlin. 2011. Peat bog wildfire smoke exposure in rural North Carolina is associated with cardiopulmonary emergency department visits assessed through syndromic surveillance. 10: *Environmental Health Perspectives* 119 (10): 1415-1420.

Semenza, J.C., S. Herbst, A. Rechenburg, J.E. Suk, C. Höser, C. Schreiber, T. Kistemann. 2012. Climate change impact assessment of food and waterborne diseases. *Critical Reviews in Environmental Science and Technology* 42 (8): 857-890.

Setzer, C. and M.E. Domino. 2004. Medicaid outpatient utilization for waterborne pathogenic illness following Hurricane Floyd. *Public Health Reports* 119 (5): 472-478.

Shehane, S.D., V.J. Harwood, J.E. Whitlock, J.B. Rose. 2005. The influence of rainfall on the incidence of microbial faecal indicators and the dominant sources of faecal pollution in a Florida river. *Journal of Applied Microbiology* 98 (5): 1127-1136.

Sheppa, C.M., J. Stevens, J.T. Philbrick, M. Canada. 1993. The effect of a Class IV hurricane on emergency department operations. *The American Journal of Emergency Medicine* 11 (5): 464-467.

Sheridan, S.C., A.J. Kalkstein, L.S. Kalkstein. 2009. Trends in heat-related mortality in the United States, 1975-2004. *Natural Hazards,* 50 (1): 145-160.

Sheridan, S.C. and A.J. Kalkstein. 2010. Seasonal variability in heat-related mortality across the United States. *Natural Hazards* 55 (2): 291-305.

Singh, R.B., S. Hales, N. de Wet, R. Raj, M. Hearnden, P. Weinstein. 2001. The influence of climate variation and change on diarrheal disease in the Pacific Islands. *Environmental Health Perspectives* 109 (2): 155-159.

Smayda, T.J. 1997. What is a bloom? A commentary. *Limnology and Oceanography* 42 (5): 1132-1136.

Stumpf, C.H., M.F. Piehler, S. Thompson, R.T. Noble. 2010. Loading of fecal indicator bacteria in North Carolina tidal creek headwaters: Hydrographic patterns and terrestrial runoff relationships. *Water Research* 44 (16): 4704-4715.

Sun, G., S.G. McNulty, J.A.M. Myers, E.C. Cohen. 2008. Impacts of multiple stresses on water demand and supply across the Southeastern United States. *Journal of the American Water Resources Association* 44 (6): 1441-1457.

Tagaris, E., K.J. Liao, A.J. Delucia, L. Deck, P. Amar, A.G. Russell. 2009. Potential impact of climate change on air pollution-related human health effects. *Environmental Science & Technology* 43 (13): 4979-4988.

Tagaris, E., K. Manomaiphiboon, K.J. Liao, L.R. Leung, J.H. Woo, S. He, P. Amar, A.G. Russell. 2007. Impacts of global climate change and emissions on regional ozone and fine particulate matter concentrations over the United States. *Journal of Geophysical Research–Atmospheres* 112, D14312; doi:10.1029/2006JD008262.

Tester, P.A., R.L. Feldman, A.W. Nau, S.R. Kibler, R.W. Litaker. 2010. Ciguatera fish poisoning and sea surface temperatures in the Caribbean Sea and the West Indies. *Toxicon* 56 (5): 698-710.

Tester, P.A., R.P. Stumpf, F.M. Vukovich, P.K. Fowler, J.T. Turner. 1991. An expatriate red tide bloom: Transport, distribution, and persistence. *Limnology and Oceanography* 36 (5): 1053-1061.

Tirado, M.C., R. Clarke, L.A. Jaykus, A. McQuatters-Gollop, J.M. Frank. 2010. Climate change and food safety: A review. *Food Research International* 43 (7): 1745-1765.

USGCRP (United States Global Change Research Program). 2009. Global climate change impacts in the United States. T.R. Karl, J.M. Melillo, and T.C. Peterson, eds. United States Global Change Research Program. NYC: Cambridge University Press.

Vereen, E., R.R. Lowrance, D.J. Cole, E.K. Lipp. 2007. Distribution and ecology of campylobacters in coastal plain streams (Georgia, United States of America). *Applied and Environmental Microbiology*,73 (5): 1395-1403.

Villareal, T., S. Hanson, S. Qualia, E. Jester, H. Granade, R. Dickey. 2007. Petroleum production platforms as sites for the expansion of ciguatera in the Northwestern Gulf of Mexico. *Harmful Algae* 6 (2): 253-259.

Wang, H., R. Fu, W. Li. 2008. Intensification of summer rainfall variability in the southeastern United States. *Science and Technology Infusion Climate Bulletin NOAA's National Weather Service.* Lincoln NE: 33rd NOAA Annual Climate Diagnostics and Prediction Workshop.

Watts, D.M., D.S. Burke, B.A. Harrison, R.E. Whitmire, A. Nisalak. 1987. Effect of temperature on the vector efficiency of *Aedes aegypti* for Dengue 2 virus. *The American Journal of Tropical Medicine and Hygiene* 36 (1): 143-152.

West, T.D., C.M. Browner, M.J. Foster, B. Babbitt, D. Glickman, W.M. Daley. 1997. *Evaluation report to the U.S. Congress on the effectiveness of Louisiana coastal wetland restoration projects.* Louisiana Coastal Wetlands Conservation and Restoration Task Force. http://lacoast.gov/reports/rtc/1997/title.htm.

Weis, K.E., R.M. Hammond, R. Hutchinson, C.G.M. Blackmore. 2011. *Vibrio* illness in Florida, 1998-2007. *Epidemiology and Infection* 139 (4): 591-598.

Wiedner, C., J. Rücker, R. Brüggemann, B. Nixdorf. 2007. Climate change affects timing and size of populations of an invasive Cyanobacterium in temperate regions. *Oecologia* 152 (3): 473-484.

Wilson, S.M., R. Richard, L. Joseph, E. Williams. 2010. Climate change, environmental justice, and vulnerability: An exploratory spatial analysis. *Environmental Justice* 3 (1): 13-19.

Wu, L., B. Wang, S.A. Braun. 2008. Implications of tropical cyclone power dissipation index. *International Journal of Climatology* 28 (6): 727-731.

Wu, S., L.J. Mickley, D.J. Jacob, D. Rind, D.G. Streets. 2008. Effects of 2000-2050 changes in climate and emissions on global tropospheric ozone and the policy-relevant background ozone in the United States. *Journal of Geophysical Research–Atmospheres* 113, D18312; doi:10.1029/2007JD009639.

Yoder, J., V. Roberts, G.F. Craun, V. Hill, L. Hicks, N.T. Alexander, V. Radke, R.L. Calderon, M.C. Hlavsa, M.J. Beach, S.L. Roy. 2008. Surveillance for waterborne disease and outbreaks associated with drinking water and water not intended for drinking–United States, 2005-2006. *Morbidity and Mortality Weekly Report* 57 (9): 39-62.

Zanobetti, A., J. Schwartz. 2006. Air pollution and emergency admissions in Boston, MA. *Journal of Epidemiology and Community Health* 60 (10): 890-895.

Chapter 4

Energy Production, Use, and Vulnerability to Climate Change in the Southeast USA

LEAD AUTHOR

Kenneth L. Mitchell (mitchell.ken@epa.gov; US Environmental Protection Agency, Atlanta, Georgia)

CONTRIBUTING AUTHORS

Marilyn Brown (Georgia Institute of Technology, Atlanta, Georgia)
Ryan Brown (US Environmental Protection Agency, Atlanta, Georgia)
Diana Burk (Southface, Atlanta, Georgia)
Dennis Creech (Southface, Atlanta, Georgia)
Garry P. Garrett (Southern States Energy Board, Norcross, Georgia)
Daniel Garver (US Environmental Protection Agency, Atlanta, Georgia)
Julie Harrington (Florida State University, Tallahassee, Florida)
David Letson (University of Miami, Miami, Florida)
Pat Long (East Carolina University, Greenville, North Carolina)
Stephen A. Smith (Southern Alliance for Clean Energy, Knoxville, Tennessee)
Karen Utt (Tennessee Valley Authority, Chattanooga, Tennessee)
Thomas J. Wilbanks (Oakridge National Laboratory, Oakridge, Tennessee)

The southeastern USA is home to large and varied, though unevenly concentrated, energy resource reserves, including coal, gas, and oil as well as renewable energy sources such as solar, biomass, and wind. In addition to being one of the most important domestic producers of energy in the United States, it is also one of the biggest users.

Key Findings

- At approximately 27% of the USA total, the Southeast (SE) consumes more energy as a region and per person than any other NCA region.
- Energy consumption in the SE in 2009 was dominated by the industrial sector (31%) and transportation (28%), both of which are higher than the national average.
- Residential use accounted for 23% of SE energy consumption while commercial activity consumed 18%, both of which are lower than the national average.
- As the climate changes, concerns exist for energy services in the SE due to the potential for changing patterns of demand, such as increased demand for air conditioning, as well as the potential impacts on electricity generating capacity and energy distribution infrastructure.
- An improved ability to project climate change and its impacts at a more local level, a better understanding of changing regional patterns of energy use, and enhanced strategies to improve the resiliency of energy supply systems are just a few of the areas that will be needed to ensure energy supplies in the SE.

4.1 Status and Outlook for Energy Production and Use in the Southeast

For purposes of this chapter, the Southeast is comprised of Louisiana, Alabama, Mississippi, Florida, Georgia, South Carolina, North Carolina, Virginia, Tennessee, Kentucky, Arkansas, Puerto Rico, and the US Virgin Islands. Unless otherwise noted, the statistics presented are focused on the 11 continental states. In 2010, states in the SE produced 15% of the coal and approximately one-quarter of the nation's domestic crude oil (EIA 2012a and b). In 2009, three SE states ranked in the top ten nationally in renewable energy installed or cumulative capacity in millions of watts (MW) in one or more resource types: Alabama (fifth in biopower), Florida (fourth in biopower and fifth in solar photovoltaic or PV), Louisiana (second in biopower), and North Carolina (tenth in annual solar PV capacity additions) (NREL 2009). However, no southeastern state ranked in the top ten in wind or geothermal development. In addition to being a major supplier of energy, the region is also a large consumer of electricity and other fuels. Of the 11 states in the SE, six import more electricity than they generate; two with greater than 20% deficit and four between 20% and 0% deficit. Puerto Rico and the US Virgin Islands have few conventional energy sources and generate most of their electricity from imported fossil fuels (EIA 2012c).

This chapter explores the status of the SE as a source and user of energy. It also looks at how a changing climate may impact the region's ability to supply energy into the future and identifies key uncertainties in the understanding of these issues.

Existing Energy Resources in the Southeast

The SE is home to large and varied, though unevenly concentrated, energy resource reserves. Approximately 10% to 11% of national hydroelectric power comes from the SE, with more than half of that from Alabama and Tennessee; some additional future potential still available (Kosnick 2008). Coal deposits are distributed throughout Appalachia and beyond. Natural gas and oil reserves exist both onshore and offshore. Insolation is above average for the eastern part of the nation. Significant amounts of biomass energy are available. In specific locations, wind and geothermal resources are also potential sources of energy (EIA 2012d; NREL 2012). In the ongoing development of these various energy resources, a number of issues will have to be considered, including permitting requirements, costs, transmission distance, environmental impacts, and the number of projects needed to reach generation goals.

Coal. In 2011, recoverable coal reserves in the SE were estimated at 2,081 million short tons (approximately 10.8 of the USA total) (EIA 2012e). Southeastern coal reserves are primarily located in two key states, including Kentucky with 1,419 million tons and Virginia with 348 million tons. About 71 percent of coal mined in the US is transported by train for at least part of its trip to market. Coal can also be transported by barge, ship, truck, and even pipeline (EIA 2012f).

There are also lignite resources available in Arkansas, Mississippi, and Louisiana that could play a role in future electric generation. Mississippi Power Company's 582 MW Integrated Gasification Combined Cycle (IGCC) power plant in Kemper County, for example, is set to burn lignite as its fuel supply beginning in 2014, and will also include carbon capture and sequestration technology (Southern Company 2012).

Oil and Natural Gas. Figure 4.1 shows natural gas production in the USA from 1990 through 2009 with forecasts through 2035. While onshore and offshore conventional supplies make up a significant portion of historical production, shale gas is forecast to play a key role in future supply due to improved exploration and production technologies (EIA 2011a). Key shale finds include the Fayetteville shale in Arkansas and the Haynesville/Bossier in Louisiana. Of the 97 trillion cubic feet (Tcf) of shale play reserves in the USA, 27 Tcf are found in the Haynesville/Bossier and Fayetteville plays (EIA 2012g).

The distribution of natural gas occurs in a major pipeline network (Figure 4.2) with significant pipeline capacity in the SE. Several liquefied natural gas (LNG) terminals are in Louisiana and Georgia (EIA 2012h).

Biomass. One estimate of the biomass resource in the SE is 106,710 thousand tons of material per year, which is 25% of the USA total (Brown et al. 2010). Wood pellet mills are among the most successful group of new woody biomass consumers, with pellet mills currently consuming 6.2 million tons of wood per year and producing 3.1 million tons of export quality wood pellets (Forisk Consulting 2011). This is largely due to demand for biomass co-firing in European countries that have opted to use wood pellets because of increasing fossil fuel prices and environmental concerns (Force Technology 2012).

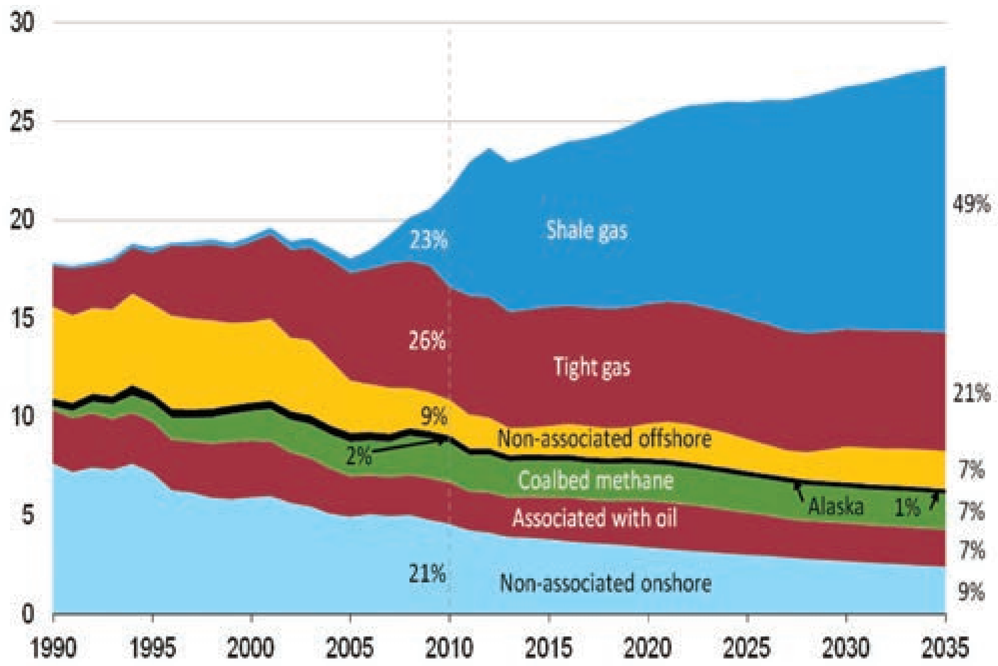


Figure 4.1 Natural gas production, 1990 to 2005, (trillion cubic feet). *Source*: *EIA, Energy Annual Outlook 2012 Early Release*

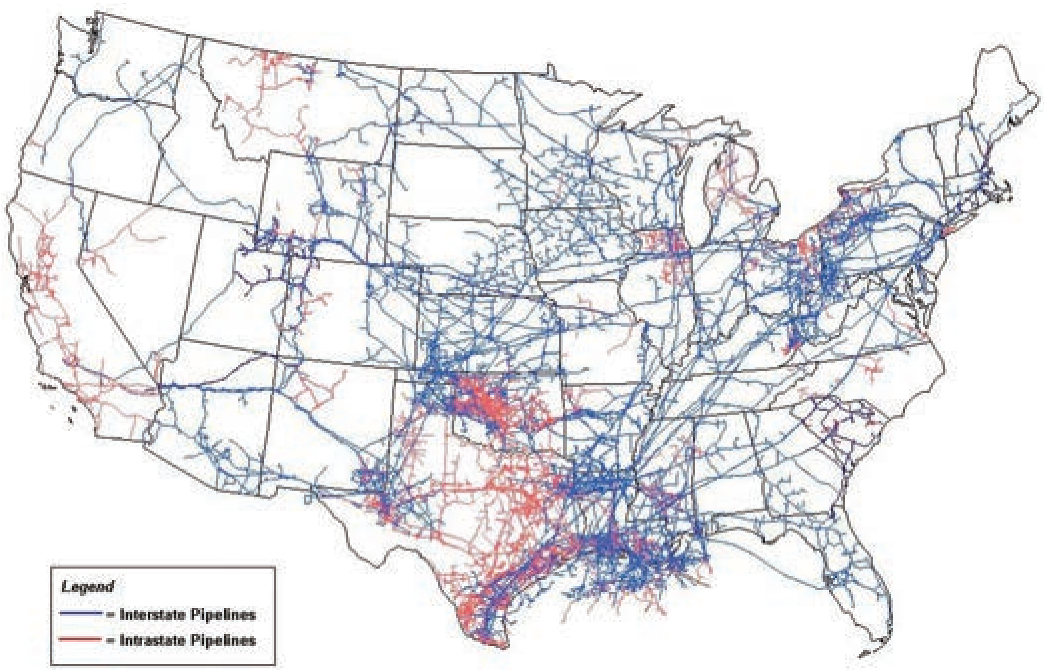


Figure 4.2 Natural gas pipelines. *Source*: *Energy Information Administration, Office of Oil & Gas, Natural Gas Division, Gas Transfortation nformation System.*

Nuclear. Of the 104 nuclear reactors in the USA, 37 are located in the SE and account for more than 36,400 MW of electrical power. In 2010, these units generated some 285 billion Kwh, operating at a capacity factor slightly less than 90% (Nuclear Energy Institute 2011).

Hydro and Marine Hydrokinetic. Every SE state except Mississippi generates some electricity via hydroelectric power. In 2010, the SE produced 14% of the total USA hydroelectric (EIA 2012i). Tennessee, Arkansas, and Mississippi each have approximately 4 gigawatts (GW) of developable hydroelectric resources remaining. North Carolina, Georgia, Alabama, and Louisiana have between 2 and 4 GW of developable hydroelectric resources remaining. South Carolina, Kentucky, and Florida have about 1 GW of hydroelectric potential each (NREL 2004). These resources are mostly available from retrofitting and upgrading existing hydroelectric dams, or installing small or microscale hydroelectric systems.

The US Department of the Interior estimates that 0.1% of the Florida Straits Current could supply 35% of Florida's electrical demand via marine hydrokinetic electric generation (MMS 2006). Some energy generation potential also exists for Georgia (Hunt et al. 2010) and North Carolina (Seim et al. 2010) and likely in similar fashion for South Carolina from wave, tidal, and currents using marine hydrokinetic technology.

Solar. Solar resources in the 11 states of the SE are not as robust as those found in the western USA, but resources near or in excess of 5 watts per square meter are significantly better than in much of the country east of the Mississippi River. Among SE states, Florida has the best solar resources as measured in $kWh/m^2/d$ (NREL 2008a). Puerto Rico and the US Virgin Islands also have high solar resource potential (Lantz et al. 2011, Irizarry-Rivera et al. 2008).

Wind. In the SE wind energy resources are less robust than resources in the Plains states; however, wind resources exist in specific mountainous, coastal, and offshore areas. A scenario outlined by the National Renewable Energy Laboratory estimated that as part of a national strategy to generate 20% of the nation's electricity from wind energy by 2030, the SE could provide between 17 and 32 GW of wind energy capacity, including onshore and offshore resources (NREL 2008b). North Carolina, for example, has among the best potential offshore wind resources in the country (Schwartz et al. 2010).

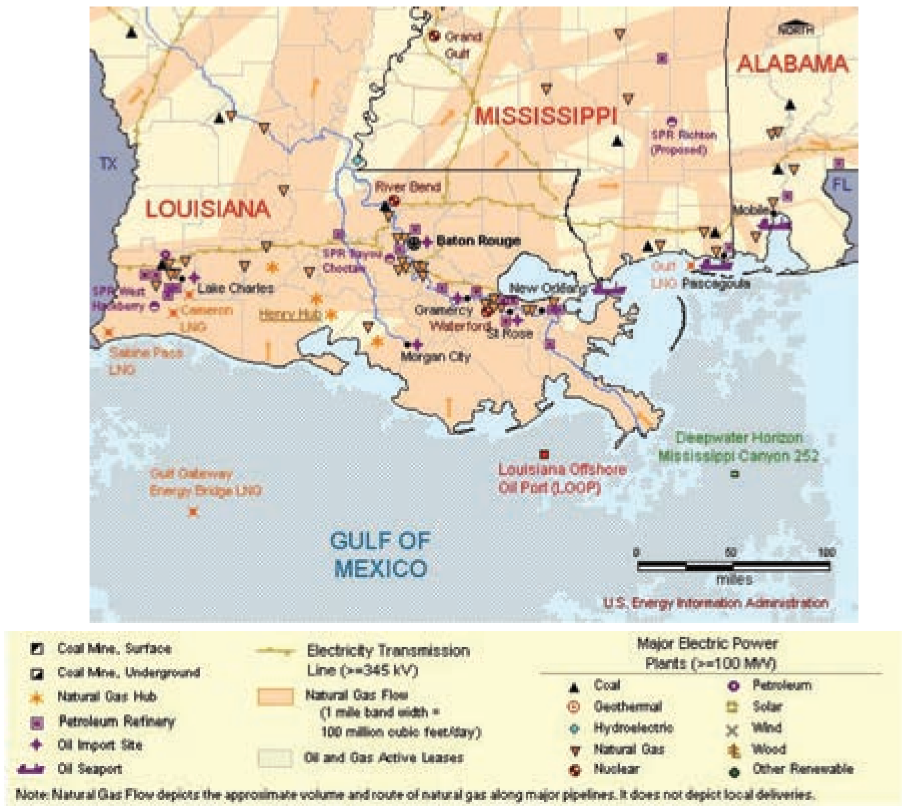
Geothermal. The SE has few viable opportunities for geothermal power generation sites. However, co-produced fluids, such as water from oil and gas production, could provide up to 771 MW of geothermal energy using existing wells in Alabama, Arkansas, Florida, Louisiana, and Mississippi (Green et al. 2006).

Energy Efficiency. Energy efficiency initiatives in the SE are a powerful way to reduce per capita energy consumption, conserve fuels, and reduce the need for new generating capacity into the future. Additional energy efficiency resources and initiatives are discussed in chapters 5 and 12.

Case Study: Louisiana

Louisiana is an important state for both the production and distribution of fuel in the USA. For example, the Louisiana Offshore Oil Port (LOOP) is the only port in the country capable of accommodating deep draft tankers; two of the US Strategic Petroleum Reserve's four storage facilities are located in Louisiana; and the Henry Hub is the largest centralized point for natural gas spot-and-futures trading in the USA, providing access to major markets throughout the country. In addition, the liquefied natural gas (LNG) import terminal at Sabine is the largest of nine existing LNG import sites in the USA.

Energy Information Administration, State Profiles, Louisiana, November 2009 Update. http://www.eia.gov/state/state-energy-profiles.cfm?sid=LA



Landscape of Energy Production, Delivery, and Use in the Southeast

Electricity Production. Peak demand for electricity in the SE, which was more than 238 GW in 2010, represents about 32% of the total national demand. Likewise, generating capacity in the SE is approximately 32% of the total nationwide. Nationally, fossil fuel-based capacity represents some 71% of the total generating capacity while nuclear, hydro, and other renewables make up around 25%. In the SE, traditional fossil-based generating capacity is some 235 GW or 78% of the total generating capacity of 300 GW. In addition to fossil fuels, nuclear power in 2009 provided 36 GW, and renewables and pumped storage 28 GW of generating capacity (Table 4.1).

Table 4.1 Southeastern States Generation Capacity (2009).

Fuel	**GW**	**Percent**
Coal	94	31.3
Petroleum	19	6.3
Natural Gas	122	40.5
Nuclear	36	12.1
Renewables	19	6.3
Pumped Storage	9	3.1
Total	**300 GW**	**100%**

The SE has a balanced portfolio of resources from an operational perspective. Traditional base load resources such as nuclear and coal provide power around the clock. Pumped storage and gas turbine units provide energy during peak load conditions. The generation of electricity on an hourly basis, measured in kilowatt-hours, provides a different picture. In 2009 nuclear power provided around 292 billion Kwh of electricity, some 25% of the electrical needs of the SE. In contrast, coal generation in 2009 delivered 491 billion Kwh, while natural gas combined cycle units produced some 277 billion Kwh of electricity. From 2005 to 2009, coal fired generation dropped from 50% to 43% of the total generation, while natural gas picked up the majority of the difference (EIA 2011b).

With regard to growth in the electric power sector, a 2004 study by the Department of Energy projected a 63% to 79% increase in thermoelectric capacity by year 2025 for much of the SE (Figure 4.3) (Hoffmann et al. 2004). Updated estimates for growth in the electric power sector (all fuel types) indicates more modest growth in electric generating capacity between 2010 and 2035 of 23% for Florida and 15% for the rest of the region. The 15% increase noted represents the combined increase in capacity for the SERC Reliability Corporation Delta (SRDA), Southeastern (SRSE), Central (SRCE), and Virginia-Carolina (SRVC) regions (EIA 2012j).

With regard to renewables, including conventional hydropower, the SE produced 67 billion Kwh in 2009 (EIA 2011b) with this value expected to grow over time. For example, 29 MW of generation capacity from wind turbines currently exist at the Tennessee Valley Authority's Buffalo Mountain site (TVA 2012a), and at least five utility-scale wind farms have been proposed in the following locations: Invenergy, NC, 80 MW; Iberdrola, NC, 300 MW; Invenergy, NC, 300 MW; Next Era, KY, 100 MW; and Wind Capital Group, FL, 150 MW (News & Observer of Raleigh 2011, Iberdrola 2011, Beamon 2011, Toncray 2011, Wind Capital 2011).

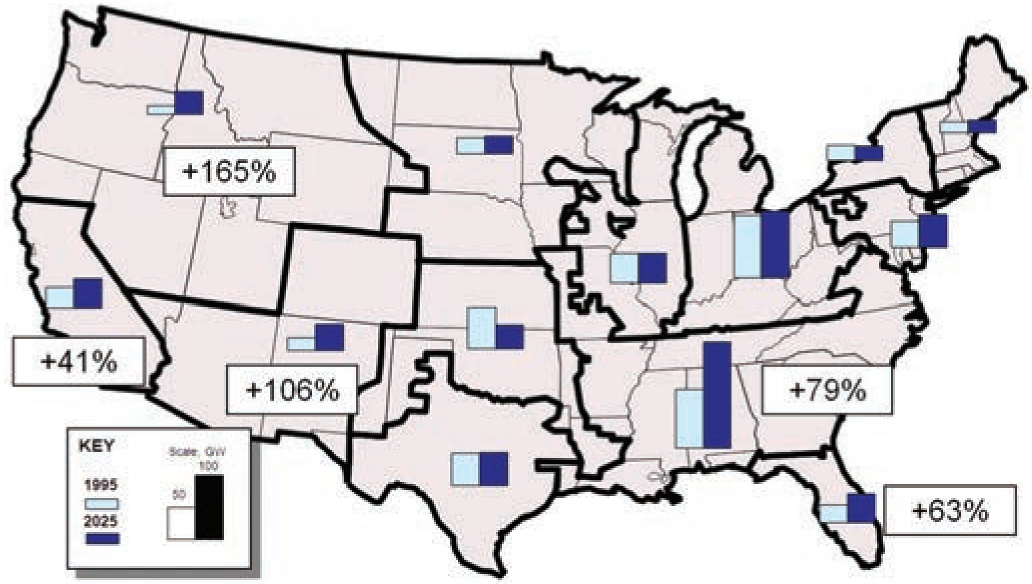


Figure 4.3 Comparison of regional thermoelectric generation capacity by North American Electric Reliability Council Region, 1995-2025.

As another example, TVA has 300 kW of solar photovoltaic capacity installed, an additional 16 MW under contract, and 34 MW approved under the *Generation Partners* program (TVA 2012b). Duke Energy owns, purchases, or has installed up to 24 MW of solar capacity in North Carolina and South Carolina (Duke Energy 2012). Georgia Power is soliciting 50 MW of large-scale solar capacity to be added to the Georgia system by 2015 (Platts 2011), and National Solar Power LLC has announced its plans to develop a 400 MW solar power plant in Florida (Heller 2011). Florida Power and Light's existing three solar power plants generate 110 MW of clean energy for 4.5 million customers throughout the state, preventing the emission of more than 3.5 million tons of greenhouse gas-equivalent to removing 25,000 cars from the road every year (FPL 2012).

The Caribbean also has significant renewable energy resources. For example, a recent study estimated available resources for electricity production on the island of Puerto Rico (Table 4.2) (Irizarry-Rivera 2008). In 2010, the US Virgin Islands signed a memorandum of understanding with both the US Department of Energy (DOE) and US Department of the Interior (DOI) to establish a deployment strategy for the islands' significant renewable energy resources. The plan includes transportation, electricity generation and transmission, energy efficiency, tourism and industry, and public education (NREL 2010). As of March 2012, several utility-scale wind and solar projects were under construction in Puerto Rico, according to information provided by the Puerto Rico Energy Affairs Administration (PREAA 2012).

Electrical Transmission System. The electrical transmission system in the SE is widely interconnected throughout the Eastern Interconnection. The Eastern Interconnection links states east of the Rocky Mountains, except Texas, with more than 280,000 miles of transmission lines of more than 100 kilovolts (kV). The SE grid consists of almost

Table 4.2 Estimated Renewable Energy Potential for Electricity Production in Puerto Rico.

Renewable Resource/ Technology*	Electric Energy Production Estimate MWh/year if 10% of Resource is Used to Produce Electricity	Percent of the 2006 Electric Energy Demand**
Wind	2,977,052	14.4
Ocean	16,935,360	82.2
Solar (photovoltaic)	3,900,000	18.9
Biomass – Agricultural	1,200,000 (traditional) 24,000,000 (microalgae)	5.8 to 116.5
Biomass – Waste	~90,000	0.4
Micro Hydro	2.628	0.01

* Fuel Cells were also considered in the source paper for this table, but not shown here.
** According to the Banco de Desarrollo Economico de Puerto Rico, the island had an electricity demand of 20,600,000 MWh in 2006.

110,000 miles of transmission lines above 10 kV and primarily includes the SERC Reliability Corporation and the Florida Reliability Coordinating Council, (regional entities that operate and insure reliability of the electrical grid (Figure 4.4) (SERC 2012). As of 2009, this represented 35% of the transmission found in the Eastern Interconnection and 26% of the entire USA transmission of 372,340 miles. In 2009, approximately 8,800 circuit miles of new transmission were added to the North American bulk power system with some 2,600 miles greater than 200 kV. More than 5,000 miles of that new transmission was added in the SE, particularly in Florida. The bulk transmission system has more than 100 kV and is forecast to consist of over 115,000 miles by 2018 with the Eastern Interconnection totaling 296,000 miles within a national system of 407,000 miles of power lines (NERC 2010).

Some energy sources have special transmission considerations. For example, DOE has noted that the rapid development of wind power requires substantial additions to the national transmission infrastructure in certain locations due to the geographically-dependent nature of wind resources. The relatively low capacity of wind plants and the short time it typically takes to build a new wind project versus the longer time required to develop new transmission infrastructure add to the challenge (Mills et al. 2009). That said, wind energy-related projects are moving forward to provide electricity for the SE. TVA contracted in 2010 for more than 1,300 MW of wind energy from projects throughout the Midwest (TVA 2012c); and Alabama Power has signed a power purchase agreement for 202 MW of wind energy from Oklahoma (Platts 2011). Pattern Energy has proposed its Southern Cross long-distance transmission project that would connect up to 3,000 MW of Texas wind farm energy to an offloading location in Northeastern Mississippi by 2016 (Southern Cross 2012) and Clean Line Energy has proposed its Plains & Eastern project that would provide up to 7,000 MW of wind energy capacity from farms in Kansas, Oklahoma, and Texas to an offloading point in Memphis, TN, which is TVA territory (Clean Line 2012).

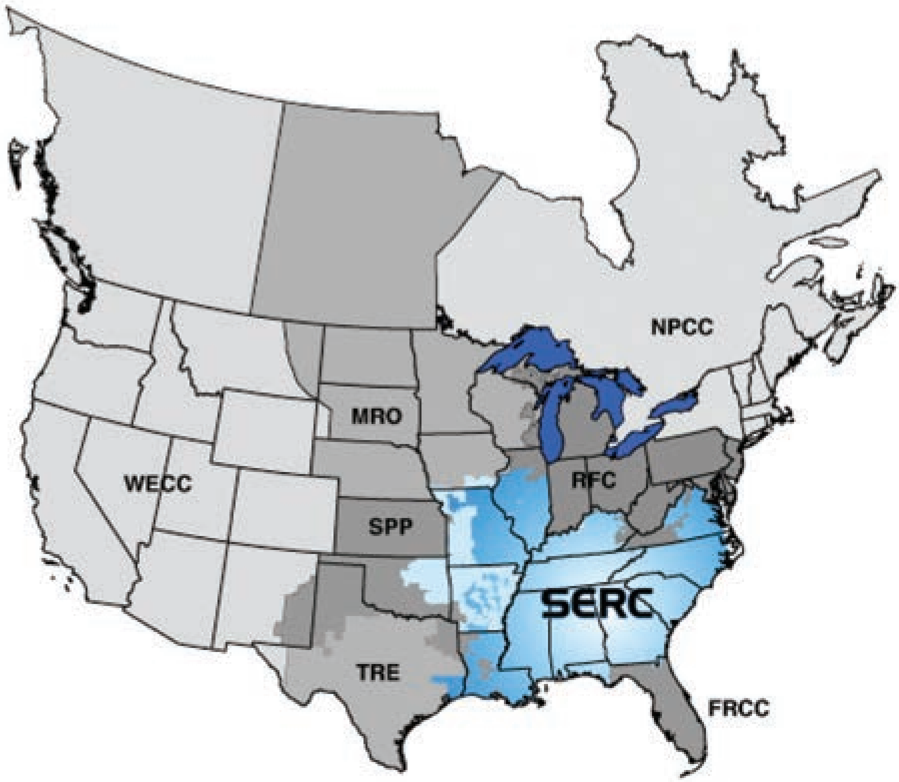


Figure 4.4 Regions for North American Reliability Corporations.

Electricity Assets in the Southeast. The nation's current inventory of electric power generators has a wide range of sizes and ages. Of the nation's 1,266 coal steam electric generating units, for example, the largest (250 MW and up) represents 36% of the generators and have been in service an average of 34 years. The smallest units (0 to 25 MW), which make up 15% of the generators have been in service an average age of 45 years (US EPA 2011). In the SE, there have been numerous coal plant retirement announcements, including 269 MW at 4 units by Dominion Power; 800 MW at four Cliffside units in North Carolina by Duke Power; 1,481 MW at 14 units, also by Duke, each of which was built between 1941 and 1958. Progress Energy is retiring 11 units of 1951 to 1972 vintage in North Carolina totaling 1,513 MW; Southern Company is retiring over 1,094 MW units built in the 1960s. TVA has announced plans to retire 21 coal-fired generating units in Tennessee and Alabama, totaling 3,231 MW at plants built between 1952 and 1959. In total, this represents around 8,388 MW of electrical generating capacity that will eventually be replaced with more efficient, cleaner electrical supply options (EEI 2011).

In the American Society of Civil Engineers (ASCE) Report Card for America's Infrastructure 2009, the energy sector received a grade of D+, which is consistent with other segments of USA infrastructure, such as water, roads, bridges, and transit. ASCE has noted that "while progress has been made in grid reinforcement since 2005 and substantial investment in generation, transmission and distribution is expected over the next two decades, demand for electricity continues to grow (25% since 1990) and permitting for much needed modernization of production facilities has been difficult. Projected electric utility investment needs could be as much as $1.5 trillion by 2030 (ASCE 2009)."

Case Study: DeSoto Next Generation Solar Energy Center

When opened in October 2009, Florida Power and Light's DeSoto County Next Generation Solar Energy Center was the largest solar photovoltaic plant in the USA. The facility's 90,500 solar panels have an annual estimated generation of approximately 42,000 MWh—enough power to serve about 3,000 homes.

Over 30 years, the solar facility will prevent emission of more than 575,000 tons of GHGs, equivalent of removing more than 4,500 cars from the road every year for the entire life of the project.

The project is also estimated to decrease fossil-fuel usage by approximately 7 billion cubic feet of natural gas and 277,000 barrels of oil.

http://www.fpl.com/environment/solar/desoto.shtml

Energy Use in the Southeast. At approximately 27% of the USA total, the SE consumes more energy as a region and per person than any other NCA Region (Figure 4.5). That consumption in 2009 was dominated by the industrial sector (31%) and transportation (28%), both of which are higher than the national average. Among industrial energy consumption, Louisiana is substantially higher than other southeastern states. Residential use accounted for 23% of SE energy consumption while commercial activity consumed 18%, both of which are lower than the national average. Of the southeastern states, Florida dominates in terms of consumption (Figure 4.6). It is noteworthy that among residential users, the per capita consumption of energy in the SE has risen steadily since the 1960s (Figure 4.7) (EIA 2012k).

With regard to petroleum, the SE is the largest consumer of petroleum products in the USA, with one quarter of all petroleum consumed by the region's eleven states (Table 4.3) (EIA 2012l). For example, about 28% of all automotive gasoline consumed in the USA was purchased in the SE in 2009, reflecting both the high population and the number of vehicle miles traveled (VMT) in this region (including Puerto Rico). It is also noteworthy that in addition to having the highest VMT among all NCA regions (Figure 4.8), the per capita VMT in the SE is also the highest (FHA 2009).

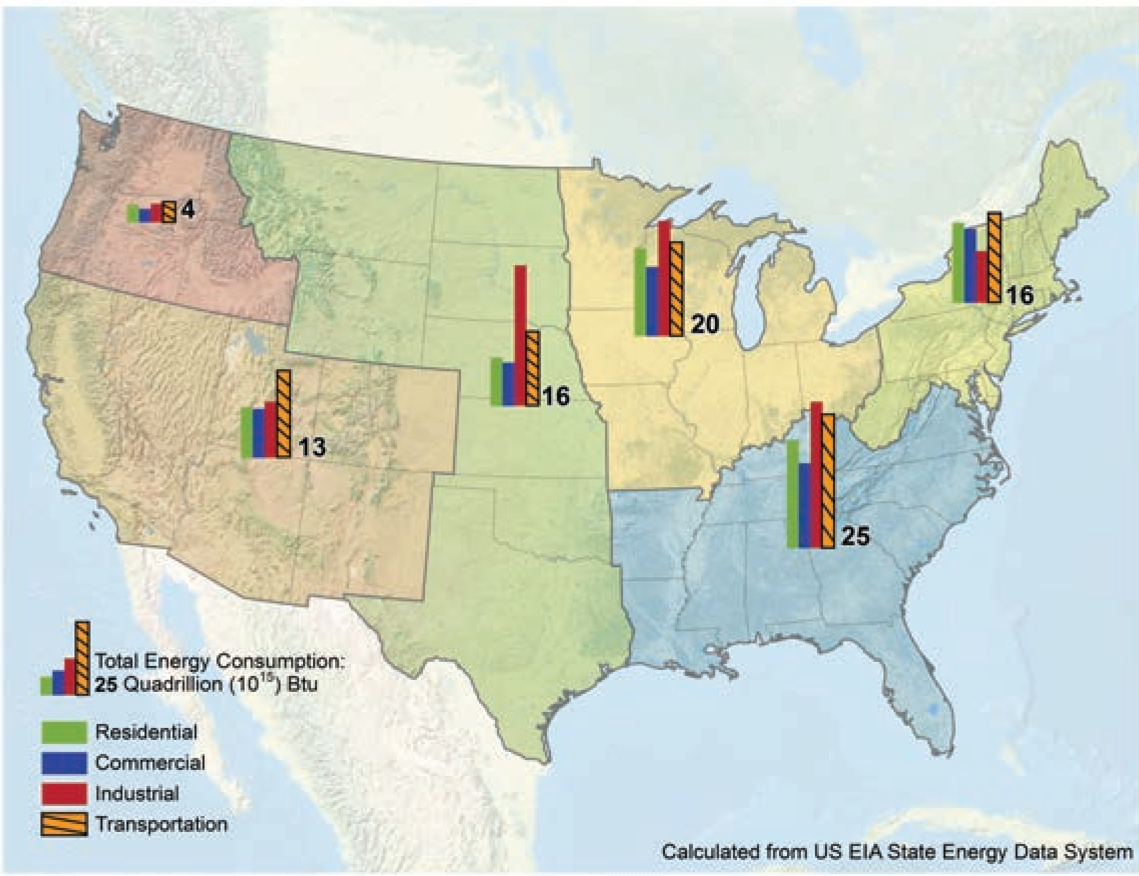


Figure 4.5 Energy consumption by National Climate Assessment (NCA) region.

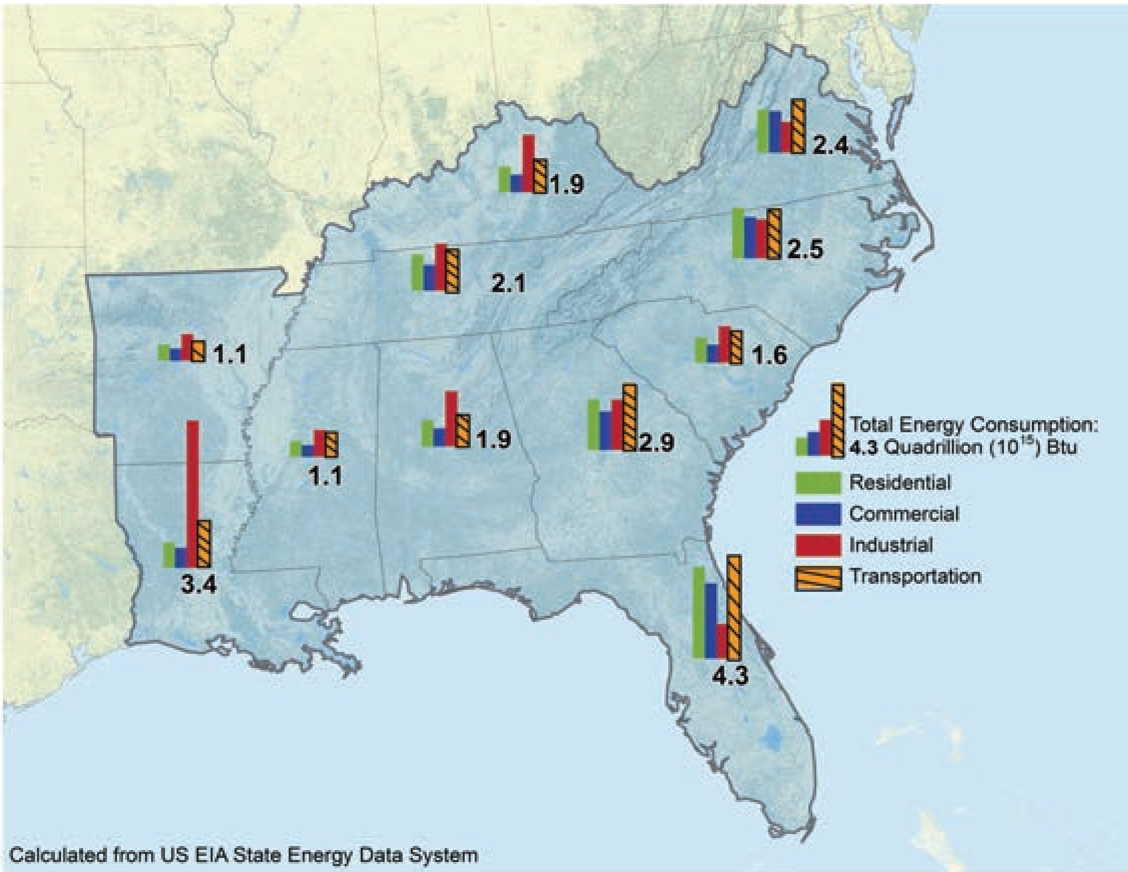


Figure 4.6 Energy consumption by state in the Southeast.

4.2 Impact of Climate Change on Energy Supply and Demand in the Southeast

Climate change is of concern for energy services in the SE due to the potential for changing patterns of demand, such as increased demand for air conditioning, as well as the potential impacts on electricity generating capacity and energy distribution infrastructure. The US Climate Change Science Program has summarized this issue as follows (Wilbanks et al. 2008):

> ***How might climate change affect energy consumption in the United States?*** The research evidence is relatively clear that climate warming will mean reductions in total U.S. heating requirements and increases in total cooling requirements for buildings. These changes will vary by region and by season, but they will affect household and business energy costs and their demands on energy supply institutions. In general, the changes imply increased demands for electricity, which supplies virtually all cooling energy services but only some heating services. Other effects on energy consumption are less clear.

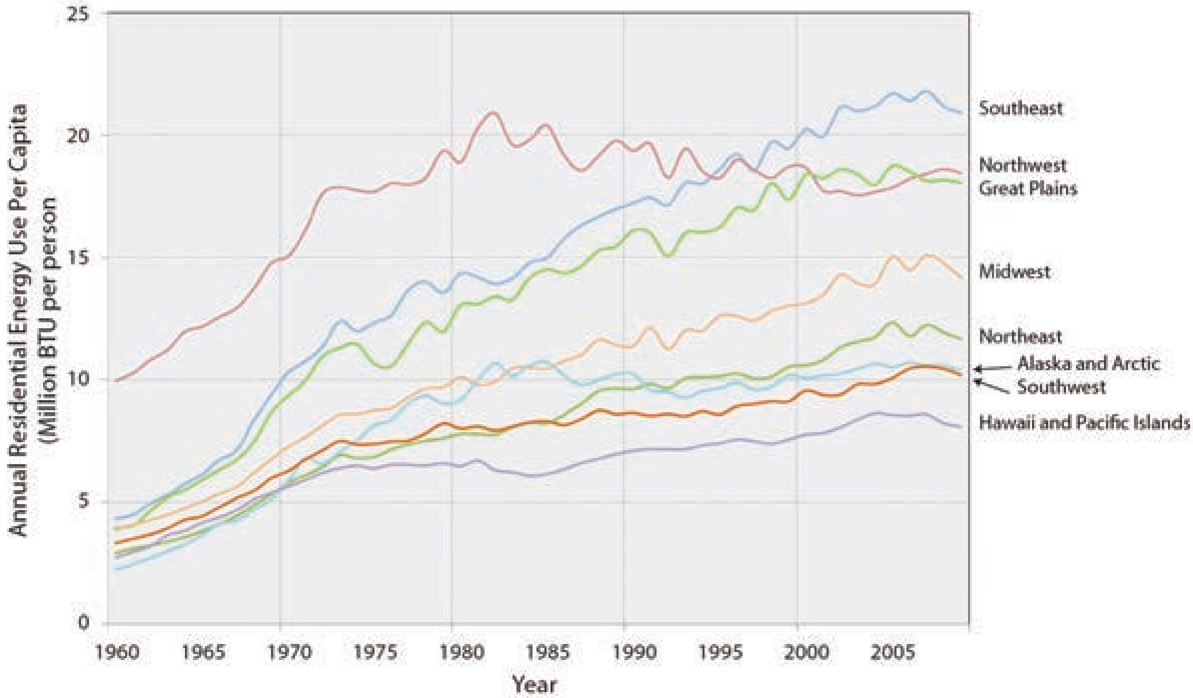


Figure 4.7 Per capita energy use by National Climate Assessment (NCA) region.

How might climate change affect energy production and supply in the United States? The research evidence about effects is not as strong as for energy consumption, but climate change could affect energy production and supply (a) if extreme weather events become more intense, (b) where regions dependent on water supplies for hydropower and/or thermal power plant cooling face reductions in water supplies, (c) where temperature increases decrease overall thermoelectric power generation efficiencies, and (d) where changed conditions affect facility siting decisions. Most effects are likely to be modest except for possible regional effects of extreme weather events and water shortages.

How might climate change have other effects that indirectly shape energy production and consumption in the United States? The research evidence about indirect effects ranges from abundant information about possible effects of climate change policies on energy technology choices to extremely limited information about such issues as effects on energy security. Based on this mixed evidence, it appears that climate change is likely to affect risk management in the investment behavior of some energy institutions, and it is very likely to have some effects on energy technology R&D investments and energy resource and technology choices. In addition, climate change can be expected to affect other countries in ways that in turn affect U.S. energy conditions through their participation in global and hemispheric energy markets, and climate change concerns could interact with some driving forces behind policies focused on U.S. energy security.

In most cases, the availability of peer-reviewed published literature on these issues is limited, including at the regional level, although there is a broad consensus about the general vulnerabilities and risks based partly on reputable expert group assessments.

The remainder of this section provides brief examples of some of the potential climate risks and vulnerabilities to SE energy production and use. As noted previously, chapter 2 of this report provides additional detail about historical climate trends in the SE and projections of future climate (along with citations for this information).

Climate Impacts on Energy Demand

The SE already experiences high heat and humidity, resulting in elevated heat indices in summer months with higher temperatures projected for the future. Higher

Table 4.3 Energy Consumption Estimates for Petroleum Energy Sources in Physical Units, 2009.

	MILLION BARRELS							
	Distillate Fuel Oil	Jet Fuel[a]	LPG[b]	Motor Gasoline[c]	Residual Fuel Oil	Other[d]	Total	
	PETROLEUM							FUEL ETHANOL[e]
Alabama	24.4	1.7	3.7	62.8	0.9	16.1	109.7	2.6
Arkansas	22	0.8	2.9	34.8	0.1	4.1	64.8	1.7
Florida	46.4	31.5	5.5	200.6	13.8	13	310.8	17
Kentucky	27.7	9.8	8.6	53.4	0.1	25.6	125.3	4.9
Louisiana	32.7	16.1	58.5	54.7	16.4	86.2	264.6	3.1
Mississippi	19.9	4.9	3.4	37.6	0.8	9.4	75.9	2
North Carolina	31.3	1.9	12.2	105.9	2.7	11.1	165	9
South Carolina	19	1.1	2.7	65.6	2.9	12.5	103.7	5.4
Tennessee	25.2	11.2	3.3	75.4	(s)	28.6	143.8	7.6
Virginia	34.3	15.7	5.6	94.5	3	7.1	160.3	8.6
Southeast	**321.1**	**112.7**	**111.8**	**903.1**	**48**	**223.1**	**1720**	**71.8**
United States	**1325.3**	**508.5**	**748.7**	**3283.7**	**186.6**	**798.7**	**6851.6**	**262.8**
Southeast as a % of U.S. Total	**24**	**22**	**15**	**28**	**26**	**28**	**25**	**27**

[a] Includes kerosene-type jet fuel only; naphtha-type jet fuel is included in "Other Petroleum"
[b] Liquefied petroleum gases
[c] Motor gasoline as it is consumed; includes fuel ethanol blended into motor gasoline
[d] Includes asphalt and road oil, aviation gasoline, kerosene, lubricants, and the 16 other petroleum products
[e] Includes denaturant
Where shown, (s) = Value less than 0.05.

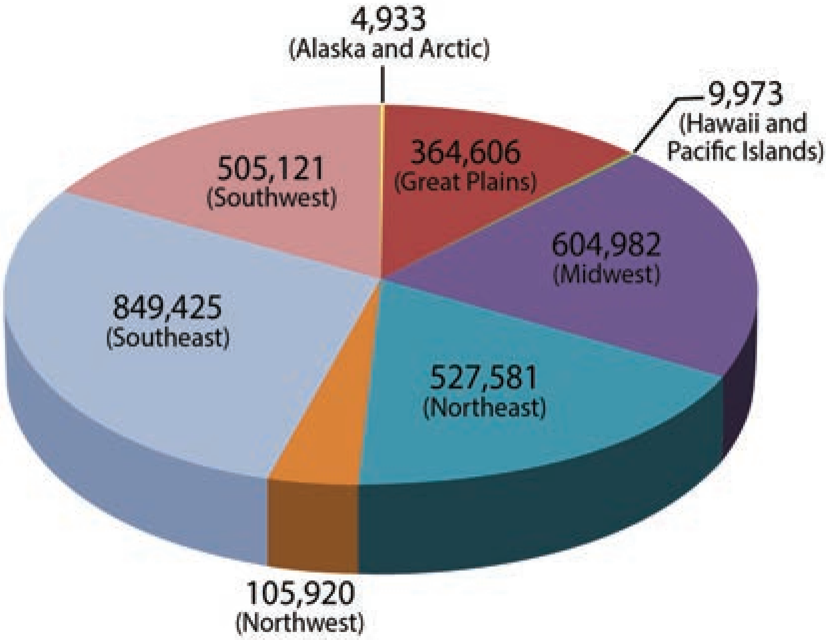


Figure 4.8 Annual vehicle miles traveled (VMT) by National Climate Assessment (NCA) region (millions). Source: Federal Highway Administration, 2009 Highway Statistics Series.

temperatures raise warm season demands for electricity to cool homes, work places, commercial spaces, and indoor recreational spaces. Urban heat island effects may further increase demands for cooling. In cooler seasons, energy demands for space warming will likely decrease, possibly reducing net annual demands for non-electricity fuels for interior heating. Overall, the net change for energy demand (cooling and heating) in the SE is expected to be an increase, which is of particular concern for lower income households that may not be able to weatherize their homes and install and operate air conditioning systems or to improve the efficiency of existing systems (Hadley et al. 2006, US EPA 2012).

For example, a 2006 analysis looked at heating energy, cooling energy, and net changes, by Region, under two climate projections. The study estimated that cooling demands in the SE would increase by 2025 for either a high or a low temperature-change scenario (Figure 4.9 Hadley et al. 2006).

Other climate effects on energy demand are less clear, such as lower fuel mileage from increased vehicle air conditioning use or more use of lawn irrigation systems in response to high temperatures or droughts (Wilbanks et al. 2008). While some of these changes may not be large, they may contribute to increases in regional energy demands.

Climate-related demographic shifts are another consideration for energy needs in the SE. For example, the American Planning Association has noted that shifts in migration in the SE may occur in response to climate-related risks in coastal areas and rising heat indexes (APA 2011). Such shifts in population and economic activities would change patterns of energy demand within the region.

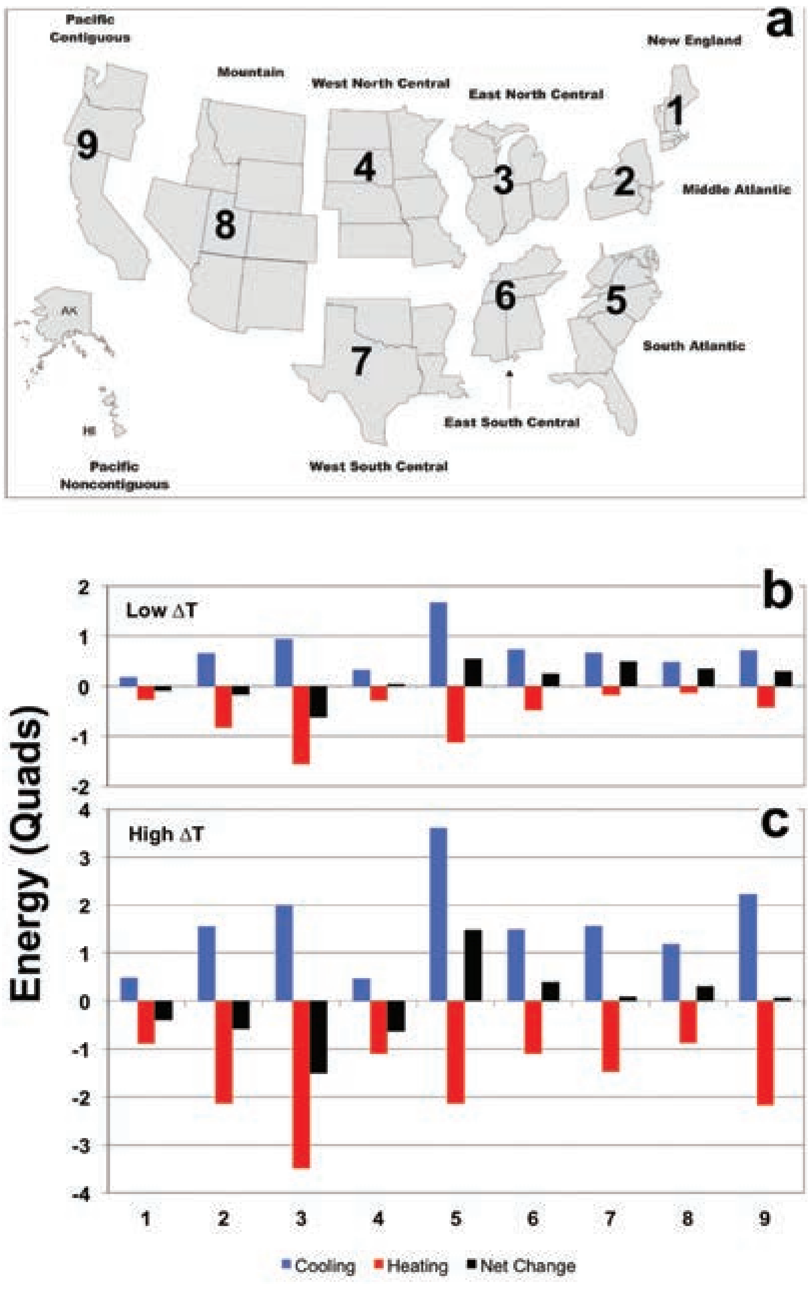


Figure 4.9 (a) The nine US Census divisions and projected cumulative (2003-2025) changes in primary heating energy, cooling energy, and net changes, as departures from the reference case, for (b) the low ΔT (change in temperature) scenario and (c) the high ΔT (change in temperature) scenario. The Census divisions are: (1) New England; (2) Middle Atlantic; (3) East North Central; (4) West North Central; (5) South Atlantic; (6) East South Central; (7) West South Central; (8) Mountain; and (9) Pacific contiguous, Alaska and Hawaii, Pacific noncontiguous. (Note: read energy graphs b and c in the order of key—first bar is cooling, second bar is heating, and third bar is net change—for each region.) ©2006 American Geophysical Union; reproduced by permission of the American Geophysical Union.

Case Study: Browns Ferry Nuclear Plant

Browns Ferry Nuclear Plant is on the north shore of Wheeler Reservoir in north Alabama and was the largest in the world when it opened in 1974. It was also the first nuclear plant in the world to generate more than 1 billion watts of power. Browns Ferry has had to operate at reduced power production for significant periods of time during hot summer months and low water flow conditions in order to maintain the plant discharge within environmental limits. In 2010, for example, existing climate conditions resulted in reduced plant operations and $50 million in additional costs to TVA customers. TVA is currently working on a project to expand their cooling tower capacity in order to continue operating during high river temperatures.

http://www.tva.gov/sites/brownsferry.htm

http://www.tva.gov/abouttva/board/pdf/11-4- 2010_board_final.pdf

Climate Impacts on Energy Production and Distribution

Critical SE regional infrastructure, such as energy, transportation, and hospitals, already experience the effects of extreme events such as floods, hurricanes, high ambient temperatures, and tornados. Damage to these assets can disrupt services from days to months.

Of these risks, one has received substantial attention in recent years—coastal infrastructure exposure to hurricanes, sea-level rise, and land subsidence along the Gulf Coast. For example, sea level rise and storm surge has the potential to affect coastal highways, ports, and rail (Savonis et al. 2008). Climate change poses risks of major temporary disruptions in energy supply, including both coastal and offshore facilities for extracting and processing oil and gas as well as electricity production systems. Climate change could also increase capital expenditures to harden existing facilities, to build more robust new facilities, or to move facilities and activities to less vulnerable locations.

The impact of current climate extremes on oil and gas production and refining was demonstrated in 2005 when hurricanes Katrina and Rita hit the Gulf. Figure 4.10 shows the large magnitude of impact and slow recovery of production following the two storms (Dismukes et al. 2011). To put these numbers into a national perspective, Katrina alone resulted in the shut-in of more than 95% of offshore Gulf crude oil production and approximately 27% of total US crude production. This local domestic production could not be rapidly replaced by imports since major oil import terminals were also interrupted, resulting in an estimated 32% reduction of total USA crude oil import capacity. In addition, Katrina and Rita forced the shutdown of about 32 refineries representing a loss of up to 26% of USA refining capacity. According to the Federal Trade Commission, these interruptions were largely responsible for gasoline price increases of about 17%, which did not disappear until several months after the storms (FTC 2006).

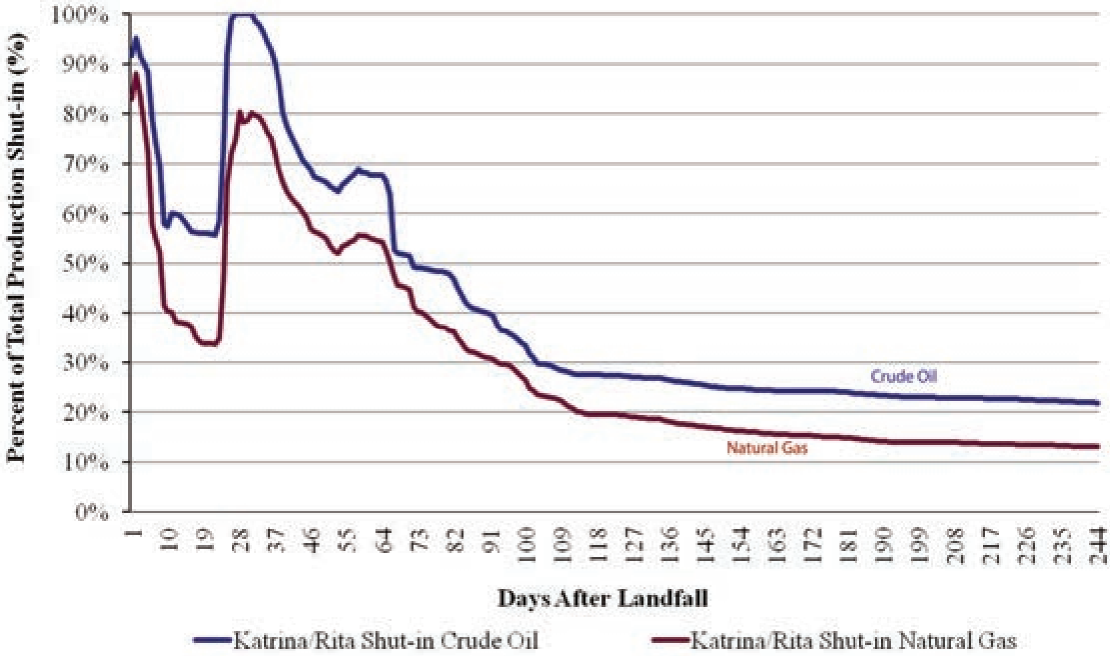


Figure 4.10 Time history of offshore oil and gas production in the Gulf of Mexico following Hurricane Katrina and Hurricane Rita. Katrina made landfall on day 1 and Rita on about day 28.

Based on climate projections discussed in chapter 2, other potentially important considerations for certain areas of the SE may include (a) increased droughts that reduce the availability of water for power generation; (b) higher temperatures, particularly during summer months, that cause electricity demands to rise over periods that are long enough to exceed supply and that could jeopardize electricity availability; (c) reductions in thermal power plant capacities due, for example, to higher water temperatures (see the Browns Ferry case study); and (d) possible effects on renewable energy sources such as biopower which are generally thought to be more sensitive to climate variability than fossil or nuclear energy systems(Wilbanks et al. 2008).

Indirect Effects of Climate Change on Energy Production and Use: Possible Cascading Impacts

Climate change may have important indirect implications for energy supply and use. Indirect effects could affect other economic sectors that, in turn, could have implications for energy supply and demand. Other areas of potential indirect effects include energy technology development and choice, energy prices, and energy security (Wilbanks et al. 2008). The following discussion illustrates this concept using southeastern agricultural and tourism energy needs as examples.

All agricultural crops have an optimum range of environmental conditions relative to maximum yield. Most crops cultivated in the SE are at, or near, their optimal growing temperatures for the CO_2 and water conditions that currently prevail. A rise in temperature and CO_2 concentration in the SE is expected to have a direct effect on the agricultural yield and may, consequently, affect related energy needs, such as for irrigation pumps.

Specifically, warmer temperatures will speed annual crops through their developmental phases but at a cost of possible increased daily water requirements and resulting lower grain number, size, and quality (Fraisse et al. 2009). Increased water requirements result in greater water pumping and transportation needs, all at a significant energy cost. Periods of drought may necessitate additional irrigation further increasing electric and diesel pump loads.

Overall, the southern tier of the SE is expected to increase its need for irrigation water and result in a corresponding energy demand. In contrast, the northern tier is expected to decrease its relative need for irrigation, with a corresponding decreased energy demand (Burkett et al. 2000).

Similar to crops, the effects of climate change on livestock are likely to be variable, based on the magnitude of the temperature increase, animal feed prices, and the cost of electricity for cooling. Dairy cows, for example, produce milk at an optimum temperature between 40°F and 75°F. Areas with increasing temperatures will consequently pose a cooling issue for livestock owners (Fraisse et al. 2009).

Another SE economic sector that has an important link to energy is tourism, a complex and multifaceted industry that includes a variety of operating sectors such as transportation, accommodations, food service, attractions and events, and outdoor recreation. Within the 11 state NCA SE region, tourism spending exceeds $181 billion, including $28.6 billion in tax receipts, and over two million jobs with a payroll of $48 billion (Long et al. 2011. US Travel Association 2010).

The important connection of tourism to energy is illustrated by vacation rentals where in 2007 in the USA they represented a $24.3 billion market, equaling more than 22% of the USA hotel market and 8% of the entire travel and tourism market. The vacation rental market is particularly strong in the south Atlantic region where fully one-third of the nation's vacation accommodations were rented in just three states: 22% in Florida, 7% in North Carolina and 5% in South Carolina (Connolly et al. 2009).

Each year, the average energy expenditure on American hotel rooms is $2,196, representing about 6% of all operating costs (Energy Star Program 2011). This relatively high level of energy consumption, along with water consumption, waste levels, and the use of potentially hazardous chemicals, has made this industry a focus of pollution prevention efforts. As such, the availability, type, and cost of energy, and its associated greenhouse emissions, are important considerations for climate change issues and the tourism sector in the SE.

4.3 Key Issues and Uncertainties

The US Climate Change Science Program has articulated a core set of research priorities to better understand the relationship between energy and climate change (Wilbanks et al. 2008). In general, the areas of research articulated at the national level are equally relevant to the SE USA. An improved ability to project climate change and its impacts at a more local level, a better understanding of changing regional patterns of energy use, and enhanced strategies to improve the resiliency of energy supply systems are just a few of the areas that will be needed to ensure energy supplies in the SE.

4.4 References

APA (American Planning Association). Policy Guide on Planning and Climate Change. Adopted April 27, 2008; Updated April 11, 2011. http://www.planning.org/policy/guides/pdf/climatechange.pdf

ASCE (American Society of Civil Engineers). 2009. Facts about energy. In *2009 report card of America's infrastructure*, 132-139. Reston, VA: American Society of Civil Engineers. http://www.infrastructurereportcard.org/fact-sheet/energy

Beamon, C. "Camden, Currituck eyed for turbines", *The Daily Advance*, May 5, 2011. http://www.thinkcurrituck.com/windenergy.aspx

Brown, M.A., E. Gumerman, Y. Baek, C. Morris, Y. Wang. 2010. *Renewable energy in the south: A policy brief*. Atlanta, GA: Georgia Institute of Technology: School of Public Policy. http://www.spp.gatech.edu/faculty/workingpapers/wp58.pdf

Burkett, V., R. Ritschard, S. McNulty, J.J. O'Brien, R. Abt, J. Jones, U. Hatch, B. Murray, S. Jagtap, J. Cruise. 2000. Potential consequences of climate variability and change for the southeastern United States. In *Climate change impacts on the United States: The potential consequences of climate variability and change,* 137-164. Washington, DC: US Global Change Research Program. http://www.usgcrp.gov/usgcrp/Library/nationalassessment/05SE.pdf

Clean Line Energy Partners. 2012. http://www.plainsandeasterncleanline.com/site/home

Connolly, D.J. and D. Quinby. 2009. *Vacation rental marketplace: Poised for change*. Sherman, CT: PhoCusWright

Dismukes, D.E. et al. 2011. *Diversifying energy industry risk in the Gulf of Mexico: Post-2004 changes in offshore oil and gas insurance markets*. Washington, DC: Bureau of Ocean Energy Management. http://www.data.boem.gov/PI/PDFImages/ESPIS/5/5164.pdf

Duke Energy. 2012. *Duke energy renewable & clean energy initiatives*. Charlotte, NC: Duke Energy. http://www.duke-energy.com/pdfs/Renewable-Clean-Energy-Initiatives-Fact.pdf

EEI (Edison Electric Institute). 2011. Coal fleet retirement announcements. Presented at 2011 EEI Wall Street Briefing, New York, NY, August 10, 2011. http://www.eei.org/meetings/Meeting%20Documents/2011-08-10-WallStreetBriefing-CoalFleetRetirementAnnouncementsSumm.pdf

EIA (Energy Information Adminstration). 2011a. *Annual energy outlook 2011: With projections to 2035*. Washington, DC: US Department of Energy. http://www.eia.gov/forecasts/archive/aeo11/pdf/0383(2011).pdf

EIA. (Energy Information Adminstration). 2011b. *State electricity profiles 2009*. Washington, DC: US Department of Energy. http://www.eia.gov/electricity/archive/aeo11/sep2009.pdf

EIA. (Energy Information Adminstration). 2012b. *Oil: Crude and petroleum products explained: Data and statistics*. Washington, DC: US Department of Energy. (Accessed 12/14/11) http://www.eia.gov/energyexplained/index.cfm?page=oil_home#tab2

EIA. (Energy Information Adminstration). 2012c. State profiles and energy estimates (Beta version). Washington, DC: US Department of Energy. http://www.eia.gov/beta/state/

EIA. (Energy Information Adminstration). 2012d. *U.S. crude oil, natural gas, and natural gas liquids proved reserves, 2010*. Washington, DC: U.S. Department of Energy. http://www.eia.gov/naturalgas/crudeoilreserves/pdf/uscrudeoil.pdf

EIA. (Energy Information Adminstration). 2012e. *Annual Coal Report 2011.* Washington, DC: US Department of Energy. http://www.eia.gov/coal/annual/pdf/acr.pdf

EIA. (Energy Information Adminstration). 2012f. *Coal explained: Coal mining and transportation.* Washington, DC: US Department of Energy. http://www.eia.gov/energyexplained/index.cfm?page=coal_mining

EIA. (Energy Information Adminstration). 2012g. *U.S. Crude Oil, Natural Gas, and NG Liquids Proved Reserves; Table 3. Principal shale gas plays: natural gas production and proved reserves, 2008-2010.* http://www.eia.gov/naturalgas/crudeoilreserves/pdf/table_3.pdf

EIA. (Energy Information Adminstration). 2012h. About U.S. Natural Gas Pipelines—Transporting Natural Gas. http://www.eia.gov/pub/oil_gas/natural_gas/analysis_publications/ngpipeline/index.html

EIA. (Energy Information Adminstration). 2012i. Renewables and Alternative Fuels. Table 1.13.B. Net Generation from Hydroelectric (Conventional) Power by State by Sector, Year-to-Date through December 2010 and 2009. http://www.eia.gov/cneaf/solar.renewables/page/hydroelec/hydroelec.html

EIA. (Energy Information Adminstration). 2012j. 2012 *Annual energy outlook: 2012*. Washington, DC: US Department of Energy. http://www.eia.gov/forecasts/aeo/tables_ref.cfm.pdf

EIA. (Energy Information Adminstration). 2012k. State Energy Data System (beta). http://www.eia.gov/beta/state/seds/?sid=US

EIA. (Energy Information Adminstration). 2012l. *Energy consumption estimates for major energy sources in physical units, 2009*. Washington, DC: US Department of Energy. http://www.eia.gov/beta/state/seds/data.cfm?incfile=sep_sum/plain_html/sum_use_tot.html

Energy Star Program. 2011. *Hotels: An overview of energy use and energy efficiency opportunities*. Washington, DC: US Environmental Protection Agency. http://www.energystar.gov/ia/business/challenge/learn_more/Hotel.pdf

FHA (Federal Highway Administration). 2009. *Highway statistics 2009*. Washington, DC: US Department of Transportation. http://www.fhwa.dot.gov/policyinformation/statistics/2009/

FPL (Florida Power and Light). 2012. FPL's Next Generation Solar Energy Centers. http://www.fpl.com/environment/solar/projects.shtml?id=alias

Force Technology. 2012. Pellets Atlas. *European Wood Pellet Markets*. http://www.pelletsatlas.info/cms/site.aspx?p=9064

Forisk Consulting, LLC. 2011. *Wood Bioenergy US Database (September 2011 edition; available by subscription).*

Fraisse, C.W., N.E. Breuer, D. Zierden, K.T. Ingram. 2009. From climate variability to climate change: Challenges and opportunities to extension. *Journal of Extension*, 47 (2): 2FEA9. http://www.joe.org/joe/2009april/pdf/JOE_v47_2a9.pdf

FTC (Federal Trade Commission). 2006. *Investigation of gasoline price manipulation and post-Katrina gasoline price increases*. Washington, DC: Federal Trade Commission. http://www.ftc.gov/reports/060518PublicGasolinePricesInvestigationReportFinal.pdf

Green, B.D. et al. 2006. *Geothermal--the energy under our feet: Geothermal resource estimates for the United States*. Golden, CO: National Renewable Energy Laboratory. http://www1.eere.energy.gov/geothermal/pdfs/40665.pdf

Hadley, S.W., D.J. Erickson III, J.L. Hernandez, C.T. Broniak, T.J. Blasing. 2006. Responses of energy use to climate change: A climate modeling study. *Geophysical research letters,* 33, L17703; doi:10.1029/2006GL026652

Heller, D. "Florida lands one of world's largest solar power farms", *Florida Coast News*, September 26, 2011. http://www.firstcoastnews.com/news/article/220499/4Florida-Lands-One-of-Worlds-Largest-Solar-Power-Farms

Hoffmann, J., S. Forbes, T. Feeley. 2004. *Estimating freshwater needs to meet 2025 electricity generating capacity forecasts*. Washington, DC: US Department of Energy. http://www.ne.doe.gov/peis/references/RM636_NETL_2004.pdf

Hunt, M.H., A. Giarrusso, V. Douangchai, S. Shelton. 2010. *Georgia's offshore renewable energy potential: Spatial mapping and planning*. Savannah, GA: Georgia Institute of Technology. http://www.cgis.gatech.edu/sites/files/cgis/files/FinalReport_GOREP.pdf

Iberdrola. 2011. Iberdrola renewables announces permit application for North Carolina wind power project. *Iberdrola Renewables*. http://www.iberdrolarenewables.us/rel_11.01.27.html

Irizarry-Rivera, A.A., J.A. Colucci-Rios, E. O'Neill-Carrillo. 2008. *Achievable renewable energy targets: For Puerto Rico's renewable energy portfolio standard*. San Juan, PR: Puerto Rico Energy Affairs Administration. http://www.uprm.edu/aret/docs/ARET_for_PR_RPS.pdf

Kosnick, L. 2008. The potential of water power in the fight against global warming in the US. *Energy Policy* 36 (9): 3252-3265. http://www.sciencedirect.com/science/article/pii/S0301421508002310

Lantz, E., D. Olis, A. Warran. 2011. *U.S. Virgin Islands energy road map: Analysis*. Golden, CO: National Renewable Energy Laboratory. http://www.edinenergy.org/pdfs/52360.pdf

Long, P. and A. Naar. 2011. *Tourism and Energy in the S.E. United States: A Briefing Paper*. Center for Sustainable Tourism, Division of Research and Graduate Studies, East Carolina University. Occasional paper series. pp. 1-3

Mills, A., R. Wiser, K. Porter. 2009. *The cost of transmission for wind energy: A review of transmission planning studies*. Berkeley, CA: Ernest Orlando Lawrence Berkeley National Laboratory. http://eetd.lbl.gov/ea/emp/reports/lbnl-1471e.pdf

MMS (Minerals Management Service). 2006. *Ocean current energy potential on the U.S. outer continental shelf*. Washington, DC: US Department of the Interior. http://ocsenergy.anl.gov/documents/docs/OCS_EIS_WhitePaper_Current.pdf

NREL (National Renewable Energy Laboratory). 2004. Office of Energy Efficiency and Renewable Energy. *Hydropower: Setting a Course for Our Energy Future*. Washington, DC: US Department of Energy. http://www.nrel.gov/docs/fy04osti/34916.pdf

NREL. (National Renewable Energy Laboratory). 2008a. Photovoltaic solar resource of the United States. Washington, DC: US Department of Energy. http://www.nrel.gov/gis/images/map_pv_national_lo-res.jpg

NREL. (National Renewable Energy Laboratory). 2008b. 20% wind energy by 2030: Increasing wind energy's contribution to U.S. electricity supply. Washington, DC: US Department of Energy. http://www.20percentwind.org/20percent_wind_energy_report_revOct08.pdf

NREL. (National Renewable Energy Laboratory). 2009. *2009 U.S. State Clean Energy Data Book.* http://www.nrel.gov/tech_deployment/state_local_activities/pdfs/48212.pdf

NREL. (National Renewable Energy Laboratory). "U.S. Virgin Islands makes aggressive energy pledge at NREL", *NREL Newsroom*, March 1, 2010. http://www.nrel.gov/news/press/2010/817.html

NREL. (National Renewable Energy Laboratory). 2012. *Dynamic Maps, Geographic Information System (GIS) Data and Analysis Tools website.* http://www.nrel.gov/gis/

NERC (North American Electric Reliability Corporation). 2010. *2010 long term reliability assessment*. Princeton, NJ: NERC. http://www.nerc.com/files/2010%20LTRA.pdf

News & Observer of Raleigh. "Plan for wind farm in N.C. floated", *News & Record,* September 6, 2011.

Nuclear Energy Institute. 2011. *State Electricity Generation Fuel Shares*. http://www.nei.org/resourcesandstats/documentlibrary/reliableandaffordableenergy/graphicsandcharts/stateelectricitygenerationfuelshares/

Platts. 2011. State regulators OK Alabama power 202-MW wind PPA, *Electric Power Daily*. http://www.tradewindenergy.com/WorkArea/downloadasset.aspx?id=2056

PREAA (Puerto Rico Energy Affairs Administration). 2012. Personal communication with Paul Simon, US EPA Region 2. See also http://www.aae.gobierno.pr/ and http://www.aae.gobierno.pr/det_news.asp?cnt_id=69

Savonis, M.J., V.R. Burkett, J.R. Potter. 2008. *Impacts of climate change and variability on transportation systems and infrastructure: Gulf Coast study, phase I*. Washington, DC: US Climate Change Science Program. http://www.climatescience.gov/Library/sap/sap4-7/final-report/sap4-7-final-all.pdf

Schwartz, M., D. Heimiller, S. Haymes, W. Musial. 2010. *Assessment of offshore wind energy resources for the United States*. Golden, CO: National Renewable Energy Laboratory. http://www.nrel.gov/docs/fy10osti/45889.pdf

Seim, H. et al. 2010. *Quantitative assessment of ocean-based renewable energy zones in North Carolina*. Chapel Hill, NC: University of North Carolina. http://www.nrel.gov/docs/fy11osti/52360.pdf

SERC Reliability Corporation. 2012. http://www.serc1.org/Application/HomePageView.aspx

Southern Company. 2012. *Kemper County Energy Facility.* http://www.mississippipower.com/kemper/home.asp

Southern Cross. 2012. http://www.southerncrosstransmission.com/

Toncray, M. "Future of wind turbines discussed during Mason Fiscal Court", *The Ledger Independent,* June 14, 2011.

TVA (Tennessee Valley Authority). 2012a. Wind turbine energy. Knoxville, TN: Tennessee Valley Authority. http://www.tva.gov/greenpowerswitch/wind_faq.htm

TVA. (Tennessee Valley Authority). 2012b. Solar power. Knoxville, TN: Tennessee Valley Authority. http://tva.gov/greenpowerswitch/green_mainfaq.htm

TVA. (Tennessee Valley Authority). 2012c. Wind purchases. Knoxville, TN: Tennessee Valley Authority. http://www.tva.gov/power/wind_purchases.htm

US EPA (US Environmental Protection Agency). 2011. *Regulatory impact analysis for the final mercury and air toxics standards*. Research Triangle Park, NC: US Environmental Protection Agency. http://www.epa.gov/ttn/ecas/regdata/RIAs/matsriafinal.pdf

US EPA. (US Environmental Protection Agency). 2012. *Impacts from Heat Waves*. http://www.epa.gov/climatechange/impacts-adaptation/health.html#impactsheat

US Travel Association. 2010. Retrieved from http://poweroftravel.org/statistics/datacenter.htm. October 10, 2010.

Wilbanks, T.J., V. Bhatt, D.E. Bilello, S.R. Bull, J. Ekmann, W.C. Horak, Y.J. Huang, M.D. Levine, M.J. Sale, D.K. Schmalzer, M.J. Scott. 2008. *Effects of climate change on energy production and use in the United States*. Washington, DC: US Climate Change Science Program. http://www.climatescience.gov/Library/sap/sap4-5/final-report/sap4-5-final-all.pdf

Wind Capital Group. 2011. *Sugarland Wind*. http://www.sugarlandwind.com/

Chapter 5

Climate Interactions with the Built Environment in the Southeast USA

LEAD AUTHOR

Dale Quattrochi (dale.quattrochi@nasa.gov; NASA, Earth Science Office, Marshall Space Flight Center, Huntsville, Alabama)

CONTRIBUTING AUTHORS

Kirstin Dow (Carolinas Integrated Sciences and Assessments; Department of Geography, University of South Carolina, Columbia, South Carolina)

Jeff Gaffney (Chair, Department of Chemistry, University of Arkansas at Little Rock, Little Rock, Arkansas)

Pat Long (Director, Center for Sustainable Tourism, East Carolina University, Greenville, North Carolina)

Steve McNulty (US Forest Service, Raleigh, North Carolina)

Marshall Shepherd (Department of Geography, University of Georgia, Athens, Georgia)

Scott Shuford (Development Services Department, City of Fayetteville, North Carolina)

Brian Stone (School of City and Regional Planning, Georgia Institute of Technology, Atlanta, Georgia)

The built environment in the Southeast (SE) United States comprises components influenced by human alteration of the landscape, and subsequent physical, environmental, and socio-economic systems related to landscape modification. Thus, the built environment is manifested at spatial scales ranging from small (e.g., offices, houses, hospitals, shopping malls, schools), to larger scales (e.g., transportation networks, communities), or as highly modified landscapes such as cities (Younger et al., 2008). The impacts of climate change on the built environment, therefore, may have a multitude of affects on humans and the land, and the impact of climate change may be exacerbated by the interaction of different events that singularly may be minor, but together, may have a synergistic set of impacts that are quite significant. As a consequence, climate change impacts will affect many aspects of the built environment in the southeastern US.

Key Findings

- Areas of the built environment likely to be affected by climate change include human health (from a specifically urban perspective primarily as related to air quality); the urban heat island effect, precipitation, urban flooding, the urban-wild land interface, tourism, energy, poverty and socio-economic vulnerability, migration, the coastal environment, and even have implications on national security.
- Development of adaptation plans to maintain built environment infrastructure and its natural milieu are imperative to cope with the effects of climate change and to ensure built environment sustainability.
- Because of the complexity of the built environment and its supporting ecosystems, we must operate at a component-by-component level to assess various types of adaptability measures needed to make the individual systems sustainable and resilient.
- Good stewardship of the resources that comprise the subcomponents of systems related to the built environment, as well as climate change adaptation planning, are primary requirements of success in dealing with these challenges.

5.1 Background

In this report, the "built environment" refers to the part of the overall landscape that is distinct from the natural environment, that part where humans have in some way transformed or imprinted non-natural features across the landscape. The impact of climate change has the potential to be exacerbated by the interaction of different events that singly could be minor, but together could have a synergistic set of impacts that are significant. Also, there are possible feedback mechanisms wherein the built environment, particularly cities, could affect weather and the climate on local and regional scales. The impacts of climate change on built environments in the Southeast (SE) will have a collective impact on the overall urban ecosystems for cities in the region. An urban ecosystem can be defined as a composite of (1) the natural environment, (2) the built environment, and (3) the socioeconomic environment (Clark 2008).

This chapter describes some of the key impacts that climate change will have on the urban ecosystems of the SE. The urban ecosystem is complex, encompassing interactions that occur between the urban atmosphere (e.g., urban-atmosphere interrelationships); the urban biosphere (e.g., vegetation, animal life); urban hydrosphere (e.g., water use); the urban lithosphere (e.g., soils/bedrock); and the urban fabric, of which the built environment is a fundamental part. Thus, the exchanges that occur within the urban ecosystem are highly intermingled wherein the disruption of one of the key elements can have cascading impacts throughout the entire ecosystem. How climate change may impact the built environment via alteration of inputs and outputs to the urban ecosystems in the southeastern USA are described in this section and threaded throughout the various chapters in this report. Moreover, a forthcoming National Climate Assessment (NCA) technical report, *U.S. Cities and Climate Change: Urban Infrastructure, and Vulnerability Issues,* has as its foundation, the assessment of how climate change will impact urban ecosystems in the USA, including extensive examples on impacts specific to the SE, and has one chapter dedicated entirely to ecosystems and the built environment (see Chapter 3, Section 3.6).

This section of the technical report focuses on the potential impacts that a changing climate is likely to have on several key aspects of the built environment in the southeastern USA: air quality; the urban heat island effect; precipitation; urban flooding; urban forestry and the urban-wild land interface; tourism; energy, poverty, and socioeconomic vulnerabilities; and urban migration. There are significant and definitive ways to mitigate and/or adapt to the effects of climate change on the built environment, and there are numerous example of actions being planned or undertaken in the SE, which are discussed in Chapter 13. The key to successfully implementing such strategies is to educate policy and decision makers, planners, and the general public. In this era of widespread usage of digital technology, there are numerous ways to communicate both the potential impacts of climate change on the built environment and subsequent methods for adapting to, or mitigating, these impacts. Establishment of publically accessible websites, blogs, and Wiki's that clearly articulate the nature of climate cause and effect impacts, and indicators that definitely point to the onset and progression of climate change are of critical importance within the overall scope of climate change education and communication. Such communications should be geared towards users of this information, such as metropolitan county and municipal governments, nonprofit or nongovernmental entitites, and the interested general public. This information must also be conveyed through online magazines, newspapers, and trade magazines, as well as the print and broadcast media. Additionally, there is an emerging industry of communication and engagement technology, especially in gaming and risk communications, that use relational databases similar to climate indicators that could be used to reach broad audiences, including interacting with K-12 and higher education (NCA 2011).

The impact of climate change on urban areas in the USA can potentially have far-reaching effects on the local and regional environment and in cities and their adjacent surroundings, sometimes referred to as the "periurban" environment. These impacts likely will affect the atmosphere above and around cities through alteration of the physical parameters that govern the land-atmosphere interface over urban areas. In turn, this may have broader impacts on atmospheric phenomena and regional interactions that encompass large-scale physical and environmental processes. Feedback mechanisms in urban areas have potential effects on physical parameters and interactions that can influence local and regional meteorology, and, in the long-term, the climate (World Bank 2010, Lankao 2008). Three impacts are of concern: (1) degradation of air quality; (2) an increase in the size and extent of the urban heat island (UHI) effect; and (3) changes in precipitation, including increases or decreases in amount or intensity.

Many of the examples of how climate change will affect the built environment are focused on the Atlanta, GA, metropolitan area only because several contributors to this report have extensively investigated key climate change impacts within this geographical area. The examples given in this section provide insight into how climate change will impact specific elements relevant to Atlanta in order to identify how key impacts will affect the largest urban/built environment within the SE. This certainly is not to the purposeful exclusion of examples for other cities across the southeastern USA, particularly those located on the Atlantic and Gulf of Mexico coasts. Many of the impacts that will affect coastal and inland cities in the southeastern USA are described in other sections of this report, as well as in a forthcoming NCA technical report *U.S. Cities and Climate Change: Urban, Infrastructure, and Vulnerability Issues*, and *Climate Change and Infrastructure, Urban Systems, and Vulnerabilities.*

5.2 Air Quality

Air quality in the SE, particularly over cities, is currently problematic and is projected to be even more so in the future (Stone 2008, Levy 2009). Purturbations that contribute to increases in stagnant air in many regions include (1) effects of increased temperatures on atmospheric reactions; (2) effects of increased temperature on atmospheric reaction rates; (3) effects of increased water vapor concentrations; and (4) effects of increased pollutant levels at the inflow boundary layer (Millstein and Harley 2009). An observed correlation between surface ozone and temperature in polluted regions suggests a detrimental effect of warming (Sillman and Samson 1995, Jacob and Winner 2006, Stone 2011). Studies of global climate models (GCMs) coupled with chemical transport models (CTMs) show that climate change alone will increase summertime surface ozone in polluted regions by 1 to 10 parts per billion (ppb) over the coming decade, with the largest effects in urban areas and during pollution episodes (Jacob and Winner 2006). Ozone (O_3), which is emitted at ground level, is created by a chemical reaction between oxides (NO_x) and volatile organic compounds (VOCs) in the presence of sunlight (Figure 5.1). Motor vehicle exhaust and industrial emissions, gasoline vapors, and chemical solvents also contribute to ozone formation. Sunlight and hot weather cause ground-level O_3 to form harmful concentrations in the air. Peak O_3 levels typically occur during hot, dry, stagnant summertime conditions that are exacerbated by the urban heat island effect. The length of the ozone season varies from region to region. Southern and southwestern cities could have an ozone season that lasts for several months.

The effect of increased temperatures on particulate matter is more complicated and uncertain than are the effects on ozone. Course particulate matter also contributes to air pollution. Particles with diameters between 2.5 and 10 micrometers (μg) are referred to as "coarse." Sources of coarse particles include crushing or grinding operations, and dust from paved and unpaved roads. Other types of particles may be formed in the air from chemical changes that are indirectly created when gases from burning fuels react with sunlight and water vapor. These particles can result from fuel combustion in motor vehicles, at power plants, and other industrial processes (EPA 2011). Studies illustrate that increased temperatures are likely to increase particulate matter in polluted environments by $\pm$0.1-1 μg m^{-3} over the coming decades (Jacob and Winner 2006).

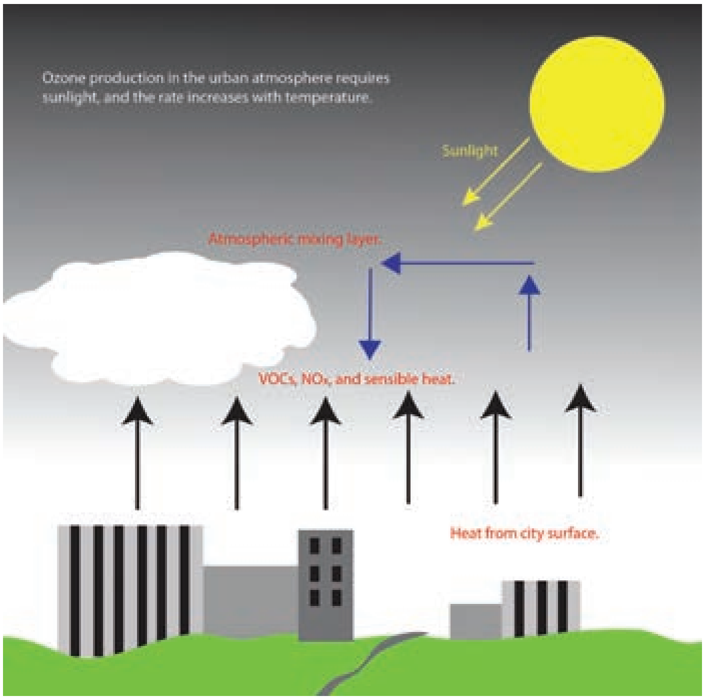


Figure 5.1 Ozone formation in the urban atmosphere (Quattrochi et al. 2006).

5.3 The Urban Heat Island Effect

The urban heat island effect is the term used when temperatures in urban environments surpass those seen in the surrounding rural areas (Landsberg 1981). The most significant effects have been observed in mid-latitude urban centers where the difference in temperatures is typically 2°C to 3°C or higher than surrounding rural areas (Oke 1987). Initial research on urban heat island issues has been on large megacity environments such as Mexico City (Oke et al. 1999) and New York City (Jin et al. 2005). However, temperature increases have also been observed in midscale urban areas such as Atlanta and other major urban centers in the southeastern USA (Stone 2007).

As urbanization continues and forest, agricultural, and natural open lands are consumed as part of urban growth, changes in land cover around cities lead to an urban heat island (UHI). A UHI is a dome of elevated air temperatures over cities. They arise as a result of the transition from pervious to impervious surfaces increase (Landsberg

1981, Voogt 2002, Souch and Grimmond 2006, Grimmond 2010, Weng et al. 2004, Hua and Weng 2008). Development of the UHI is generated by a number of causes related to the land and atmosphere interactions that occur over cities. These include surface geometry, surface thermal properties, surface conditions, anthropogenic heat, and the urban greenhouse effect (Voogt 2002). Research using historical meteorological and satellite data illustrate that the UHI size and dimension is associated with urban growth (Oke 1973, Remar 2010, ELI 2011). This relationship is expected to continue in cities in both developed and developing countries (Goldman 2004, Dodman 2009, Zhang et al. 2011, Zhou et al. 2011, Peng et al. 2012). Moreover, it is becoming clear that the amplitude of thermal intensity of the UHI has an effect on biomes surrounding cities (Imhoff et al. 2010). As cities continue to grow, more research will be required to determine how cities will affect and be affected by climate changes locally and regionally.

The most comprehensive study of urbanization and climate change in the USA focuses on 50 of the most populous metropolitan regions, including 13 cities in the SE. Through this study, monthly temperature records dating back to the 1950s were obtained for urban and proximate rural weather stations to assess the extent to which the UHI effect has increased in these regions over time. Urban temperature trends in the majority of the cities studied had increased at a rate of 0.31°C per decade compared to a rural rate of increase of 0.12°C per decade. These findings suggest that most large USA cities are warming at a rate more than double that of the planetary warming rate (Stone 2007).

Studies of temperatures in Atlanta, GA, show typical UHI effects characterized by differences in nighttime temperatures, for example, the differences between temperatures in urban and rural areas. The temperature differences where urban surfaces are much warmer that rural areas represent the main differences in increased heat loads, due primarily to increased heat trapped in the land-atmosphere boundary layer by various gases over urban areas at night (Zhou and Shepherd 2010). These higher levels of gases are a function of increased energy use, such as air conditioning and motor vehicle traffic in the urban area. In addition, the emission of reactive biogenic hydrocarbons from conifers and deciduous trees in nearby forested areas interacts with nitrogen oxide emissions in the urban area to form ozone, which like nitrogen dioxide, is a potent heat-trapping gas. Increases in regional background levels of ozone have been a major issue in the SE USA, particularly in urban centers such as Atlanta and Knoxville, which are located near heavily forested regions (Stone 2007 and 2008).

The increased pace of warming in urban environments in the USA is likely to amplify the intensity of heat waves in the present period as well as enhance the magnitude of future warming trends. For example, recent studies have found the UHI effect is contributing to the increasing number of extreme heat events in SE cities (Stone et al. 2010), as well as to an amplification of heat-wave events in large cities such as Atlanta (Zhou and Shepherd 2010). Increased rates of extreme heat are more evident in sprawling cities than in more spatially compact urban areas–a relationship that is independent of where the city is located from a climate perspective, metropolitan population size, or rate of population growth (Stone et al. 2010). Another study has pointed to the likelihood that global heat waves of the future will be more intense, greater in frequency, and longer lasting (Meehl and Tebaldi 2004).

Urban-scale climate change suggests potential for health threats associated with extreme heat events. Methods to mitigate the UHI effect are necessary to abate such threats. Over the last two decades, a large number of studies have found that variable combinations of tree planting and vegetative cover, albedo enhancement, and reductions in waste heat emissions reduce urban temperatures by a minimum of 1°C to more than 6°C (Kikegawa et al. 2006, Lynn et al.2009, Rosenzweig et al. 2006, Taha 2007, Zhou and Shepherd 2010). Of the various approaches to heat island mitigation, tree planting and other vegetative strategies where water resources are sufficient are generally found to be effective. Surface reflectivity and waste heat management typically account for somewhat lower reductions of near surface air temperatures, depending upon the spatial extent of coverage and the regional landscape type (Akbari and Konopacki 2005, Hart and Sailor 2009, Lynn et al. 2009, Zhou and Shepherd 2010).

Many synergies exist between strategies designed to control greenhouse gas emissions and strategies designed to reduce the urban heat island effect. For instance, a direct cooling of the ambient air through vegetation and albedo enhancement carries benefits for reduced energy consumption in the summer. While such strategies may serve to increase energy consumption during winter heating, studies have found the net benefits of reduced cooling for greenhouse emissions to be greater for mid- to low-latitude settings, a geographic region encompassing most large cities in the USA (Akbari, Konopacki, and Pomerantz 1999). When implemented extensively throughout a metropolitan region, such approaches have been shown to reduce energy consumption by as much as 10%, suggesting the potential for emission reductions and surface heat abatement to be managed concurrently (Akbari et al. 2001).

5.4 Effects on Precipitation

While urban heat islands and urban air pollution are fairly common in the public and scientific vernacular, the "urban rainfall effect" (Shepherd et al. 2010a) is not. Yet, the literature is fairly conclusive on urban land cover and pollution altering components of the hydroclimate, such as clouds, precipitation, and surface runoff. Historical perspectives, global confirmation of urban precipitation effects and societal implications are discussed in Ashley et al. 2012, Shepherd et al. 2011, Niyogi et al. 2011, Shepherd et al. 2010b. We present a few examples here with relevance to the SE region.

Ashley et al. (2012) conducted a climatological synthesis of how the urban environment modifies convection in various cities in the SE. Researchers used lightning and high-resolution radar to study precipitation in the cities and adjacent control regions during June through August over a 10-year period. The results confirmed positive urban amplification of thunderstorm activity (frequency and intensity) for larger SE cities such as Atlanta. Figure 5.2 illustrates that Atlanta's convective frequency counts and occurrences slope from the central business district to relatively lower values in rural areas, a conclusion that is consistent with numerous findings in the literature. Results vary as a function of size and geometry of various cities.

On the other hand, Rosenfeld et al. (2008) discussed the apparent conflicting role of aerosols in the precipitation processes. Aerosols may enhance or suppress convection under certain atmospheric conditions. While research into urban aerosol effects on precipitation has been conducted globally (Lin et al. 2011, Stjern et al. 2011, Jin and

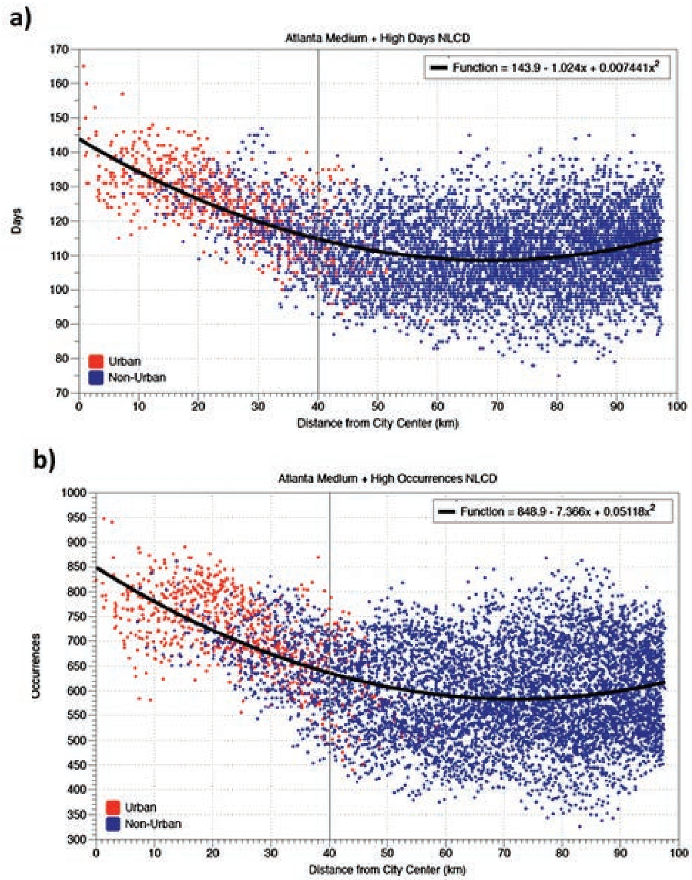


Figure 5.2 Composite radar analysis for Atlanta, GA: (a) The total number of days ≥ 40 dBZ and (b) the total number of 5-minute occurrences ≥ 40 dBZ for each 2-km grid cell versus distance from city center in the Atlanta domain for the 10-year, June through August. National Land Cover Database urban delineated cells are colored red/grey, whereas nonurban cells are blue/black. (Ashley et al. 2012).

Shepherd 2008), more research is needed in the USA. Although uncertainty remains regarding supporting details driving change in precipitation, the literature confirms the influence of the built, urban environment on precipitation. Both observational and numerical modeling research (Shepherd et al. 2010b) have indicated that one or a combination of the following processes contribute to urban precipitation effects: (1) atmospheric destabilization related to the heat island and thermal mixing, (2) enhanced convergence from building-induced mechanical turbulence and mixing, (3) modified dynamic and microphysical processes related to urban aerosols, and (4) bifurcation-physical modification because of physical or thermodynamic barriers. More research is needed to determine the relative contributions of these processes while considering other factors such as topography, urban geometry, seasonality, diurnal effects, and moisture.

While the urban rainfall effect is an important scientific issue in its own right, there are also vital connections of this effect on contemporary research and prediction problems in climatology, meteorology, and hydrology. Precipitation issues in a built, urban environment present significant challenges for key societal processes and potential vulnerabilities related to urban flooding, urban planning, public health, water resources, agricultural systems and hazard management. Some of these are discussed in the following sections.

Urban Flooding

The Intergovernmental Panel on Climate Change (IPCC 2007) notes that instances of hydrological extremes such as flooding and drought have increased markedly in the last three decades with more intense and longer episodes (Trenberth et al. 2007). Analysis by the National Oceanic and Atmospheric Administration's (NOAA) National Climatic Data Center (NCDC 2009) suggests that in the SE an increasing trend is detectable in the extreme precipitation record (Figure 5.3). Increased urban flooding has been noted in several global regions including SE cities such as Atlanta and Nashville. The southeastern USA will be increasingly vulnerable to extreme hydroclimate events because of increasing populations and population density (Seager et al. 2009). While many urban-related floods are explained by large scale meteorological and hydrological forcing (Shepherd et al. 2011), it is also clear that an urban environment may modify or increase the likelihood of flooding. Ntelekos et al. (2007) suggested that urban land cover and aerosols could have assisted in the meteorological set-up for a flood event in the Baltimore-Washington DC area. Shepherd et al. (2011) speculated that the urban landscape, through urban-enhanced precipitation, discussed elsewhere in this report, could have explained various regions of enhanced flooding around Atlanta during the historic North Georgia floods of 2009 (Figure 5.4) even as large-scale hydro-meteorological processes governed the main flooding event.

The conversion of natural landscapes to built, urban environments changes various water cycle components including evapotranspiration, surface runoff, infiltration, precipitation, and groundwater recharge. In discussing the Atlanta floods, Shepherd et al. (2011) noted that urban impervious surfaces increased the land surface hydrological response in Atlanta in a similar manner observed in other urban locations. Reynolds et al. (2008) found that impervious surfaces in Houston distributed stormwater to conveyance systems with more volume over a shorter amount of time, which increases the risk of overwhelming the capacity of the system.

Urban areas are increasingly affected by complex hydrometeorological-urban interactions. Scholars and stakeholders are beginning to question whether urban planners have properly considered shifting precipitation regimes (intensity and/or frequency) associated with urban hydroclimate changes, land use changes and expanding areas of impervious surfaces, and climate change (Burian et al. 2004). Hydrometeorological scientists have warned that current urban flood assessment is based on outdated assumptions concerning rainfall intensity, frequency, and stability. Modeling tools and methodologies must be updated with current data that reflect changing urban landscapes, population density, and climate predictions in order for mitigation and adaptation plans to be successful.

Hydrological modeling systems are important tools for assessment and prediction of hydrological flows (Poelmans et al. 2010). Urban impervious surface areas and morphological parameters are represented in such models using various technologies, such

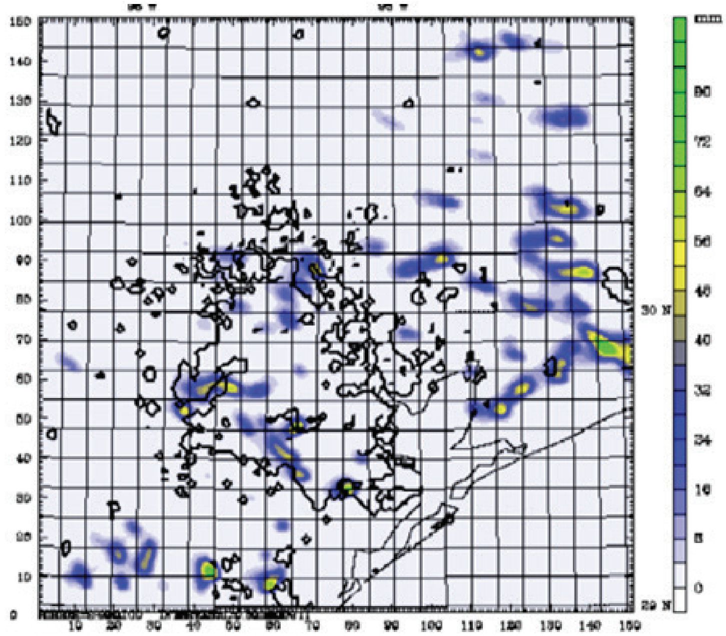


Figure 5.3 Difference (2025 Current Land Cover) in simulated rainfall amount for a typical case day in Houston, Texas. Black outline represents 2025 urban land cover. Rainfall amounts illustrated in the image correspond to the bar graph on the right hand side of the figure (Shepherd et al. 2010a).

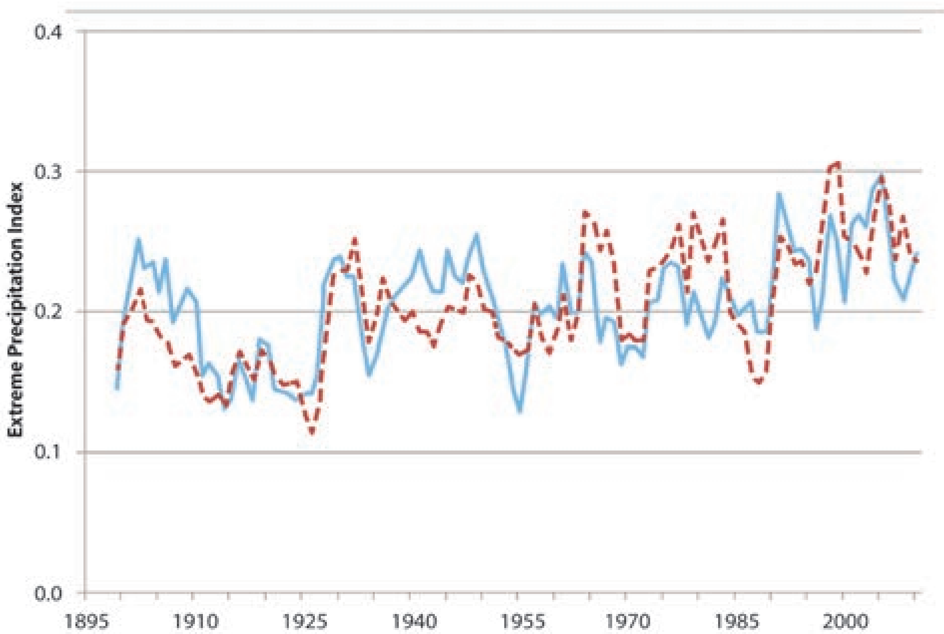


Figure 5.4 Trends in the extreme precipitation index for the southeastern USA. Red dotted line is 1 day, 1 in 5-year event. Blue line is 5-day, 1 in 5-year event Kunkel et al. 2013).

as remote sensing, aerial photography, high-resolution optical imagery, and LIDAR. However, Coon and Reddy (2008) noted that hydrological modeling still suffers from uncertainties related to input precipitation data, calibration errors, assumptions and parameterizations, land cover classification errors, and catchment scale-transfer errors. Reduction of such errors is required as increasingly complex urban landscapes and processes become explicitly represented in models.

Weather, climate, and hydrological systems are linked. Researchers and stakeholders must work collaboratively to understand what aspects of and in what ways the built environment modifies water cycle processes.

5.5 Effects on the Wild Land-Urban Interface (WUI)

The population of the SE is increasing at one of the fastest rates in the USA (US Census Bureau 2010). As a result there are unique forest-management challenges associated with climate change and population interactions. Land managers are developing adaptation and mitigation strategies, but the implementation of these plans could be significantly hampered by ownership fragmentation associated with population growth. Historically, private landowners controlled large parcels of forestland, but the size of these individually owned parcels has been steadily decreasing for decades (Wear and Greis 2002). As the parcel size decreases below levels that are commercially viable to manage, the cost and complexity of management increases and activities such as wildfire fuel reductions, selective harvesting to encourage more climate-change adapted species such as hickory and oak, or the removal of trees in insect outbreak areas are less likely to occur (Wear and Greis 2002). Increased drought events (Seager et al. 2009), longer insect breeding seasons (Ayres and Lombardero 2000), and increased potential for strong hurricanes (Mann and Emanuel 2006) could synergistically combine with reduced management options to significantly reduce forest health (McNulty and Boggs 2010).

In addition to the challenges associated with managing SE ecosystems, urban and WUI dwellers will likely face new challenges associated with climate variability. General circulation models universally project increasing air temperature and increases or decreases in precipitation across the region (see Chapter 2). As air temperature increases, forest water use increases. Given that forests represent approximately 40% of the total land area within the SE (Fry et al. 2009), future forests may provide less water for metropolitan areas even if precipitation increases (Sun et al. 2008). While the southeastern USA is considered a "water rich" region, water limitations in metropolitan areas could impact current and future economic development (Town of Apex 2012). As with other areas of the country, water disputes have already caused intense legal battles in the SE. Most notable is the cross-state dispute that formed around Atlanta's population increase subsequent draw-downs of water in Lake Lanier, which affects flow into the Chattahoochee River, which serves the neighboring states of Alabama and Florida. As a consequence, there has been sustained litigation against Georgia by these neighboring states. (Moore 1999, Goodman 2010, The Economist, 2010).

Climate change could also affect recreational activities due to altered ecosystems and unusual weather patterns, extreme weather events, and fire. Fisheries could decline, adequate snow for winter sports is likely to decrease, and inclement weather could keep people from enjoying outdoor activities (Wear and Greis 2002, Scholze et al. 2006, Dale et al. 2001).

Despite being affected by climate change, urban and WUI areas also have the potential to help mitigate these effects. Heavily wooded SE cities provide plenty of trees that cool the air through evapotranspiration and sequester carbon dioxide in their trunks as they grow. City parks, lawns, and green spaces have the potential to sequester carbon when properly managed and have the potential to become climate change regulators as urban land managers learn how to utilize the unique conditions present in urban and WUI ecosystems.

5.6 Vulnerability and Risks to Tourism

Tourism is a complex and multifaceted industry that includes a variety of operating sectors such as transportation, accommodations, food service, attractions, entertainment, events, travel trade, tourism services, and adventure and outdoor recreation. In the USA as of 2010, business and leisure travel accounts for $758.7 billion of travel expenditures, $188.4 billion of travel-generated payroll and 7.4 million jobs, $117.6 billion of travel-generated tax revenue, and $31.7 billion of travel trade surplus. International travelers paid a total of $31.3 billion to domestic air carriers on international passenger fares, with additional spending on international passenger fares totaling $134.4 billion (US Travel Association 2010a). Tourism spending in the SE exceeds $181 billion in sales, garner $28.6 billion in tax receipts, and creates 2.06 million jobs with a payroll of about $48 billion (US Travel Association 2010b).

Climate change is likely to create distinct and unique changes in the tourism industry in the southeastern USA. Potential impacts to the SE include droughts, floods, water quality problems, sea level rise, storm surge, heat stress, poor air quality, extreme weather events, increases in heavy downpours, rising temperatures, lengthening growing seasons, and alterations in river flows (USGCRP 2009). The effects of some of these climate changes will impact consumer travel tourism and potentially create new markets while collapsing others (Scott and Lemieux 2009). For example, having prolonged warmer days in the spring and fall would extend the golfing season, whereas such days would cut short the snow skiing season. Coastal areas that rely on tourism will likely experience the physical effects of climate change in a variety of ways from ecosystem stress and habitat loss to saltwater intrusion, drought, and flooding. Direct economic losses may include higher insurance costs, lower property values, and a decrease in tourism. However, local or regional factors, such as projected changes in population and economic growth, as well as specific weather events, may cause some of these direct economic losses (Bin et al. 2007).

Tourism and attendant recreational sectors could adapt to a changing climate in various ways, for example, alternative sources or recycled water available for golf courses, water-saving measures for the hospitality industry, or changes in a business model for ski slopes—more summer activities (Becken and Hay 2007, Curtis et al. 2011). As noted by Scott and Lemieux (2009), climate change will constitute an increasing risk for tourism operators in many destinations. Many tourism activities are heavily dependent on the climate and insurance policies that are increasingly affected by natural hazards. Thus, accurate weather information and forecasting of extreme climatic events are becoming ever more important for tourism businesses (Scott and Lemieux 2009).

Vacation and Second Homes

Vacation and second homes are a substantive part of the built environment highly susceptible to the effects of climate change in the SE. These properties are most often found in coastal or mountain environments that are highly desirable places to live and vacation due to their natural beauty and recreational amenities (Long et. al 2012). The 2010 US Census Data for General Housing Characteristics reports more than 1.4 million housing units in the "Seasonal, Recreational or Occasional Use" category across the 11-state SE region, representing just over 4% of the housing stock (Mazur and Wilson 2011). Collateral expenditures increase the value of vacation and secondary homes to the communities they are in and include economic benefits from construction and related services, enhanced retail trade, real estate services, and leisure and hospitality services (Long and Hao 2009).

Dare County, NC, provides an example of how climate change affects such communities. The county represents a significant part of the state's Outer Banks tourism trade and more than 70% of the housing stock consists of second homes. The Outer Banks is increasingly susceptible to rising sea level and more frequent and severe storms. For example, the cost of building one bridge over a storm-created inlet that severed NC Highway 12 just north of Rodanthe was $12 million (Waggoner 2011). In another study (Long and Hao 2009), full-time and second home property owners were asked about perceived effects on future property values of sea level rise; coastal flooding; number and intensity of coastal storms; availability of fresh water; and changes in temperature, humidity, and precipitation. The study was conducted just prior to the impact of Hurricane Irene in 2011 that affected the coastal county of Currituck, North Carolina, located just north of Dare County. The study found significant statistical differences between the concerns expressed by resident property owners. These statistical differences were primarily a function of education level. People who perceived that climate and weather would affect both their current property ownership and future property values had a comparatively high level of education. Property owners that perceived climate and weather would not affect their current property ownership, but would nevertheless affect their future property values, were the most educated. Respondents who perceived that climate and weather would not affect their current property ownership or their future property values had the lowest level of education.

Second homes represent a substantial part of the vacation rental market. In 2009 vacation rentals in the USA represented a $24.3 billion market, which at the time represented 22% of the hotel market and 8% of the travel and tourism market (PhoCusWright 2009). The vacation rental market is a significant part of the economy in the SE. The PhoCusWright study found that Florida, North Carolina, and South Carolina represented 34% of the total vacation rental market. The Outer Banks Visitors Bureau also found that 43% of overnight visitors used vacation rental homes (Outer Banks 2005-2006).

Extreme weather events in the SE caused by climate change will likely impact the tourism economy in various direct or indirect ways. For example, people could choose other locations for second homes; storms may cause severe damange to vacation properties, transportation infrastructure, and utilities; erosion could increasingly endanger coastal vacation homes; and erratic weather patterns could deter vacationers. More research is needed to investigate adaptation and mitigation strategies for the tourism industry. Research might include developing databases for the tourism industry to assess climate prediction models and help decision makers to make better informed choices depending upon location and circumstances; for instance coastal versus mountain areas; looking at how various tourist-related businesses have responded to disasters and why some fared better than others; and analyzing market concerns and solutions for tourism with regard to climate change impact.

5.7 Impacts on Energy, Poverty, and Socioeconomic Vulnerability

Climate models for the Southeast project substantial increases in days above 90°F and in numbers of consecutive very warm days. (See regional projections being finalized by Chip Konrad and Chris Furman. Also see Table 2, Kunkel et al. 2013). Comparisons of 1971 to 2000 records with 2041 to 2070 projections from dynamic and statistically downscaled models show increases of 44% to 49% in the number of cooling degree days. There is less consistency in projections of the maximum run days for high temperatures. Mean projected increases range from 97% to 234% for maximum runs of days greater than 95°F and 132% to 575% for maximum runs of days greater than 100° Fahrenheit (Table 2.2 in Chapter 2).

The potential impacts of increased cooling costs are significant because meeting energy costs is already a burden for many in the SE. Nationwide in 2009, home cooling costs represented approximately 12% of residential energy expenditures (USDHHS 2011). In the southern USA, according to US Census regions data, 98% of households overall have means to cool their home including central and room air conditioning, and other cooling devices such as ceiling fans, or evaporative coolers. Southern low-income households spent approximately 10% of their income on energy costs (USDHHS 2011). Low income households are defined as those households with incomes at or below 150 percent of HHS poverty guidelines. Of that 10% total for low-income households in this broadly defined southern region, almost 4% is related to home cooling (USDHHS 2011).

The Low Income Home Energy Assistance Program (LIHEAP) administered by the US Department of Health and Human Services serves a subset of low-income households (USDHS 2011). Table 5.1 provides more information on the number of households eligible for LIHEAP assistance, the distribution by state within the SE, and the numbers of household members who could be particularly stressed due to other vulnerabilities. There are approximately 11.5 million households in the National Climate Assessment SE region that are eligible for assistance to cover energy costs (Table 5.1). The largest number of households and households with a member over 60 years old are in Florida, where the greatest increases in heating-degree days are projected (Figure 2.12, Chapter 2).

Table 5.1 Households in the Southeastern United States Eligible for Energy Assistance.

Low-Income Home Energy Assistance Program (LIHEAP) Home Energy Notebook for FY 2009: Appendix B: Income Eligible Household Estimates

State-level estimates of the number of LIHEAP income eligible households using the Federal maximum LIHEAP income standard of 75 percent of SMI by vulnerability category [1,2]

Three-Year American Community Survey (ACS) 2007-2009

			LIHEAP eligible households by vulnerability category		
	Total number of LIHEAP eligible house-holds [3,4]	**At least one person 60+**	**At least one child less than 6 years old**	**At Least one person with a disability** [5]	**LIHEAP eligible households with no vulnerable members**
Alabama	730,898	270,669	126,992	107,911	270,852
Arkansas	409,926	152,575	80,822	59,225	141,515
Florida	2,562,971	1,099,474	415,284	209,177	951,745
Georgia	1,308,090	422,644	277,853	132,709	542,440
Kentucky	675,932	248,033	125,256	121,642	227,068
Louisiana	649,385	234,254	122,056	84,046	247,838
Mississippi	437,229	160,342	85,644	69,730	153,240
Missouri	839,453	310,617	152,937	100,394	313,575
North Carolina	1,304,413	461,248	253,120	136,434	513,727
South Carolina	629,722	234,882	116,713	70,706	240,890
Tennessee	914,211	339,673	168,986	117,288	341,212
Virginia	1,025,078	378,297	186,910	98,574	406,974
SE states total	11,487,308	4,312,708	2,112,573	1,307,836	4,351,076
All States	41,767,370	15,379,522	7,990,905	4,187,416	16,155,505
	27.5%	28.0%	26.4%	31.2%	26.9%

Data for this table are summarized from “Administration for Children and Families LIHEAP Home Energy Note-book for Fiscal Year 2009” (USDHHS 2011).

[1] State estimates are subject to sampling error and may not sum to “All States” total due to rounding.

[2] The greater of 75% of state median income estimates or 150% of the US Health and Human Services (HHS) Poverty Guidelines. For “All States,” 75% of state median income is greater than 150% of the HHS Poverty Guide lines.

[3] The three-year ACS estimate of the total number of all USA households is 113,104,074.

[4] A household can be counted under more than one vulnerability category.

[5] The U.S. Census Bureau changed the questions on disability in ACS in 2008. Since the new questions were not comparable to those in previous years, all disability questions were removed from the 2007-2009 ACS data file. The definition only includes individuals ages 15 through 64 who received Supplemental Security Income in the past year and non-widowed individuals ages 19 through 61 who received Social Security income in the past year. The reader should exercise caution in comparing these estimates with those in previous LIHEAP Notebooks.

5.8 Impacts on National Security

Recently, the US Department of Defense and other national security agencies in the USA have released key reports addressing aspects of climate change impacts on national security (Defense Science Board Task Force 2011, Committee on National Security Implications of Climate Change for US Naval Forces 2011). These reports highlight key issues related to how changing climate events such as sea level rise, declining sea ice, and extreme weather are apt to affect the built infrastructure supporting national security. The reports provide information on the complex national and international security issues that arise in a stressed climate system. These security issues include, for example, food and water supply, humanitarian aid, and climate refugees and migration. The SE region is home to several military installations and assets (SERDP 2012). This unique built environment can be particularly vulnerable so it is important to continue to monitor the implications, study climate changes carefully, and plan mitigation and adaptation strategies.

5.9 Impacts on Urban Migration

Throughout history, people have frequently migrated because of climate, moving from coastal areas because of flooding or from drought-stricken areas in search of water and better growing conditions. In contemporary times, the USA has seen a migration to the Sunbelt during the past several decades as many people, particularly retirees, sought more temperate weather (Svart 1976, Graves 1980). Climate change, however, can greatly affect shifts in populations when severe weather events, such as Hurricane Katrina or droughts, devastate SE regions. A significant portion of the population of New Orleans, for instance, has chosen not to return to that city after Hurricane Katrina (Grier 2005, Groen and Polivka 2009, Fussell, Sastry, VanLandingham, 2010). In other cases migration may be due to physical conditions such as property inundation due to sea-level rise or lifestyle choices such as a desire for cooler weather.

Potable water supply for urban areas has the potential to be affected directly and indirectly by climate change (Cromwell, Smith, and Raucher 2007). Regional climate change impacts that include increased frequency of drought, greater evaporation as a result of higher temperatures, saltwater intrusion, reduced groundwater recharge, and flooding threaten ground and surface water supplies. As water supply options become more limited, technological and economic water treatment challenges may emerge as more polluted water sources or saltwater sources are pressed into service. Higher temperatures could result in algae and microbe growth. Additionally, water treatment plants, transmission lines, pump stations, and other infrastructure that are located in areas vulnerable to flooding, temporary or permanent inundation, or extreme weather events will likely be at risk. Constraints in water supply and treatment options may result in limits to future growth, including an inability to meet the needs of industry or even relocation of existing residents. Communities that want to grow—or simply maintain current population—must secure stable future water supplies, which could be more difficult due to climate change challenges. Communities that cannot find adequate potable water supplies could be subject to outmigration and economic difficulties.

Regions of the USA projected to experience less severe climate change impacts, stand to gain population and economic development. (Shuford et al. 2010) The SE USA is particularly vulnerable to climate change impacts along coastal areas, and up to 46,000 km² (17,760 mi²) of land could be lost in the region from a sea level rise of 1.5 meters. (Titus and Richman 2000) The Miami, FL, metropolitan area is projected to have 4,795,000 people exposed to coastal flooding by 2070, ranking ninth in the world's coastal metropolitan regions for such exposure (Nicholls et al. 2008).

Rapid population growth may strain infrastructure, cause tension between new residents and established ones, influence changes in community character, and create significant stress on social services. These effects may be compounded if there are USA humanitarian efforts to relocate noncitizens from severely impacted areas of the world. Some changes, though, may be perceived as positive for some urban residents. For instance, rapid population decline in communities may create more affordable housing, less congestion, and more open space (Shuford et. al, 2010). Additionally, as people move away from vulnerable areas population increases may result in economic booms for areas less affected by climate change effects.

5.10 Impacts on Coastal Environments

Although built environments throughout the southeastern USA are subject to the impacts previously discussed in this section, perhaps the most vulnerable areas affected by climate change are built environments located in coastal areas. Given the extensive area of the coastal SE that is urbanized, there are numerous examples in this report of possible impacts climate change could have on coastal cities in the region. These impacts are far-ranging and include storm surges from tropical storms (Chapter 2), heavy precipitation events (Chapter 2, Section 2.3.2), and sea level rise (Chapter 2, Section 2.3.8). Specific aspects of climate change impacts on coastal built environments, such as human health and transportation, are described throughout this report (Chapters 3, 4, 6, and 13). An even more thorough examination of climate change impacts on coastal cities in the USA is presented in the forthcoming NCA technical report *U.S. Cities and Climate Change: Urban, Infrastructure, and Vulnerability Issues* (Chapter 3, Section 3.7).

5.11 Summary of Climate Change Impacts on the Built Environment

It is apparent that the impacts of climate change on the built environment will be local and regional, direct and indirect and could potentially range from mild to severe. These impacts may be single events such as hurricanes, but likely will be interrelated; for example, heavy precipitation events that create regional flooding will synergistically have a series of cascading impacts, such as effects on transportation and utilities, residential and business infrastructure, land use, and population. Moreover, the built environment has the potential to impact climate via mechanisms related to physical exchanges with the lower atmosphere, such as an increase in the intensity and size of the urban heat island effect or an increase or decrease in precipitation over urban areas. Climate changes caused by circumstances external to (e.g., global increase in greenhouse gases) or directly related to (e.g., increase in impervious versus pervious surfaces) the built environment will have have wide-ranging affects on social and economic structure. While these impacts will be felt at different spatial and temporal scales, they could have significant effects on the socioeconomic and demographic structure of the built environment. In the SE, population fluctuations, economic decline including a potential decline in tourism, vulnerability of energy supplies, and challenges to built infrastructure and natural areas are apt to be consequences of climate changes in the coming decades.

The outlook, however, is not entirely gloomy. Adaptation strategies within the built environment are numerous. For example, increased tree planting, albedo enhancement (e.g., white roofs), and green roofs (e.g., plants on the roof) have the potential to moderate some effects of climate change especially related to the urban heat island. Such actions could create opportunities for reduced energy consumption, reduced heat impacts on people, and reduced GHG emissions, thus contributing both adaptations and mitigation actions. More pervious surfaces (e.g., porous paving) result in less runoff, which will decrease the magnitude of flooding during heavy precipitation events and contribute to aquifer recharge. An important aspect to successfully meeting the challenges of future climate changes is the inclusion of policy and decision makers, planners, and the general public in the planning, education efforts, and discussions. The discussions should embrace many aspects of the issues including the long-term cost benefits of adaptation strategies and how and when to apply practical strategies for implementation

5.12 References

Akbari, H. and S. Konopacki. 2005. Calculating energy saving potentials of heat-island reduction strategies. *Energy Policy* 33 (6): 721-756.

Akbari, H., S. Konopacki, M. Pomerantz. 1999. Cooling energy savings potential of reflective roofs for residential and commercial buildings in the United States. *Energy* 24 (5): 391-407.

Akbari, H., M. Pomerantz, H. Taha. 2001. Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. *Solar Energy* 70 (3): 295-310.

Ashley, W.S., M.L. Bentley, J. Anthony Stallins. 2012. Urban induced thunderstorm modification in the southeast United States. *Climatic Change,* 113 (2): 481-498.

Ayres, M. and M.J. Lombardero. 2000. Assessing the consequences of global change for forest disturbance from herbivores and pathogens. *The Science of the Total Environment* 262 (3): 263-286.

Becken, S. and J. Hay 2007. *Tourism and Climate Change: Risks and Opportunities*. Channel View Publications, Bristol, UK.

Bin, O., C. Dumas, B. poulter, and J. Whitehead 2007. Measuring the Impacts of Climate Changes on North Carolina Coastal Resources. Final report for the National Committee on Energy Policy. Washington, DC, 91pp.

Burian, S., W. Stetson, W.S. Han, J.K.S. Ching, D.W. Byun. 2004. *High-resolution dataset of urban canopy parameters for Houston, Texas*. Vancouver: Proceedings of the AMS Fifth Conference on the Urban Environment.

Clark, A.L. 2008. Environmental challenges to urban planning: Fringe areas, ecological footprints and climate change. *Science* 319.

Committee on National Security Implications of Climate Change for U.S. Naval Forces. 2011. *National Security Implications of Climate Change for U.S. Naval Forces*. Washington, DC: The National Academies Press.

Coon, W.F. and J.E. Reddy. 2008. *Hydrologic and water-quality characterization and modeling of the Onondaga Lake Basin, Onondaga County, New York*. Reston, VA: US Geological Survey Scientific Investigations.

Cromwell, J.E., J.B. Smith, R.S. Raucher 2007. Implications of Climate Change for Urban Water Utilities. Report prepared for the Association of Metropolitan Agencies http://www.amwa.net/galleries/climate-change/AMWA_Climate_Change_Paper_12.13.07.pdf

Curtis, S., P. Long, J. Arrigo. 2011. Climate, weather, and tourism: Issues and opportunities. *Bulletin of the American Meteorological Society* 92 (3): 361-363.

Curtis, S., Arrigo, J., Long, P. and Covington, R. (2010). Climate, weather and tourism: Bridging science and practice. Publication of the Center for Sustainable Tourism, Division of Research and Graduate Studies. East Carolina University: Greenville, NC.

Dale, V.H., L.A. Joyce, S.G. McNulty, R.P. Neilson, M.P. Ayres, M.D. Flannigan, P.J. Hanson, L.C. Irland, A.E. Lugo, C.J. Peterson, D. Simberloff, F.J. Swanson, B.J. Stocks, B.M. Wotton. 2001. Climate change and forest disturbances. *BioScience* 51 (9): 723-734.

Defense Science Board Task Force. 2011. *Trends and implications of climate change for national and international security*. Washington, DC: Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics. http://www.acq.osd.mil/dsb/reports/ADA552760.pdf

Dodman D. 2009. Urban Density and Climate Change. United Nations Population Fund (UNFPA). http://www.unfpa.org/webdav/site/global/users/schensul/public/CCPD/papers/Dodman%20Paper.pdf

ELI (Environmental Literacy and Inquiry). 2011. Urban sprawl, urban heat islands, and urban deforestation. http://www.ei.lehigh.edu/eli/luc/sprawl.html.

EPA 2012. Air Trends. U.S. Environmental Protection Agency www.epa.gov/airtrends/index.html.

Fussell, E., N. Sastry, M. VanLandingham. 2010. Race, socioeconomic status, and return migration to New Orleans after Hurricane Katrina. *Population and Environment* 31: 20-42.

Fry, J.A., M.J. Coan, C.G. Homer, D.K. Meyer, J.D. Wickham. 2009. *Completion of the national land cover database (NLCD) 1992–2001 land cover change retrofit product: US Geological Survey Open-File Report*. Reston, VA: US Geological Survey. http://pubs.usgs.gov/of/2008/1379/pdf/ofr2008-1379.pdf.

Goldman J.S., 2004. The built environment induced urban heat island effect in rapidly urbanizing arid regions—a sustainable urban engineering complexity. *Environmental Sciences* 1: 321-349.

Goodman, J. 2010. Southeastern water wars. *Governing* (February). http://www.governing.com/topics/energy-env/Southeastern-Water-Wars.html

Graves, P.E. 1980. Migration and climate. *Journal of Regional Science* 20 (2): 227-237.

Grier, P. 2005. The Great Katrina Migration. *The Christian Science Monitor* (September). http://www.csmonitor.com/2005/0912/p01s01-ussc.html.

Grimmond, C.S.B., M. Roth, T.R. Oke, Y.C. Au, M. Best, R. Betts, G. Carmichael, H. Cleugh, W. Dabberdt, R. Emmanuel, E. Freitas, K. Fortuniak, S. Hanna, P. Klein, L.S. Kalkstein, C.H. Liu, A. Nickson, D. Pearlmutter, D. Sailor, J.D. Voogt. 2010. Climate and more sustainable cities: Climate information for improved planning and management of cities (producers/capabilities perspective). *Procedia Environmental Sciences* 1 (World Climate Conference 3): 247-274. http://www.sciencedirect.com/science/article/pii/S1878029610000174.

Groen, J.A. and A.E. Polivka. 2009. *Going Home after Hurricane Katrina: Determinants of Return Migration and Changes in Affected Areas*. Bureau of Labor Statistics Working Paper 428. http://www.bls.gov/ore/pdf/ec090060.pdf

Hart, M. and D. Sailor. 2009. Quantifying the influence of land-use and surface characteristics on spatial variability in the urban heat island. *Theoretical and Applied Climatology* 95 (3-4): 397-406.

Hua, L. and Q. Weng. 2008. Seasonal variations in the relationship between landscape pattern and land surface temperature in Indianapolis, USA. *Environmental Monitoring Assessment* 144 (1-3): 199-219.

Imhoff, M., P. Zhang, R.E. Wolfe, and L. Bounoua 2010. Remote sensing of the urban heat island effect across biomes in the continental USA. Remote Sensing of Environment 114504-513.

IPCC (Intergovernmental Panel on Climate Change). 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, H.L. Miller. New York and United Kingdom: Cambridge University Press.

Jacob, D.J. and D.A. Winner. 2006. Effect of climate change on air quality. *Atmosphereic Environment*, 43 (1): 51-63.

Jin, M. and J.M. Shepherd. 2008. Aerosol relationships to warm season clouds and rainfall at monthly scales over East China: Urban land versus ocean. *Journal of Geophysical Research–Atmospheres* 113, D24S90; doi:10.1029/2008JD010276.

Jin, M.E., R.E. Dickinson, D. Zhang. 2005. The footprint of urban areas on global climate as characterised by MODIS. *Journal of Climate* 18 (10): 1551-1565.

Kikegawa, Y., Y. Genchi, H. Kondo, K. Hanaki. 2006. Impacts of city-block-scale countermeasures against urban heat-island phenomena upon a building's energy-consumption for air-conditioning. *Applied Energy* 83 (6): 649-668.

Kunkel, K.E., L.E. Stevens, S.E. Stevens, L. Sun, E. Janssen, D. Weubbles, C.E. Konrad, C.M. Fuhrmann, B.D. Keim, M.C. Kruk, A. Billot, H. Needham, M. Shafer, and J.G. Dobson, 2013: Regional Climate Trends and Scenarios for the U.S. National Climate Assessment. Part 2: Climate of the Southeast United States. NOAA Technical Report NESDIS 142-2.

Landsberg, H. 1981. *The urban climate*. New York: Academic Press.

Lankao, P.R. 2008. Urban areas and climate change: Review of current issues and trends issues paper for the 2011 global report on human settlements. National Center for Atmospheric Research (http://www.ral.ucar.edu/staff/prlankao/GRHS_2011_IssuesPaperfinal.pdf)

Levy, F. 2009. America's most toxic cities. *Forbes.* http://www.forbes.com/2009/11/02/toxic-cities-pollution-lifestyle-real-estate-toxic-cities.html.

Lin, Y., Q. Min, G. Zhuang, Z. Wang, W. Gong, R. Li. 2011. Spatial features of rain frequency change and pollution and associated aerosols. *Atmospheric Chemistry and Physics Discussions* 11 (3): 8747-8776.

Long, P. and H. Hao.-2009. *Tourism impacts and second home development in Dare County: A sustainable approach*. Greenville, NC: Center for Sustainable Tourism.

Long, P., M. Ireland, D. Alderman, H. Hao. 2012. Rural tourism and second home development. In *Handbook of Tourism and Quality-of-Life Research: Enhancing the Lives of Tourists and Residents of Host Communities*, ed. M. Uysal, R. Perdue, M.J. Sirgy, 607-633. Netherlands: Springer Science+Business Media B.V.

Lynn, B.H., R. Goldberg, L. Druyan, S. Gaffen, L. Parshall, T.N. Carlson. 2009. A modification to the NOAH LSM to simulate heat mitigation strategies in the New York City Metropolitan Area. *Journal of Applied Meteorology and Climatology* 48 (2): 199-216.

Mann, M.E. and K.A. Emanuel. 2006. Atlantic hurricane trends linked to climate change. *EOS, Transactions, American Geophysical Union* 87 (24): 233-244.

Mazur, C. and E. Wilson. 2011. *Housing characteristics: 2010: 2010 census briefs*. Suitland, MD: US Census Bureau. http://www.census.gov/prod/cen2010/briefs/c2010br-07.pdf

McNulty, S.G. and J.L. Boggs. 2010. A conceptual framework: Redefining forest soil's critical acid loads under a changing climate. *Environmental Pollution* 158 (6): 2053-2058.

Meehl, G. and C. Tebaldi. 2004. More intense, more frequent, and longer lasting heat waves in the 21st century. *Science* 305 (5686): 994-997.

Millstein, D.E. and R.A. Harley. 2009. Impact of climate change on photochemical air pollution in southern California. *Atmospheric Chemistry and Physics* 9 (11): 3745-3754.

Moore, C.G. 1999. Water wars: Interstate water allocation in the Southeast. *Natural Resources and Environment* 14 (1): 5-10. http://heinonline.org/HOL/LandingPage?collection+journals&handle=hein.journals/nre14&div=6&8id=&page=

NCDC (National Climatic Data Center). 2009. User Engagement Fact Sheet for the Tourism Sector. Asheville, NC: Customer Services Branch, NOAA's National Climatic Data Center.

Nicholls, R.J., S. Hanson, C. Herweijer, N. Patmore, S. Hallegatte, J. Corfree-Morlot, J. Chateau,R. Muir-Wood. 2008. Ranking port cities with high exposure and vulnerability to climate Extremes: Exposure estimates. OECD Environmental Working Papers, No. 1, OECD Publishing http://dx.doi.org/10.1787/011766488208.

Niyogi, D., P. Pyle, M. Lei, S.P. Arya, C. Kishtawal, M. Shepherd, F. Chen, B. Wolfe. 2011. Urban modification of thunderstorms: An observational storm climatology and model case study for the Indianapolis urban region. *Journal of Applied Meteorology and Climatology* 50 (5): 1129-1144.

NCA 2011. Climate Change and Impacts and Responses: NCA Report Series, Volume 5C. Societal Indicators for the National Climate Assessment, April 28-29, 2011, Washington, DC.

Ntelekos, A.A., J.A. Smith, W.F. Krajewsk. 2007. Climatological analyses of thunderstorms and flash floods in the Baltimore Metropolitan Region. *Journal of Hydrometeorology* 8 (1): 88-101.

Oke, T.R. 1973. City size and the urban heat island. Atmospheric Environment 7 769-779.

Oke, T.R. 1987. *Boundary Layer Climates*. London: Routledge.

Oke, T.R., R.A. Spronken-Smith, E. Jáuregui, C.S.B. Grimmond. 1999. The energy balance of central Mexico City during the dry season. *Atmospheric Environment* 33 (24-25): 3919-3930.

Outer Banks 2005–2006. 2005–2006 year long visitor profile study. Outer Banks Convention and Visitors Bureau, Maneo, NC.

Peng, S., S. Plao, P. Ciais, P. Friedlingstein, C. Ottle, F.–Marie Bréon, H. Nan, L. Zhou, R.B. Myneni. 2012. Surface Urban Heat Island Across 419 Global Big Cities. *Envrionmental Science & Technology* 46, 696–703.

PhoCusWright. 2009. *Vacation rental marketplace: Poised for change*. Secaucus, NJ: Northstar Travel Media, LLC.

Poelmans, L., A.V. Rompaey, O. Batelaan. 2010. Coupling urban expansion models and hydrological models: How important are spatial patterns? *Land Use Policy* 27 (3): 965-975.

Quattrochi, D.A., W.M. Lapenta, W.L. Crosson, Jr., M.G. Estes, A. Limaye, M. Khan. 2006. *The application of satellite-derived high resolution land use/land cover data to improve urban air quality model forecasts*. Huntsville, AL: NASA Marshall Space Flight Center.

Remar, A. 2010. Urban heat island expansion in the greater las vegas metropolitan area. Monograph, Earth and Soil Science Department: California Polytechnic State University.

Reynolds, S., S. Burian, M. Shepherd, M. Manyin. 2008. Urban induced rainfall modifications on urban hydrologic response. In *Reliable modeling of urban water systems, Monograph 16,* ed. W. James, K.N. Irvine, E.A. McBean, R.E. Pitt, S.J. Wright, 99-122. Guelph, ON Canada: CHI (Computational Hydraulics International).

Rosenfeld, D., U. Lohmann, G.B. Raga, C.D. O'Dowd, M. Kulmala. 2008. Flood or drought: How do aerosols affect precipitation? *Science* 321 (5894): 1309-1313.

Rosenzweig, C., W. Solecki, R. Slosberg. 2006. *Mitigating New York City's Heat Island with Urban Forestry, Living Roofs, and Light Surfaces*. New York: The New York State Energy Research and Development Authority.

Scholze, M., W. Knorr, N.W. Arnell, I.C. Prentice. 2006. A climate-change risk analysis for world ecosystems. *Proceedings of the National Acedemy of Sciences of the United States of America* 103 (35): 13116-13120.

Scott, D. and C. Lemieux. 2009. *Weather and climate information for tourism*. World Meteorological Organization and Geneva and United Nations World Tourism Organization. http://sdt.unwto.org/sites/all/files/docpdf/wcc3tourismwhitepaper.pdf

Seager, R., A. Tzanova, J. Nakamura. 2009. Drought in the southeastern United States: Causes, variability over the last millennium, and the potential for future hydroclimate change. *Journal of Climate* 22 (19): 5021-5045.

SERDP (Strategic Environmental Research and Development Program). 2012. Climate change and impacts of sea level rise. (http://www.serdp.org/Featured-Initiatives/Climate-Change-and-Impacts-of-Sea-Level-Rise).

Shepherd, J.M., M. Carter, M. Manyin, D. Messen, S. Burian. 2010a. The impact of urbanization on current and future coastal convection: A case study for Houston. *Environment and Planning B: Planning and Design* 37 (2): 284-304.

Shepherd, J.M., J.A. Stallins, M. Jin, T.L. Mote. 2010b. Urbanization: Impacts on clouds, precipitation, and lightning. In *Urban ecosystem ecology*, ed. J. Aitkenhead-Peterson, A. Volder, 1-27. Madison, WI: American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America.

Shepherd, J.M., T.L. Mote, S. Nelson, S. McCutcheon, P. Knox, M. Roden, J. Dowd. 2011. An overview of synoptic and mesoscale factors contributing to the disastrous Atlanta flood of 2009. *Bulletin of the American Meteorological Society* 92 (7): 861-870.

Shuford, S., S. Rynne, J. Mueller. 2010. *Planning for a New Energy and Climate Future*. Chicago, IL: American Planning Association.

Sillman, S. and P.J. Samson. 1995. Impact of temperature on oxidant photochemistry in urban, polluted rural and remote environments. *Journal of Geophysical Research* 100: 11, 497-11, 508.

Souch, C. and C.S.B. Grimmond. 2006. Applied climatology: Urban climatology. *Progress in Physical Geography* 30: 270.

Stjern, C.W., A. Stohl, J.E. Kristjánsson. 2011. Have aerosols affected trends in visibility and precipitation in Europe. *Journal of Geophysical Research–Atmospheres* 116, D02212; doi:10.1029/2010JD014603.

Stone, B. 2007. Urban and rural temperature trends in proximity to large U.S. cities: 1951-2000. *International Journal of Climatology* 27 (13): 1801-1807.

Stone, B. 2008. Urban sprawl and air quality in large US cities. *Journal of Environmental Mangement* 86: 688–698.

Stone, B. 2011. Urban heat and air pollution: An emerging role for planners in the climate change debate. http://www.urbanclimate.gatech.edu/pubs/Urban_Heat_and_Air%20Pollution_Stone.pdf

Stone, B., J. Hess, H. Frumkin. 2010. Urban form and extreme heat events: Are sprawling cities more vulnerable to climate change than compact cities? *Environmental Health Perspectives* 118 (10): 1425-1428.

Sun, G., S.G. McNulty, J.A.M. Myers, E.C. Cohen. 2008. Impacts of multiple stresses on water demand and supply across the southeastern United States. *Journal of the American Water Resources Association* 44 (6): 1441-1457.

Svart, L.M. 1976. Environmental preference migration: A review. *Geographical Review* 66 (3): 314-330.

Taha, H. 2007. Urban climates and heat islands: Albedo, evapotranspiration, and anthropogenic heat. *Energy and Buildings* 25 (2): 99-103.

Titus, J.G. and C. Richman. 2001. Maps of lands vulnerable to sea level rise: Modeled elevations along the U.S. Atlantic and Gulf coasts. *Climate Research* 18 (3): 205-228.

The Economist. Chattahoochee blues: Are Georgia, Alabama, and Florida fighting over water or over growth? *The Economist* September 16, 2010. http://www.economist.com/node/17043462

Town of Apex. 2012. Current Water Restrictions. Apex, NC. http://www.apexnc.org/services/public-works/water/current-water-restrictions

Trenberth, K.E., P.D. Jones, P. Ambenje, R. Bojariu, D. Easterling, A.K. Tank, D. Parker, F. Rahimzadeh, J.A. Renwick, M. Rusticucci, B. Soden, P. Zhai. 2007. Observations: Surface and atmospheric climate change. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,* ed. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, H.L. Miller. New York and United Kingdom: Cambridge University Press.

USDHHS (US Department of Health and Human Services). 2011. Administration for children and families LIHEAP home energy notebookfor fiscal year 2009. U.S. Department of Health and Human Services, Administration for Children and Families, Office of Community Services, Division of Energy Assistance, Washington, D.C. http://www.acf.hhs.gov/programs/ocs/liheap.

USGCRP (United States Global Change Research Program). 2009. *Global Climate Change Impacts on the United States*. New York, N.Y.: Cambridge University Press.

US Census Bureau 2010. 2010 Census Products–United States. Demographic profile data—southeastern United States. http://2010.census.gov/2010census/data/.

US Travel Association. 2010a. Economic Impacts of Travel and Tourism. 1100 New York Avenue NW, Suite 450. Washington, DC 20005–39334.

US Travel Association 2010b. http://poweroftravel.org/statistics/datacenter.htm.

Voogt, J.A. 2002. Urban heat hsland. In *Encyclopedia of Global Environmental Change: Volume 3 Causes and Consequences of Global Environmental Change*, ed I. Douglas. John Wiley & Sons, Chichester, UK.

Waggoner, M. 2011. Irene-damaged Hatteras Island road to reopen. *Associated Press,* October 10.

Wear, D.N. and J.G. Greis. 2002. Southern forest resource assessment–Technical Report. In *General Technical Report SRS-53.* Asheville, NC: US Department of Agriculture, Forest Service, Southern Research Station.

Weng, Q., L. Dengsheng, J. Schubring. 2004. Estimation of land surface temperature-vegetation abundance relationship for urban heat island studies. *Remote Sensing of Environment* 89 (4): 467-483.

World Bank. 2010. Cities and Climate Change: An Urgent Agenda. Vol 10 (http://siteresources.worldbank.org/INTUWM/Resources/340232–1205330656272/CitiesandClimateChange.pdf)

Younger, M., H.R. Morrow-Almeida, S.M. Vindigni, A.L. Dannenberg. 2008. The built environment, climate change, and health: Opportunities for co-benefits. *American Journal of Preventative Medicine* 35 (5): 517-526.

Zhang, D.L., Y.X. Shou, R.R. Dickerson, F. Chien. 2011. Impact of upstream urbanization on the urban heat island effects along the Washington-Baltimore Corridor. *Journal of Applied Meteorology and Climatology* 50 (10): 2012-2029.

Zhou, Y. and J. Shepherd. 2010. Atlanta's urban heat island under extreme heat conditions and potential mitigation strategies. *Natural Hazards* 52 (3): 639-668.

Zhou, W., G. Hiuang, M.L. Cadenasso 2011. Does spatial configuration matter? Understanding the effects of land cover pattern on land surface temperature in urban landscapes. *Landscape and Urban Planning* 102: 54–63.

Chapter 6

Climate Change and Transportation in the Southeast USA

AUTHORS

Frederick Bloetscher (h2o_man@bellsouth.net; Florida Atlantic University)

Leonard Berry (Florida Atlantic University)

Kevin Moody (United States Federal Highway Administration)

Nicole Hernandez Hammer (Florida Center for Environmental Studies, Florida Atlantic University)

Key Findings

All transportation systems in the Southeast (SE) United States are vulnerable to both direct and indirect effects of climate change. Direct impacts of climate change include the following:

- Sea level rise (SLR) damage to transportation infrastructure, including coastal roads, railways, airports, and ports
- High-temperature damage to infrastructure and vehicles
- Extreme storm damage to infrastructure

There are engineering solutions available to adapt to most direct effects of climate change on transportation, but these solutions are often expensive. For example, modifications to roads to prevent damage by SLR are likely to cost $2 million to $3 million per lane-mile. This cost exceeds the range of typical road construction costs. Moreover, the engineering responses that might protect transportation infrastructure, may increase vulnerability of adjacent properties to flooding and other climate impacts.

6.1 Evaluation of Southeast Transportation Systems

Transportation networks in the SE USA are vulnerable to direct and indirect effects of severe weather events, which are likely to be affected by climate change, as well as by sea level rise, which is already affecting transportation systems in many coastal areas. The key to economic sustainability is the consistent ability of transportation systems and operations to provide mobility and access that is safe, reliable, and sustainable. The National Research Council (NRC 2009) recommended an evaluation of transportation and other infrastructure performance through five 21st century imperatives, challenges, or goals: (1) economic competitiveness; (2) global climate change; (3) energy supplies; (4) disaster resilience; and (5) environmental sustainability. The environmental sustainability challenge encompasses the full range of natural, built, and sociocultural environments and would, for example, consider ecosystem integrity, community health, environmental justice, and livable communities among other aspects. The United States Environmental Protection Agency (USEPA 2010) noted that there is no single definition of what constitutes a "sustainable" transportation system. However, according to the Transportation Research Board Sustainable Transportation Indicators Subcommittee (TRB 2008) a sustainable transport system does the following:

- "Allows the basic access and development needs of individuals, companies, and society to be met safely and in a manner consistent with human and ecosystem health, and promotes equity within and between successive generations.
- Is affordable, operates fairly and efficiently, offers a choice of transport mode, and supports a competitive economy, as well as balanced regional development; and
- Limits air, water, and noise emissions, waste, and resource use. Limits emissions and waste within the planet's ability to absorb them, uses renewable resources at or below their rates of generation, and uses non-renewable

resources at or below the rates of development of renewable substitutes, while minimizing the impact on the use of land and the generation of noise."

Creating a sustainable transportation system will require a change in the current model of cooperative working relationships. The Transportation Research Board (TRB 2008) and NRC (2009) suggest that the institutional arrangements that delivered the 20th century transportation network are inadequate in the face of climate change and other weather-driven events. In part these groups suggest that because of the diversity among the institutions responsible for transportation, there is little incentive to address interconnectivity and vulnerabilities that may lead to failures in policy direction and cooperative infrastructure planning. To create leadership in this regard, the federal government created the Interagency Partnership for Sustainable Communities to reinforce the importance of environmental, economic, and social sustainability. In June 2009, the US Department of Housing and Urban Development (HUD), the US Department of Transportation (USDOT), and USEPA agreed to coordinate housing, transportation, and environmental policies and investments to increase transportation options, improve accessibility to jobs and other destinations, and lower the combined cost of housing and transportation while protecting the environment in communities nationwide (USEPA 2010). But the federal working relationships need to be relevant to local, state, and regional officials in order to address the needs of communities and geographic regions, including those of built and natural environments. It is at the local level where adjustments and adaptation strategies will need to be implemented.

An important component to a sustainable transportation is economic competitiveness. Unfortunately, there are few or no data on the value or value-added of goods shipped into, out of, or through the Southeast. In general, shipping costs range from $2 per pound for air freight, $0.1 per pound for truck, $0.01 per pound for rail, and, $0.005 per pound for water hauls (Lemp 2008). Norfolk Southern railroad plans to upgrade rail infrastructure between the port of Savannah and Atlanta, suggesting that there is an economic incentive to eliminate some of the more expensive short-haul trucking options (Sneider 2013).

6.2 Climate Change and Transportation Infrastructure

In keeping with the interrelationship between the built environment and its many constituents, Bloetscher (2012) developed a framework to evaluate the impacts of climate change on infrastructure and water resources and economic development. The framework was developed in multiple steps to be readily transferrable to most communities. The first step identified topography, economic drivers, and population, and compared these to likely climate change impacts, especially increased frequency of intense rainfall events, higher temperatures, and sea level rise. Figure 6.1 outlines a simplified flow chart used as a basis for that evaluation.

Topographic and LIDAR data were used for the terrestrial characteristics. The topographic, census, and economic activity data were evaluated to determine how climate changes would impact the population and economy. Economic development requires appropriate management of water, sewer, storm water, and transportation networks,

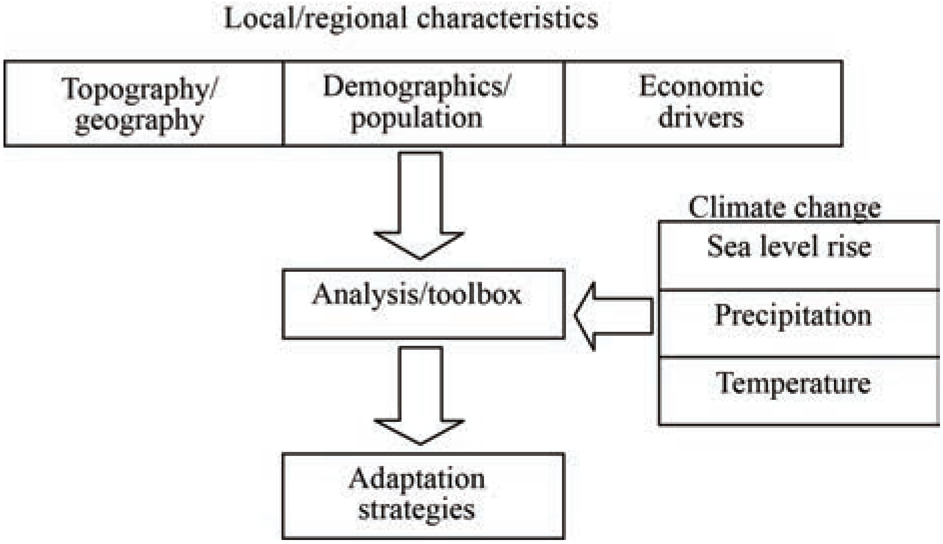


Figure 6.1 Analysis tool (Bloetscher 2012).

which immediately identifies water resource management as a key issue for climate adaptation using the toolbox approach developed by Florida Atlantic University {Heimlich et al 2009). Where water supplies are disrupted or unreliable, it is difficult to sustain long-term economy. Stormwater is the common linkage among all infrastructure.

Local and regional efforts are required to integrate current data sources to develop a methodology for assessing and mitigating the potential impacts of SLR and storm impacts on transportation infrastructure to assist transportation planning. The approach integrates the USDOT information systems with existing state and national topographical and geological data to facilitate (1) the evaluation of current and projected SLR impacts on coastline and low-lying terrain areas, (2) permit downscaling of statewide data bases to local jurisdictions, and (3) the identification of the physical transportation infrastructure most likely to be affected by a range of conditions from frequent flooding to continuous inundation due to SLR. A projection of SLR extent and the timing were outlined using a benchmark approach that brackets time intervals as opposed to specific timing for improvements (Heimlich et al. 2009—see Figure 6.2). Further research is required to evaluate the impact of sea level rise on localized ponding, groundwater levels, and storm surge, which are more difficult areas of investigation than the timing and extent projections (Bloetscher 2012).

6.3 Impacts of Climate Change on Transportation Systems

Transportation in the SE is directly affected by a suite of climate-related risks. Transportation infrastructure along the coastline and low-lying areas is vulnerable to SLR. Coastal bridges may be at risk to moving water from flood waters caused by storms. Access to roads to bridges and railroads also are at risk. In some regions, the geology permits significant migration of saltwater intrusion, thereby increasing the ease by which elevates groundwater levels are raised, causing damage to the transportation

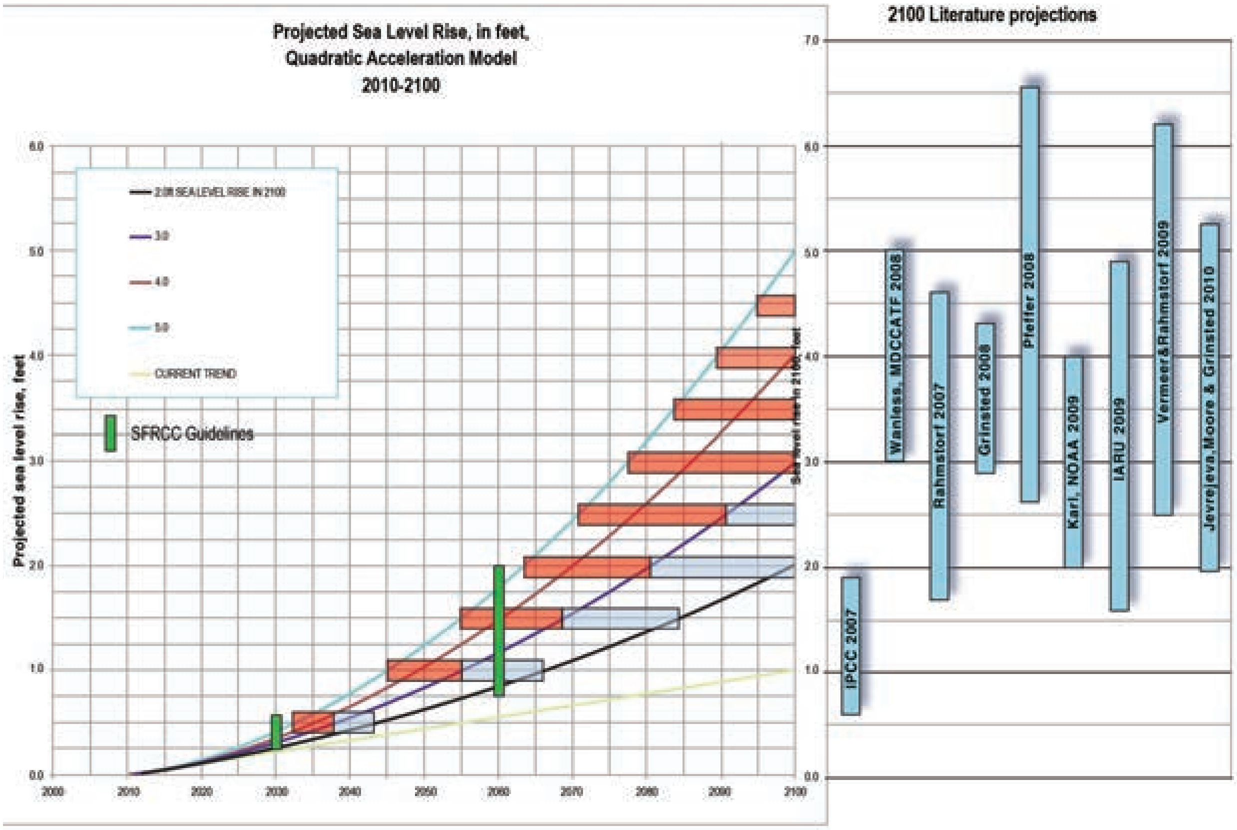


Figure 6.2 Prediction of Sea Level Rise, accounting for time and rise.

system structural base, which will ultimately lead to failure of the system. As sea level rises, groundwater will rise accordingly, which imperils a variety of infrastructure and transportation modes. In such cases, the effect of SLR might indirectly spread through the entire system affecting overall system performance. For example, the flooding of a critical road or facility access will shift traffic flow, in turn causing congestion on other roadways. Since the roadway network would be unable to carry the traffic demand, the system would experience operational failure, resulting in high travel times and delays and perhaps further shifts traffic to other nodes that become stressed. Moreover, the inundation of a critical access could cause transportation connectivity problems by blocking access to other areas.

Other effects of climate change, such as extreme heat events, can soften asphalt, cause concrete to rupture, and warp steel rails, requiring slow-downs and rerouting of certain types of transportation. Changes in hydrology can dramatically increase the consequences of highway runoff on ecosystems. Droughts and floods can directly interfere with inland waterway operations. Drought also can lead to wildfires that may create unsafe driving conditions. Snow and ice events potentially can create landslide and slope failures that create critical transportation bottlenecks. The following paragraphs outline the challenges facing each transportation sector in the Southeast.

Marine and Inland Ports. The SE supports an array of marine and inland shipping ports. Table 6.1 identifies those that rank highest in the USA in terms of tonnage transferred in 2010 and 2011. All are in low-lying coastal areas that are subject to inundation from both storm water and SLR. Three ports—New Orleans, LA, Norfolk, VA, and Mobile, AL—are in the top 10 areas that are most vulnerable to sea level rise, yet all are among the top 25 ports based on total volume of imports and exports.

Importers find economic advantage in marine ports that are physically linked to distribution centers, especially those with spur lines that provide reliable access to regional and national rail and highway transportation networks. Such ports that are linked to rail and highway networks are termed intermodal transportation hubs. Exporters find economic advantage at marine ports that are near production centers with significant intermodal transportation hubs.

While higher water levels are not a problem for ship traffic unless the ships must pass beneath bridges, SLR threatens the rail and highway components of intermodal transportation hubs. Thus, SLR could easily disrupt both import and export operations.

Changes in sea level are expected to have two general effects on ports. Sea level rise increases the depth of port, a positive benefit. However the altered hydrology and sea level are may increase sedimentation rates, which in turn affects operational costs and even the long-term sustainability of some marine ports. In addition, SLR has a cumulative effect on spring high tides and storm surge levels, increasing both. In most of the SE, it is reasonable to assume that countermeasures or hardening will be necessary to protect current infrastructure and maintain levels of service year round, but it may take up to 20 years to develop plans and construct improvements.

A nonclimate factor that will affect shipping routes is the widening of the Panama Canal to allow passage by wide-beamed ships, called "post-Panamax" ships. The Panama Canal is due to open for post-Panamax-sized ships soon, and these ships may have greater access to ports outside of the SE USA. Currently, only Norfolk can accommodate post-Panamax sized ships though several SE marine ports are in the process of expanding or planning to expand channel dimensions to accommodate post-Panamax ships. Expansion of the Panama Canal means wide-beamed ships that currently operate through the Suez Canal may be competitive in areas opened up by the Panama Canal expansion. The Port of Miami for example, is investing more than $1.2 billion to dredge the port and install raised bumpers to harden the port against the effects of SLR and permit new Panamax Canal shipping, as well as adding 4.4 miles of railroad spur to the Florida East Coast Railroad (Sneider 2013). Port Everglades is gearing up to spend hundreds of millions to dredge and update their facilities as well. Failure to harden the coast and the ports will result in damage to port facilities. Vulnerability without adaptation to climate impacts may force port operations to relocate to more protected environments.

Warmer temperatures or more frequent drought could adversely affect agriculture and related shipments. Ongoing inundation or repetitive storm damage may encourage large growers to move to more protected areas, thereby shifting their use of marine ports to other regions. Shipping routes will also change. With warmer temperatures, Arctic sea ice is melting and the Northwest Passage is expected to be ice-free and open for marine shipping within decades, which may redirect some shipping traffic.

Table 6.1 Waterborne Foreign Trade Volume Rankings for SE Customs Districts in 2011.

Rank	Port	Satellites
1	Port of South Louisiana, LA	New Orleans, Baton Rouge, Plaquemines, Morgan City, Avondale
3	Lake Charles. LA	Beaumont, TX; Port Arthur, TX; Orange, TX
10	Norfolk, VA	Newport News
13	Tampa, FL	St Petersburg, Manatee
17	Mobile, AL	
19	Pascagoula, MS	Biloxi, Gulfport
21	Port Everglades, FL	Miami, Palm Beach, Fort Lauderdale
25	Jacksonville, FL	
28	Memphis, TN	
29	Savannah, GA	
30	Charleston, SC	
34	San Juan, PR	
38	Louisville, KY	
39	Wilmington, DE	
42	Vicksburg, MS	
43	Morehead City, NC	
44	Nashville, TN	
47	Chattanooga, TN	
48	Greenville, MS	
49	Guntersville, AL	
50	Brunswick, GA	
51	Richmond, VA	Hopewell
53	Hopewell, AR	
56	Ponce, PR	

Volume is reported as thousands of metric tons. Source AAPA 2012.

Waterways. Though not well studied, coastal waterways in the SE are vulnerable to hydraulic changes, sedimentation, sea level change, storm surge, and tropical storms. Severe drought could lower water levels to a point where boat traffic is not possible, but this is unlikely to pose a threat in the next 100 years. A more likely threat is that SLR will make it difficult for some ships to pass beneath bridges in tidally affected waterways.

Railroads. Because most railroads were constructed 100 or more years ago, much of the rail system in the USA has a level of built-in protection because early railroad builders tended to construct railroads on high ground. As a result, railroads may be less subject to climate impacts than roadways and ports. Table 6.2 lists the Class 1 railroads and their locations in the SE USA, and Figure 6.3 shows the USA national network of railroads. Conversely, of great concern is that the railroads built 100-plus years ago did not anticipate the speed or weight of modern rail traffic. When combined with rising sea level or groundwater level, the risk of base saturation and deterioration increases. Figures 6.4 and 6.5 show the current and future railroad base conditions. Base failure and loosening of spikes holding down rails create long-term safety concerns. Although inland railroads are generally on higher ground than roadways, coastal railroads remain vulnerable to storm surge, damage from wind and inundated base conditions.

Table 6.2 Class 1 Freight Railroads in the Southeast USA.

Railroad	**Status**
Union Pacific	Louisiana; Arkansas
Norfolk Southern	Louisiana; Mississippi; Alabama; Georgia; Florida; Tennessee; Kentucky; South Carolina; North Carolina; Virginia
Kansas City Southern	Louisiana; Arkansas; Mississippi; Alabama
CSX	Louisiana; Mississippi; Alabama; Georgia; Florida; Tennessee; Kentucky; South Carolina; North Carolina; Virginia
Canadian National	Louisiana; Mississippi; Alabama; Tennessee
BSNF	Louisiana; Mississippi; Alabama; Arkansas; Tennessee

Airports. There are hundreds of airports in the SE USA, but only a handful that have significant freight and passenger traffic. Four airports--Atlanta at number one, Miami, Fort Lauderdale, and New Orleans--dominate foreign trade and passenger traffic in the Southeast. However, all airports are vulnerable to extreme weather events that delay or stop inbound and outbound flights. In addition, drought can adversely affect the workforce and certain manufacturing processes that drive airfreight.

Miami International Airport, with 17 million passengers annually, is 8 ft above sea level (Bureau of Transportation Statistics 2012). Fort Lauderdale/Hollywood International Airport, with 10 million passengers annually (projected to 32 million by 2030) is 5 ft above sea level and located in the coastal hazard zone. The Louis Armstrong Airport in New Orleans, with 4.07 million passengers in 2010, is 4 ft above sea level (Bureau of

Figure 6.3 Source: wikipedia.com, 2012.

Transportation Statistics). These three airports, as well as many other coastal airports, are in the process of expansion or are undergoing various stages of upgrades. Fort Lauderdale, for example, is actively constructing a runway project that will be 65 ft above sea level, (North American Vertical Datum 1988[NAVD88]). Like railroads, the runways are on higher ground than surrounding areas, but long-term base failure due to rising groundwater is a potential failure point (Figures 6.6 and 6.7). Ongoing expansions have kept the runways high and dry, but the access roads to get to the airports may be compromised (Figure 6.8), which may lead to airports becoming isolated from intermodal transportation links. Most smaller airports in the SE are owned by local governments, which may limit resources for maintenance and adaptation to climate change effects, including sea level rise.

Roadways. By far the greatest transportation infrastructure system in the USA is roadways. The network of highways and roads in the SE USA is owned by state and local transportation agencies. Five times more freight is driven over roads than railroads.

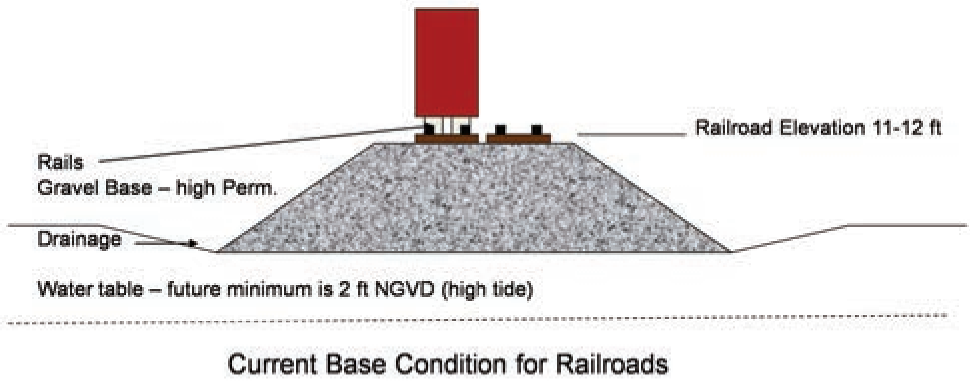


Figure 6.4 Cross sectional diagram showing the current base condition for railroads relative to the water table.

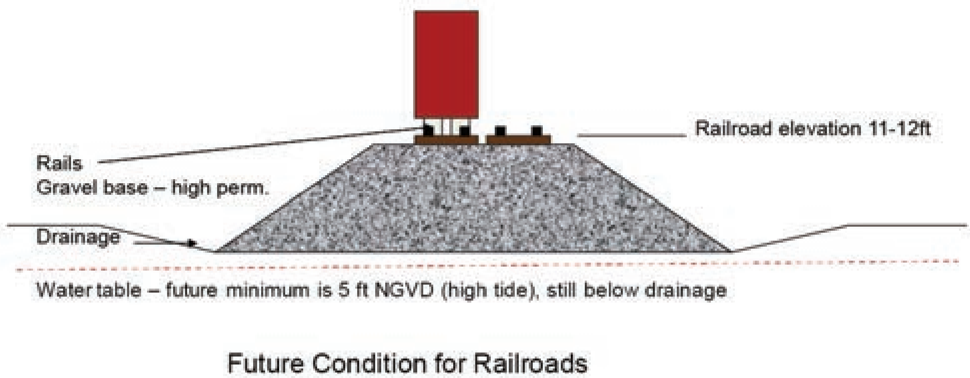


Figure 6.5 Future railroad condition showing that rising ground water level (dotted line) nearly reaches the gravel base, which can result in base deterioration and failure.

Related to the transportation infrastructure is the related effectiveness of flood control and storm-water drainage systems for the transportation corridors. The increased risk of severe flooding in low-lying terrain can adversely affect transportation infrastructures along the coastline; roads can be inundated and roadway beds can be damaged. Sea level rise will raise coastal water tables, which will compound the risk of flooding in low-lying areas because soil storage capacity would be reduced. Road bases below 5 ft NAVD88), would become saturated under this scenario, causing premature base failure. In addition, because soil storage capacity is diminished, the potential for frequent flooding of roadways would likely damage pavements. Many local roads that do not meet the standards necessary to withstand frequent flooding and would be more vulnerable to failure (see Figure 6.9).

Because it is critical to protect the roadway base, all efforts should begin with providing the base with adequate drainage systems to meet future conditions. At present most base courses are installed above the water table. As long as the base stays dry, a

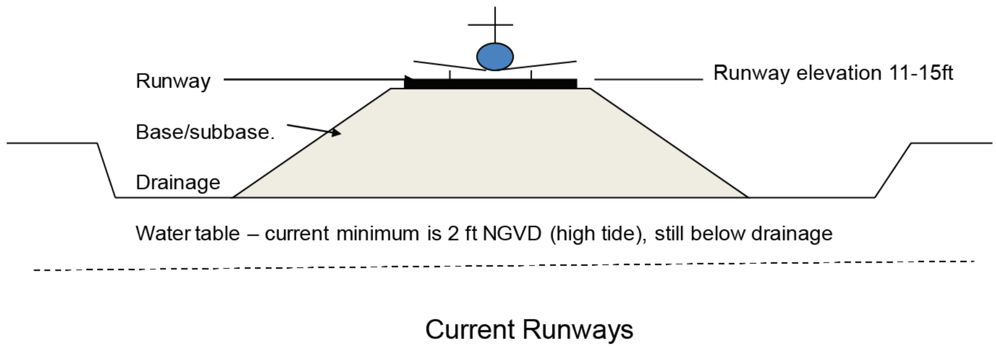


Figure 6.6 Airport runways are generally elevated. Note that water table is below drainage requirements (dotted line).

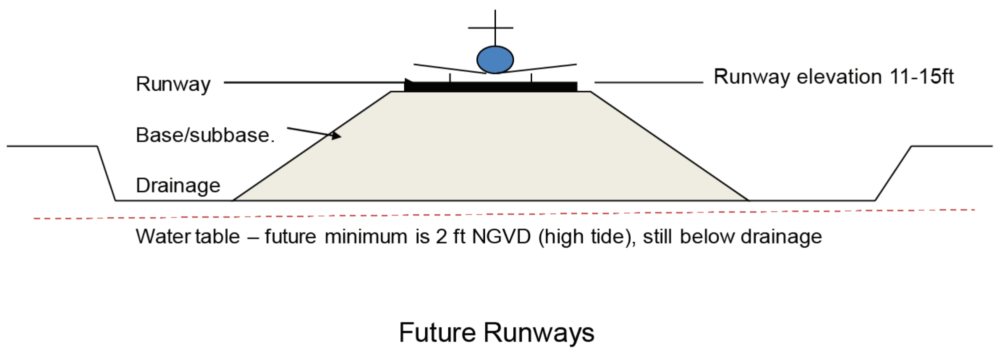


Figure 6.7 Sea level rise will threaten runways, but because runways are designed with more elevation than roadways, runways will not be affected by inundation as early as are roadways or railroads. Note that water table is still below drainage requirements (dotted line).

roadway surface will remain stable. As soon as the base is saturated, the roadway can deteriorate. Additional storm-water systems will be useful in the short term to counter sea level rise as long as adequate means for discharging increased storm water are provided. As sea level rises, wellpoint systems may be needed for more permanent drainage. Wellpoint systems are a series of small diameter wells spaced regularly along excavations of a project into the water table, which continuously pump water from roadways (see Figure 6.10). Wellpoints are most commonly used in dewatering projects on construction sites. Wellpoint water is usually turbid, containing sand, other particles, and contaminants from runoff. This form of dewatering requires treatment areas for removal of particulates and sand, which means additional area for discharge purposes will be required. Wellpoint pump stations need to be regularly spaced along a roadway at risk for flooding. As a result a series of pump stations might be needed for every mile of roadway since typical dewatering systems are generally confined to areas less than 500 ft in length. Because wellpoints do not function under flood conditions, additional drainage measures must be provided to address wellpoint failure during heavy rainfall events.

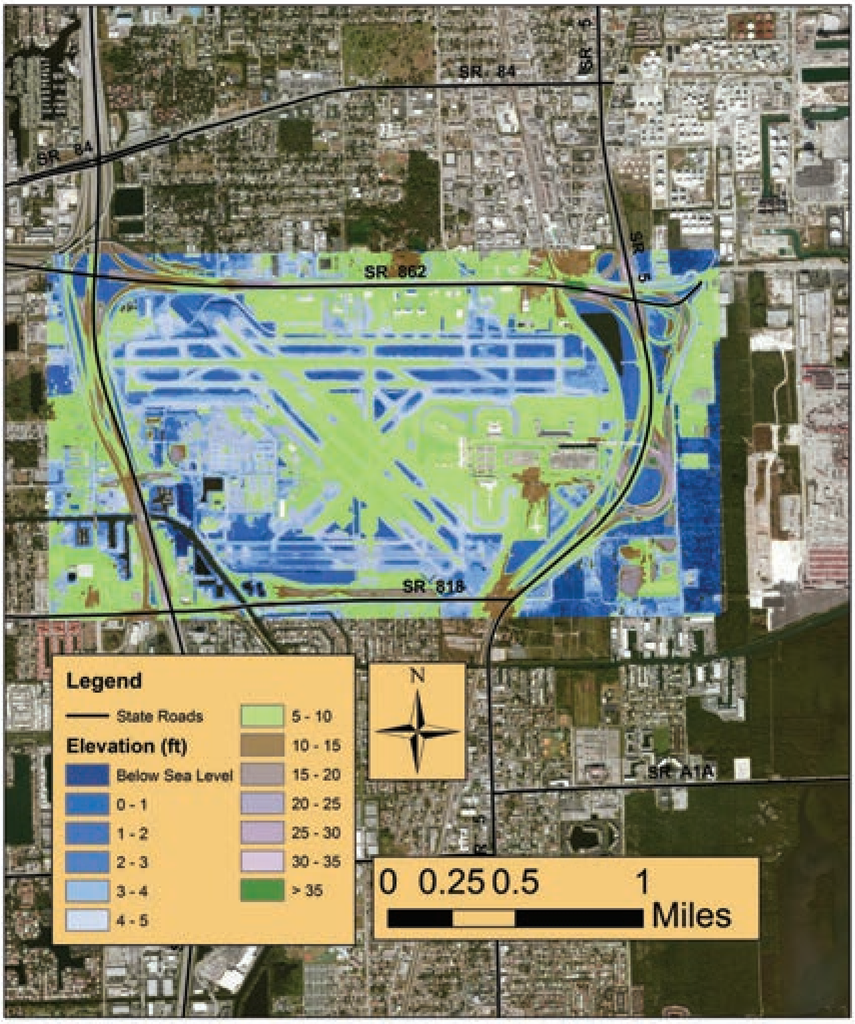


Figure 6.8 Illustration of Fort Lauderdale Hollywood International Airport. LiDAR map shows runways are currently above SLR projections; however drainage areas are not above SLR projections. Dark blue areas are would be inundated with 1 ft of sea level rise (SLR) and medium blue areas would be inundated with 3 ft of SLR.

State transportation departments and most municipalities rely heavily on exfiltration trenches or French drains. These systems work because the perforated piping is located above the water table. They cease to function if they are located below the water table. Exfiltration systems in low-lying areas will cease to work as they become submerged. However this existing infrastructure could be repurposed and extended as infiltration galleries (see Figure 6.11) along roadways, where perforated piping would be used in a similar manner as wellpoints, whereby the water will drain into the perforated pipe, and be directed to a pump station. In these situations, the pump stations might be 2000 feet apart. Storm-water systems should be designed like sanitary sewers with tight

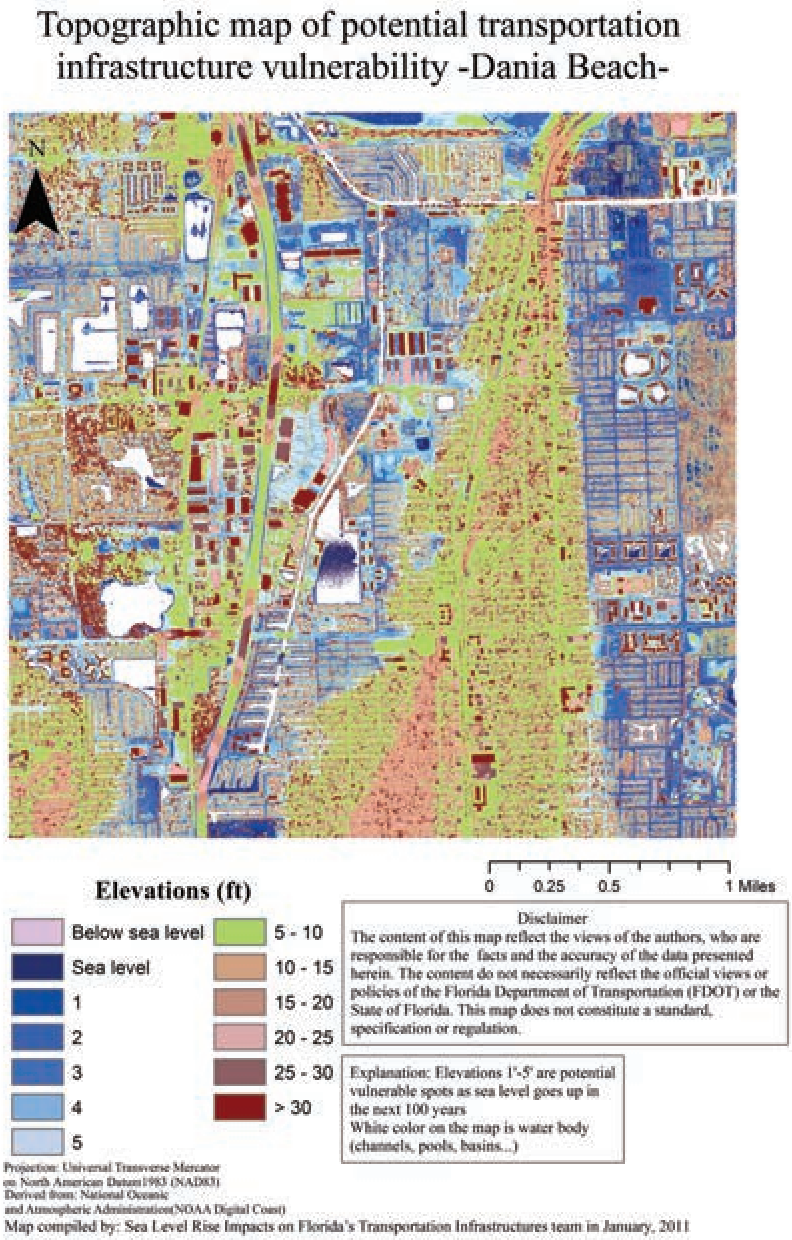


Figure 6.9 Dania Beach Overlay Map Using High Resolution LiDAR Data (7″ in vertical accuracy).

piping, minimal allowances for infiltration, and adequately sized pumping stations with permitted discharge points and means for associated treatment. The costs for such systems could exceed $1 million per lane-mile (Bloetscher et al. 2012). A much farther range issue will be the volume and contaminant content may make this water unsuitable for discharge to surface waters, but it may be treatable as a potable water supply.

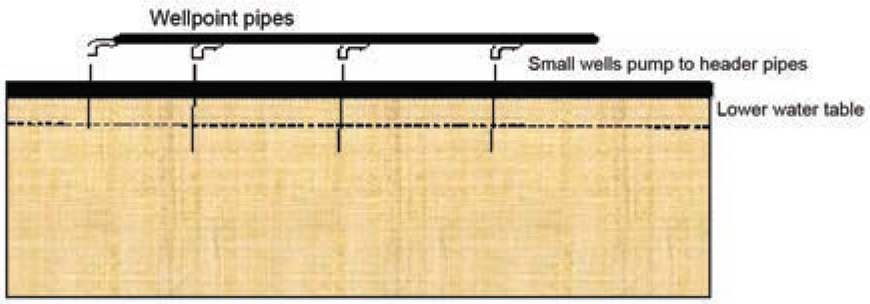


Figure 6.10 Wellpoints.

Exfiltration trenches could also be replaced by storm-water gravity wells or Class V injection wells (see Figure 6.12). Storm-water gravity wells are a useful option where saltwater underlies the surface. Drainage wells along the southeast Florida coast can drain 1 million gallons per day under certain conditions. However as sea level rises, the potential differential may be altered since the saltwater wedge may migrate inland as a result of surficial drainage efforts. Also, increased head due to water table rise will alter pump characteristics. Depending on local conditions, these wells may or may not be appropriate. Wells of this type generally cost about $150,000 each for a 24-inch diameter well. They also require splitter boxes and filters to remove solids. Regular inspections are required to insure they are not plugged or back flowing saltwater to the surface.

Gravity wells require regular maintenance increasing transportation system budgets. Obtaining permits remain a challenge, and it is likely that wells will have to be deeper than current gravity wells (Bloetscher et al. 2012). Permitting Class V injection wells requires consideration of the Underground Injection Control program under the Safe Drinking Water Act, something that is not currently considered in most transportation jurisdictions. Permitting and consistent monitoring of Class V wells is required. In addition, these 24-inch Class V injection well may have to be hundreds of feet deep in some locations. As a result, the transportation entity will have to include ongoing

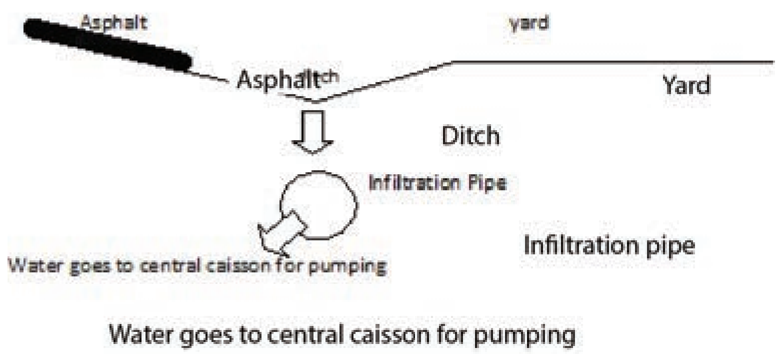


Figure 6.11 Infiltration Gallery Concept..

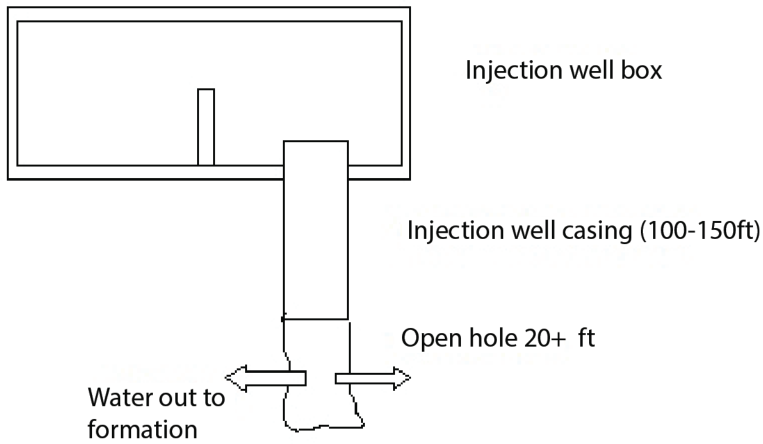


Figure 6.12 Injection Well Concept.

storm water efforts for Class V well compliance (Bloetscher et al. 2012). Elevating roads may be an option for some low-lying areas. However, this option comes with two significant issues: deciding the proper roadway elevations and impacts on adjacent properties. Roadways are designed for a 50- to 100-year service life. As a result, transportation agencies should design roadway bases to be above the mean high water table of 5 ft NGVD. Such roads would likely have surface elevations at or above 10 ft NGVD, above many existing roads in low-lying areas. Such elevated roadways will be well above adjacent properties so people living or working next to these roadways would view the sides of the road from their properties. Moreover, such elevated roads would act as dams that flood adjacent properties unless provisions, such as culverts or pumps, are made for horizontal movement of water.

Local roadway elevations are limited by the adjacent buildings. For example, in Dania Beach, FL, the typical elevation of the floors of houses east of US Highway 1 is between 6 ft and 8 ft NGVD. It makes little sense to raise roadway elevations beyond the typical lowest elevation of dwellings. Elevated roads, in situations such as this, would create bowls that have no outlet, thereby leading to prolonged flooding. Runoff would increase and runoff from private property to the right-of-way would be precluded. As a result, local neighborhoods would need extensive pumping to remove storm water that cannot flow to the right-of-way nor escape the area on its own. In addition, sanitary sewers, water mains, and other utilities underlie these pavements. Elevating the roads would require manholes to be reconstructed, water lines replaced, and most other underground utilities replaced, which would add significant costs to adaptation.

Raising roadways is expected to exceed the cost of new roads. This cost is estimated to be $1 million per lane-mile, according to one of the authors. With the added improvements, additional right-of-way, and extensive fill, the cost more likely will be much higher. Adjacent properties would need pumps to remove storm water and prevent runoff from entering properties. These costs might exceed $500,000 per property, one of the authors estimated. In addition, if property is required for retention or run-off, the costs could exceed $1 million per acre as adjacent areas are built-out. Such improvements would cause a displacement of some current residents. Where these displaced residents go is uncertain although migration and displacement of residents could result in a domino effect. In addition, residents remaining near the sites of these improvements would experience noise, dust, and inconvenience from the ongoing construction.

Moving people away from vulnerable or inundated roadways would create congestion elsewhere and cost commuters an estimated $850 to $1600 per year (FHWA 2013). Congestion means longer travel times, increased costs, and less reliable pick-up and delivery times for truck operators. To compensate, motor carriers typically add vehicles and drivers and extend their hours of operation. Over time, most of these costs are passed along to shippers and consumers. The Federal Highway Administration (FHWA) estimates that increases in travel time would cost shippers and carriers an additional $25 to $200 per hour depending on the product carried. The cost of unexpected truck delays can add another 50 percent to 250 percent (Strocko 2008).

6.4 Conclusions

All transportation networks in the Southeast USA are vulnerable to severe weather events and climate change. Ongoing efforts to identify vulnerable infrastructure and to measure the risk and disruption posed by climate change from an economic and societal perspective are generally in their infancy. From a transportation planning perspective, there is great need to understand how climate and weather effects on the economy should be incorporated into larger policy frameworks.

Warmer temperatures along with more intense rainfall events will require re-engineering of transportation surfaces and storm water collection and disposal. Permitting for disposal of storm water may pose a significant challenge to an area where nutrients create significant eutrophication problems in slow moving and coastal waterways. Outside-the-box thinking will be required to deal with the problem of too much water. However, with respect to weather phenomena, while potentially catastrophic, storm damage is temporal in nature as opposed to the permanent threat of sea level rise.

Coastal transportation infrastructure in SE USA is increasingly vulnerable to sea level rise. Given the high population density near the coasts, the potential exposure of transportation infrastructure to flooding is immense (NOAA 2010). The SE transportation system is extremely weather dependent for the two National Research Council (NRC 2009) imperatives—economic competitiveness and disaster resilience. Transportation is strongly interconnected with other infrastructure systems and is highly susceptible to natural hazards. The highest priority needs are associated development of incentives to encourage various levels of government to collaborate with each other (National Research Council 2010). The physical elements of the SE USA transportation infrastructure are vulnerable to climate impacts just as water, storm water, and power are interrelated. Approaching infrastructure renewal by continuing to use the same processes, practices, technologies, and materials that were developed in the 20th century may yield the same results: increasing instances of service disruptions, higher operating and repair costs, and the possibility of catastrophic, cascading failures. If the nation is to meet some of the challenges of the 21st century, a new paradigm for the renewal of critical infrastructure systems is needed. As the renewal of infrastructure is undertaken over the next 20 to 50 years, NRC (2009) challenges local officials to rethink the infrastructure paradigm. Solutions must be local as there are no universally applicable solutions (Bloetscher 2012). The new paradigm must recognize transportation systems are interconnected; they are not independent. Moreover, the intermodal elements of this overall transportation system are particularly vulnerable to climate-related risks. For ports and marine shipping, climate factors such as sea level change, storm surge, and sediment dynamics need to be considered.

Engineering options are already available for strengthening and protecting transportation facilities such as bridges, ports, and railroads from coastal storms and flooding, but inundation from sea level rise is a different issue. The development and implementation of technologies that monitor major transportation facilities and infrastructure, and the development, update and re-evaluation of current design standards, are required for adapting to SLR in coastal areas. Many issues require policy decisions, such as the elevation of roadway surfaces, the installation of wellpoints and infiltration galleries, new drainage systems, and roadway diversion or abandonment. However, little attention has been given to evaluation approaches for where and when such options should be pursued or to the potential co-benefits or unintended consequences (NRC 2010).

Planning for SLR adaptation in transportation infrastructure will require new approaches to engineering analysis, including the development and use of risk analysis based on uncertain SLR and the development of new engineering standards to reflect future climate conditions (NRC 2010). The US Climate Change Science Program has recommended the following approaches to incorporate climate information into transportation decision making (USDOT 2002):

- Planning time frames
- Risk assessment approach
- Integrated climate data and projections
- Risk analysis tools
- Region-based analysis
- Interdisciplinary research
- Identification of vulnerable assets and locations
- Identification of opportunities for adaptation of specific facilities
- Understanding changes in the life span of facilities caused by SLR
- Understanding the modes and consequences of failure
- Assessing the risks, costs, and benefits of adaptation

As sea level rises, populations at low elevations areas along Southeast coastline may move inland, causing changes in travel patterns. As a result, re-routing of current transit, roadway, and non-motorized systems may be necessary, along with the relocation of pipelines, freight, seaports, and airport facilities. Travel pattern changes could potentially exacerbate climate change vulnerabilities, thereby affecting the operational efficiency, capacity, and level of service of transportation systems. A significant increase of facility users, on roadways for example, could exceed the operational capacity of facilities, increasing user delays. Similarly, traffic delays will affect the reliability, efficiency, and capacity of the transit systems. Transit passengers may experience longer travel times affecting the quality of service of the transit systems. These transportation issues may significantly affect traffic safety and quality of life of the communities served by these transportation systems. Transit and other modes of transportation that are not single-occupant vehicle mode may become more prudent to reduce congestion. Traffic safety plans that address the changes in environment conditions will need to be developed and implemented, including a detailed route signing system and emergency response plans that provide new evacuation routes, accessibility, and mobility plans.

6.5 References

Bloetscher, F. 2012. Protecting people, infrastructure, economies, and ecosystem assets: Water management and adaptation in the face of climate change. *Journal of Water*, 4 doi:10.3390/w40x000x

Bloetscher, F., D.M. Meeroff, B.N. Heimlich, A.R. Brown, D. Bayler, D.M. Loucraft 2010. Improving the resilience of a municipal water utility against the likely impacts of climate change: A case study: City of Pompano Beach, Florida Water Utility: City of Pompano Beach, FL. *Journal American Water Works Association*, 102(11): 36-46, http://www.awwa.org/files/secure/index.cfm?FileID=186789

Bloetscher, F., B.N. Heimlich, T. Romah. 2011. Counteracting the effects of sea level rise in southeast Florida, J*ournal of Environmental Science and Engineering*, 5(11): 1507-1525.

Bloetscher, F., T. Romah, L. Berry, N. Hernandez Hammer, M.A. Cahill. 2012. Identification of physical transportation infrastructure vulnerable to sea level rise. *Journal of Sustainability*, 5(12).

Bureau of Transportation Statistics. 2012. http://www.rita.dot.gov/bts/node/11792, accessed 2/29/12.

Bureau of Transportation Statistics. http://www.transtats.bts.gov/DatabaseInfo.asp?DB_ID=640&Link=0

FHWA (Federal Highway Adminstration). 2013. http://ops.fhwa.dot.gov/publications/congestionpricing/sec1.htm, accessed on June 11, 2013.

Heimlich B.N., F. Bloetscher, D.E. Meeroff, J.Murley. 2009. *southeast Florida's resilient water resources: Adaptation to sea level rise and other impacts of climate change.* Boca Raton FL: Florida Atlantic University: Center for Urban and Environmental Solutions, Department of Civil Engineering, Environmental, and Geomatics Engineering. http://www.ces.fau.edu/files/projects/climate_change/SE_Florida_Resilient_Water_Resources.pdf.

Jevrejeva S., J.C. Moore, A. Grinsted. 2010. How will sea level respond to changes in natural and anthropogenic forcings by 2100? *Geophysical Research Letters*, 37, L07703, DOI:10.1029/2010GL042947.

Lemp, J.D, 2008 Quantifying The External Costs Of Vehicle Use: Evidence From America's Top Selling Light-Duty Models, *Transportation Research* 13D (8):491-504, http://www.ce.utexas.edu/prof/kockelman/public_html/trb08vehicleexternalities.pdf.

NRC (National Research Council). 2009. Sustainable critical infrastructure systems – a framework for meeting 21st century imperatives. Washington DC.

NRC (National Research Council). 2010. Adapting to the impacts of climate change. Washington, DC: NAS Press, https://download.nap.edu/catalog.php?record_id=12783.

Sneider, J. 2013 Panama Canal expansion spurs railroads, ports to prepare for new business, *Proressive* Railroading, April , 2013. http://www.progressiverailroading.com/norfolk_southern/article/Panama-Canal-expansion-spurs-railroads-ports-to-prepare-for-new-business--35793

Southeast Florida Regional Climate Change Compact (SFRCC). 2011. *Analysis of the Vulnerability of Southeast Florida to Sea Level Rise*. SFRCC Inundation Mapping and Vulnerability Assessment Work Group.

Strocko, E., 2008, Making the Case for Freight Investments, Public Roads, May/Jun 2008 Vol. 71 · No. 6.

Transportation Research Board (TRB). 2008. *Potential impacts of climate change on us transportation, transportation research board special report 290*: Washington DC: Transportation Research Board Business Office, http://www.climateneeds.umd.edu/reports/NRC-Climate%20Change%20and%20Transportation.pdf.

USEPA (United States Environmental Protection Agency). 2010. *Partnership for sustainable communities – first year* report, EPA 231-K-10-002, USEPA, Washington, DC, http://www.epa.gov/smartgrowth/pdf/partnership_year1.pdf.

USDOT (United States Department of Transportation). 2002. Climate change on transportation, U.S. Department of Transportation Center for Climate Change and Environmental Forecasting, Washington, DC. http://climate.dot.gov/documents/workshop1002/workshop.pdf.

Vermeer, M., and S. Rahmstorf. 2009. *Global sea level linked to global temperature.* PNAS 106(51): 21527–21532, http://www.pnas.org/content/106/51/21527.

Wikipedia. 2012. Railroad map. http://en.wikipedia.org/wiki/Rail_transportation_in_the_United_States. http://www.transtats.bts.gov/DatabaseInfo.asp?DB_ID=640&Link=0).

Chapter 7

Agriculture and Climate Change in the Southeast USA

LEAD AUTHOR

Senthold Asseng (sasseng@ufl.edu; University of Florida, Gainesville, Florida)

CONTRIBUTING AUTHORS

Wendy-Lin Bartels (University of Florida, Gainesville, Florida)

Kenneth J. Boote (University of Florida, Gainesville, Florida)

Norman E. Breuer (University of Miami and University of Florida, Gainesville, Florida)

Davide Cammarano (University of Florida, Gainesville, Florida)

Christine C. Fortuin (Environmental Protection Agency, Region 4, Washington, DC)

Clyde W. Fraisse (University of Florida, Gainesville, Florida)

Carrie A. Furman (University of Georgia, Griffin, Georgia)

Gerrit Hoogenboom (Washington State University, Prosser, Washington)

Keith T. Ingram (University of Florida, Gainesville, Florida)

James W. Jones (University of Florida, Gainesville, Florida)

David Letson (University of Miami, Miami, Florida)

Brenda V. Ortiz (Auburn University, Auburn, Alabama)

Mark Risse (University of Georgia, Athens, Georgia)

Fredrick Royce (University of Florida, Gainesville, Florida)

Scott D. Shuford (City of Fayetteville, Fayetteville, NC)

Daniel Solis (University of Miami, Miami, Florida)

For the southeastern agricultural sector, this chapter summarizes key vulnerabilities and impacts; describes the characteristics and importance; analyzes current and potential climate sensitivities and vulnerabilities; discusses uncertainties, summarizes subregion-specific impacts and opportunities as referred to in the literature; explores adaptation needs and opportunities; and concludes with recommendations for further assessment and research needs. We have taken into consideration a range of studies from within and outside the region to describe major impacts and likely projections for climate change in this region, which covers southeastern states, except Puerto Rico and the Virgin Islands.

Key Findings

Changes in precipitation extremes

- Drought is already a major stress for rain-fed crops in the Southeast (SE). Drought impacts are projected to become more frequent and severe, especially in the western part of the region, but there may be fewer droughts across the northern tier of the region and in the mid-Atlantic. Both dryland and irrigated agriculture will be further affected by drought as a result of greater irregularity of rainfall distribution and increasing competition with other sectors for water resources.
- Flood frequency likely will increase as a result of predicted increased numbers and intensity of storms in some areas of the region. Floods cause direct damage to crops, especially if they occur during fruit set or near crop maturity, as well as indirect damage through soil erosion, leaching of nutrients, and loss of future productivity.

Changes in temperature extremes

- High temperature stresses are predicted to become more frequent and damaging to crops. Warm temperatures during the winter months reduce fruit set on blueberry, peach, and other crops that have a chilling requirement. These adverse impacts can be partly offset through the application of growth regulators, but such methods increase costs of production.
- Increasing summer heat stress will reduce crop productivity, especially if it occurs during flowering and seed set and if it is combined with drought.
- Heat stress already limits production of dairy and livestock, especially during summer months. An increased frequency of heat stress events will have the potential to force some dairy and livestock production northward.

Changes in tropical storm strength

- Projected increases in strength of tropical storms likely will cause extensive damage to nearly all agricultural systems, particularly when storms occur during maturation and harvest. Wind damage to perennial crops is particularly expensive and long lasting.

- Storm damage will negatively impact crops by reducing yield and crop quality. In addition storms also damage agricultural land; product handling, storage, and distribution systems; and equipment and buildings.

Increased atmospheric carbon dioxide

- Atmospheric carbon dioxide concentrations have a direct benefit to photosynthesis, especially for plants with a C_3 metabolism such as legumes, cotton, some cereals and most vegetable and tree crops particularly when under drought conditions. Many weeds also will benefit from increases in atmospheric carbon dioxide concentrations resulting in increased production costs associated with weed management.

7.1 Agriculture in the Southeast USA

The Southeast (SE) represents one of the most diverse agricultural production regions in the USA (Figure 7.1). Agriculture is a major economic contributor to the region's economy and communities. Seasonal and spatial variability of climate conditions, including rainfall and temperature distributions, soil types, and access to water for irrigation have led to the development of a diverse and intensive agricultural sector.

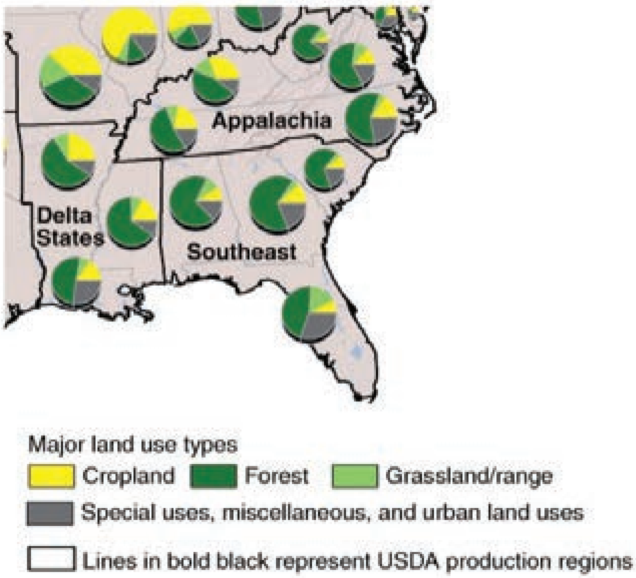
The SE has a land area of 135 million ha, which is 14.9% of the USA total. Although land use differs widely by county in the SE, 60% (about 79 million ha) is designated as forest, which is about 30% of the total forest land in the USA. Cropland in the SE totals about 21 million ha, which is about 15.7% of the region's landmass and 13% of the total cropland of the nation (Figure 7.1). Grassland pasture and ranges total about 11 million ha, which is 8.3% of the land in the region and 4.5% of the grassland pasture and ranges of the nation (Nickerson et al., 2011).

Diverse climate conditions, land-use options, access to water, availability of farm labor, proximity to urban markets, distribution systems, and financial farm income have led to large structural differences among the states and subregions. Beef cattle, most of which is grazed on improved pastures; poultry; and swine are raised throughout most of the SE. Georgia, Arkansas, and Alabama are the top three poultry producing states in the nation and North Carolina is the number two swine producing state in the nation. Crops grown in the SE include soybean, corn, fruits, and vegetables. Peanut and cotton are produced through most of the coastal plain from Mississippi to Virginia. Florida is the nation's largest producer of citrus and an important producer of sugar cane and winter vegetables. In addition to the products already mentioned, the Delta States also produce rice, sugarcane, and small grains. The Appalachian States are the nation's major producers of tobacco and horses as well as major producers of peanuts, cattle and dairy (USDA-NASS 2012).

Within the SE, Alabama, Georgia, and Florida have the largest share of urban land use, which is well above the national average. Kentucky, Tennessee, Virginia, and North Carolina also have urban shares of urban land use above the national average (Nickerson et al. 2011).

The SE produces more than $55 billion in agricultural products annually, accounting for more than 17% of the total annual USA production (Figure 7.1). Of the total SE annual sales, more than 50% are derived from animal production, with the top five commodities consisting of broilers, eggs and chicken products, cattle and calves, hogs, and dairy products (Table 7.1). Crops represent 40% of the annual production, and include fruits and vegetables, soybeans, greenhouse and nursery products, corn and cotton. The SE produces 66% of the nation's broilers, 29% of the chicken eggs, 27% of the turkeys, 50% of the aquaculture, 37% of the cotton, 62% of the peanuts, and 33% of the tomato production (Hatfield et al. 2011).

A)



B)

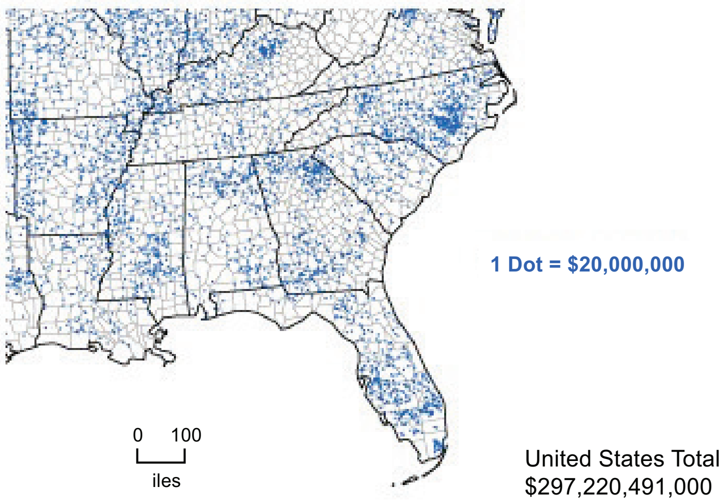


Figure 7.1 Maps show (a) shares of land use in the Southeast and (b) distribution of market value of agricultural products sold. (a) USDA Census (2007) and (b) Hatfield et al. (2011).

Table 7.1 Regional Population and Agricultural Sales in the Southeast.

Population	
Urban	59,600,000
Rural	16,900,000
Farms	528,800
Annual Sales	
Crop (Billion $)	25.6
Animal (Billion $)	31.1
Total (Billion $)	**56.7**

Source: USDA-ERS (2010).

Since 1985, agricultural land used for cropping, pasture, and ranges has consistently decreased as a consequence of expansion in non-agricultural land uses. Between the 1985 and the 2007 census the region recorded combined losses of agricultural land greater than 18% (7 million ha). Nationwide, cropping areas for the same period declined by more than 24 million ha, with the SE accounting for 36% of this loss. For the SE, there is a greater decrease in cropping land than in pastures. The states with the biggest net agricultural land loss were Georgia, Mississippi, Louisiana, and Florida (Nickerson et al. 2011). These long-term trends are linked to a number of factors, including changes in farm policies, commodity price fluctuation, crop insurance, land ownership, and urban encroachment as a result of population growth.

Agriculture consumes more than 80% of the water used in the USA (Schaible 2004). Competing demands for water from population growth, energy sector growth, and environmental needs have intensified. The development and maintenance of irrigation technology is an important factor to successful and optimal agriculture. In 2007, about 23 million ha (17% of all cropland) in the SE was irrigated. Since 1982 growth rates in irrigation have slowed down nationwide and in most parts of SE, except for large expansions in the Delta Region and Arkansas (Nickerson 2011). The SE region accounts for about 15% of the total USA water used for agriculture. Arkansas ranks second after California (Nickerson 2011).

Agriculture is a large contributor to CO_2 emissions. However agriculture also provides opportunities for carbon sequestration and increased storage that have the potential to offset high emission rates, while providing economic value to landholders and farming businesses. For the region, conversion to restorative land use and adoption of carbon sequestration practices can help to achieve a positive carbon balance in agriculture (Lal et al. 2011). Many practices that farmers implement as part of adaptations to climate changes will also mitigate carbon emissions. For example, carbon losses associated with grazing systems could be reduced through proactive management to conserve vegetative cover and to store soil carbon through integration of crop, pasture, and livestock production systems (Shepherd 2011). This topic will also be addressed in the up-coming 2012 ARS GRACEnet assessment (GRACEnet 2012).

The diverse and intensive agricultural sector in the SE is highly affected by climate conditions and requires appropriate, continuously improving management practices. Climate impacts on agriculture profits, spill over into the broader agribusiness sector. Severe climate events such as floods and droughts have large impacts on the financial performance of agricultural businesses. For instance, the 2011 floods in the Mississippi River area were estimated to cost the Arkansas agricultural industry more than $500 million (Arkansas Farm Bureau 2011). The risks associated with such events are comparatively higher than in other industry sectors and require more intense risk management strategies. Relatively few of the crops grown in the SE are covered by government risk management programs, which tend to favor the major agronomic crops such as corn, soybean, and wheat, which are relatively less important in the SE.

Land and water are the most important production resources in the agricultural sector. The costs for using these resources in agricultural production are affected by a number of factors including urban encroachment, competition for water from other sectors, sea level rise, effects of weather and climate, and land degradation. Major input costs that influence agricultural production include fuels, chemicals, seeds, labor, resource management, and marketing. Between 2002 and 2007, farm-related production expenses have increased 39%. Individually, costs for fuel and fertilizers increased more than 80% during this time (USDA-ERS 2010).The complexity of the agriculture sector requires management decisions that maximize production and minimize environmental impact on soils and water resources, in addition to mitigation of climate change and the adaptation to its likely effects (Lal et al. 2011).

7.2 Climate Sensitivities and Vulnerabilities

Agriculture is highly sensitive to climate variability and change. Increasing temperatures, changes in rainfall, and higher atmospheric CO_2 concentration affect agricultural production through various physiological mechanisms. In combination, these factors will increase or reduce agricultural production; the net effect will depend on interactions among these factors. Sea level rise and the potential for increased frequency of major hurricanes will have direct and indirect negative impacts on agriculture in coastal areas. Climate sensitivities and vulnerabilities also will affect productivity and production costs for animal production, under both free-range and confined conditions.

Adverse impacts of climate change on other economic sectors may increase the vulnerability of agriculture. For example, tourism and real-estate are important parts of the economy in most areas of the SE that have coastlines. With rising sea levels and the degradation of vulnerable coastal areas by storms and floods, the tourism industry is predicted to be substantially affected (ASP 2011). A study by Luscombe (2010) estimates that property values in the Florida Keys alone could be reduced by $11 billion by 2100 through the impact of sea level rise. A negative growth in the tourism and real estate industries will affect the region's important food service sector through reduced demand for locally produced food, representing an important market for many agricultural businesses in the region (Borisova et al. 2008).

Potential Impact of Rainfall Variability and Change

Changes in rainfall amounts can have both negative and positive effects on agricultural production. For example, in low rainfall environments higher rainfall will increase growth, where less rainfall will further limit plant production. In contrast, in high rainfall zones, too much rainfall can result in waterlogging, which damages crop growth (Dracup et al. 1993, Jiang et al. 2008) or result in nutrient leaching in sandy soils (Anderson et al. 1998). Additionally, reduced rainfall on these same soils will limit the negative impacts of waterlogging and nutrient leaching.

Rainfall distribution also plays an important role for determining crop yields. Rainfall around the time of anthesis ensures water supply during the grain-filling period and is particularly critical for grain yield in annual crops (Fischer 1979, Hatfield et al. 2011). Future changes in growing-season rainfall distribution therefore will have an impact on crop growth and yield. Balancing growth and water use before and after anthesis is one of the tools to manage uneven rainfall distribution. Options for managing the seasonal water use by crops include sowing time, nutrient management, plant density, and cultivar choice (Fischer 1979, Hatfield et al. 2011).

Extreme events are predicted to include a higher drought frequency in the western part of the region, but there may be fewer droughts across the northern tier of the region and in the mid-Atlantic (see Chapter 2, Section 2.4.3). A higher drought frequency in the western part of the region will lead to reduced crop production and yields below what is expected based on the average climate change (Easterling 2007). Particularly critical are changes in rainfall intensity and the distribution of small versus large rainfall events (Hayhoe et al. 2007), which can have significant consequences for crop production via the impact on soil infiltration depth, water balance, soil mineralization, and crop water use efficiency (Sadras and Rodriguez 2007). Extreme precipitation events have been increasing across the southeastern region, particularly over the past two decades (see Chapter 2, Section 2.3.2). The annual number of days with extreme precipitation is expected to increase across most of the region, particularly along the Southern Appalachians as well as parts of Tennessee and Kentucky (see Chapter 2, Section 2.4.1). The greatest impact of rainfall variability on livestock and poultry systems will be the indirect consequences of higher feed costs for purchased inputs. The impacts of changes in rainfall on forage production have not been as thoroughly researched as those for crop production, but prolonged droughts could significantly alter these systems as very little forage land is irrigated. Selection of drought tolerant forages and improvements in grazing management to buffer against drought could aid producers in adapting to more frequent drought conditions.

Potential Impact of Temperature Change

Temperature affects plant and crop-level processes that determine yield for all crops. Where crops are grown near their genotype specific limits of maximum temperature tolerance (Hatfield et al. 2011), heat spells can be particularly detrimental (Ferris et al. 1998). Conversely, in cooler regions, increased annual mean temperature since the 1980s has contributed to the reported increase in agriculture production (Yang et al. 2007).

Higher temperatures can negatively affect plant production indirectly as accelerated phenology (Menzel et al. 2006, Sadras and Monzon 2006) provides less time for accumulating biomass (Amthor 2001, Menzel et al. 2006) analyzed phenological data from 125,000 time series for 542 plants in 21 European countries and found that for the period 1971 to 2000, 78% of all leafing, flowering, and fruiting events occurred earlier. Sadras and Monzon (2006) modeled in detail the effect of recently realized changes in temperature on phenological development of wheat, and found earlier flowering. However, unexpectedly, no changes were noted in the duration from flowering to maturity due to the shift of flowering to cooler parts of the season.

Extreme temperature events can have large negative impacts on plant growth and yield as shown for wheat (van Herwaarden et al. 1998). Temperatures below 9°C and above 31°C around anthesis (or flowering), can reduce potential grain weight and therefore yield (Calderini et al. 2001). Higher average temperatures can reduce the frequency of frost and frost damage (Baethgen et al. 2003). However, indirect effects of temperature, such as shifting flowering to "cooler" parts of the season, may lead to the paradox of increasing frost risk at flowering (Sadras and Monzon 2006).

The impact of increasing temperatures can vary widely between crop species. Plants carrying out the C4 photosynthesis process have higher optimum temperatures for leaf photosynthesis and plant growth (i.e., more productive under high temperatures but less responsive to higher atmospheric CO_2 concentrations) than plants utilizing the C3 photosynthetic process (Goudriaan and Van Laar 1994, Hatfield et al. 2011). Species with a high base temperature for crop emergence such as maize, sorghum, millet, sunflower and some of the legumes (e.g. mung bean and cowpea) (Angus et al. 1981, Hatfield et al. 2011) might benefit from increasing temperatures in cool regions. For most of the cereals; legumes, such as field pea and lentil; and linseed and oilseed crops with a low base temperature (Angus et al. 1981), a warming climate will result in an advanced phenology. For example, Sadras and Monzon (2006) showed that the date of wheat flowering in different environments is advanced about seven days per degree increase in temperature.

Climate change is likely to have greater impacts on minimum than on maximum temperatures (Nicholls 1997), and such changes in diurnal temperature range can have different effects on various crops. An increase of average temperatures, in the frequency of hot days, warm nights and in the length of the freeze-free season is projected for the SE, but projections for changes in diurnal temperature range are not specified (see Chapter 2, Section 2.4.2). However, Lobell and Field (2007) analyzed historical yield data of wheat, rice, and maize from the leading global producers and showed that an increase in diurnal temperature range was associated with reduced yields of rice and maize in several agricultural regions worldwide. This reflects the nonlinear response of yield to temperature, which likely results from greater heat stress during hot days (Lobell 2007). Peng (2004a) suggested that rice yields declined by 15% per degree Centigrade in minimum temperature due to wasteful night respiration, but this interpretation was challenged in subsequent studies (Sheehy et al. 2006a, Sheehy et al. 2006b). Baker et al. (1995) observed 10% loss in rice yield per degree above 25°C mean daily temperature, based on extensive experiments in sunlit, controlled environment chambers.

An indirect effect of increasing temperatures due to climate change likely will be higher water demand by plants due to increased transpiration, which can potentially reduce plant production (Lawlor and Mitchell 2000; Peng et al. 2004b). In dry-land agriculture, this will directly limit plant growth, while in irrigated systems increased temperatures could result in higher irrigation demands in combination with increased losses through evaporation. However, if future temperature changes are similar to the changes in the last 50 years, where global minimum temperatures have generally increased twice as fast as maximum temperatures, resulting in a reduced diurnal temperature range (Folland et al. 2001), the impact of increasing temperatures on vapor pressure deficit and therefore on atmospheric evapotranspiration would be small (Farquhar et al. 1978). In addition, higher atmospheric CO_2 concentrations can partially compensate for the increased water demands due to higher temperatures, through lower stomatal conductance, which reduces transpiration (Kimball 2010). Reduced leaf transpiration as a consequence of higher CO_2 will also increase leaf temperature with an increased chance of plant damage due to heat stress. Plants grown at higher atmospheric CO_2 tend to have a higher leaf water potential, which results in reduced drought stress (Wall 2001).

Higher temperatures can also adversely affect grain quality as shown for grain protein content (Triboi et al. 2003, Zhao et al. 2008) and dough quality of wheat (Randall and Moss 1990; Wrigley et al. 1994). For some crops, night temperatures are critical for grain quality, as shown for fatty acid composition in sunflower (Izquierdo et al. 2002).

Increasing temperatures could have profound impacts on livestock and poultry producers. Heat stress in particular may lead to significant detrimental effects on production and reproduction of some livestock species. Heat stress in dairy cattle can have a long-term effect (weeks to months) on both milk production and birthing rates (Klinedinst et al. 1993). Dairy cows perform best under cool temperatures, with the temperature optimum for maximum milk production between 4^0C and 24^0C. At high relative humidity (>80%) heat stress in dairy cows can begin at temperatures as low as 23^oC, and stress becomes severe at 34^0C. Dairy farmers could adapt to warmer temperatures by renovating barns to improve their cooling systems, but these costs would have to be weighed against potential risks and benefits. Poultry animals are primarily grown in housed operations, so the effect of climate change more directly affects the energy requirements for building operation rather than a direct effect on the animal. Similar statements can be made for swine production as the vast majority of the animals are housed. Temperature affects animals being moved from buildings to processing plants, but because these animals are moved quickly from production to processing, this is a problem only in extreme conditions (Hatfield et al. 2011).

Potential Impact of Elevated Atmospheric CO_2 Concentrations

Elevated CO_2 has two main effects on crop growth. It increases the intercellular CO_2 concentration leading to increased net photosynthesis rates, and at the same time reduces stomatal conductance resulting in reduced transpiration and improved water use efficiency (Farquhar et al. 1978). Many experiments have shown that higher CO_2 concentrations increase plant biomass production and yield (Drake et al. 1997, Garcia et al. 1998, Ma et al. 2007,Morison 1985, Tubiello et al. 2007, Kimball 2010, Hatfield et al. 2011). However, C3 species respond differently to elevated CO_2 than do C4 species (Allen et al. 2011, Prasad et al. 2005, Kimball 2010, Hatfield et al. 2011) (see Table 7.2)

Table 7.2 Examples of C3 and C4 Species.

C3 Species	C4 Species
• Small grains such as wheat, barley, oats, and rye • Grain legumes such as soybean, peanuts, various beans and peas • Root and tuber crops such as potato, sweet potato • Most fruit (peaches, citrus), nut (pecans), vegetable and fiber crops (cotton); and cool climate forage and grassland species	• Maize, sorghum, sugarcane • Many warm-climate grass species (Bahia grass)

Increases in CO_2 concentration increase photosynthesis more than crop yield; at 500 to 550 ppm, yields of C3 crops will yield 15% to 30% more, whereas C4 crops will yield 15% to 25% more (Kimball 2010, Tubiello et al. 2007, Long et al. 2006, Hatfield et al. 2011). On average, doubling CO_2 concentrations increases photosynthesis from 30% to 50% in C3 species, and from 10% to 30% in C4 species (Kimball 2010, Tubiello et al. 2007). Lobell (2007) summarized CO_2 effects from a number of open-top chambers and Free Air Carbon-Dioxide Enrichment (FACE) experiments with 0.07% grain yield increase in wheat per ppm CO_2 increase for up to 550 ppm.

The response of pasture species to elevated CO_2 is consistent with the general response of C3 and C4 vegetation to elevated CO_2. Pasture species with C3 metabolism increase their photosynthetic rates by up to 40%, but not those with a C4 pathway (Hatfield et al. 2011). Unlike croplands, the literature for pasturelands is sparse in providing quantitative information to predict the yield change of pastureland species. Current information indicates forage yield responses of C3 versus C4 perennial forages to be similar to corresponding C3 or C4 annual crops (Hatfield et al. 2011). The projected increases in temperature and the lengthening of the growing season should be, in principle, beneficial for livestock by increasing pasture productivity and reducing the need for forage storage during the winter.

The impact of elevated CO_2 on plant production depends on water and nutrient availability. The greatest response to elevated CO_2 is found under water limiting conditions (Kang et al. 2002, Manderscheid and Weigel 2007, Kimball 2010) because higher CO_2 concentrations increase leaf and plant level water use efficiency (WUE) (Wu et al. 2004, Kimball 2010, Allen et al. 2011). Low nutrient availability can reduce the positive impact of elevated CO_2 on yield (Kimball 2010). The impacts of elevated CO_2 at field and farm levels are probably lower than those estimated in well-controlled experimental conditions because, due to production limiting factors such as low nutrient availability, pests, and weeds (Tubiello et al. 2007). An important indirect effect of higher atmospheric CO_2 is reduced plant nutrient concentrations, which can result in lower grain quality (Kimball et al. 2001, Rogers et al. 1996).

An indirect effect of elevated atmospheric CO_2 is an increase in canopy temperatures due to a reduction in stomatal conductance and therefore less evaporative cooling

(Kimball 2010, Hatfield et al. 2011). There is evidence in C3 plants, as found in experiments with wheat and cotton, that selection for improved grain yields in breeding programs is more successful when selecting for high stomatal conductance, resulting in heat avoidance through evaporative cooling in hot environments (Amani et al. 1996, Lu 1994, Radin et al. 1994). Reduced stomatal conductance in response to increased atmospheric CO_2 might therefore have additional effects on crop growth and development similar to an increase in temperatures (Allen et al. 2011).

Potential Impact of Tornados, Hurricanes, and Sea Level Rise

High wind speeds of tornados and hurricanes can damage summer crops through lodging (falling over) which can make crops unharvestable. The impacts on confined poultry or livestock can be devastating if facilities are destroyed resulting in long periods without production and considerable animal mortality. Heavy rainfall from hurricanes can lead to soil water-logging, delays in harvesting, degraded crop quality and overall yield losses. Sea level rise will affect ground water availability for irrigation near the coast due to salt water intrusion. During drought periods, there can be greater levels of salinity intrusion up coastal rivers affecting surface water withdrawals. In addition, retreating urban populations from the current coast line will put pressure on agricultural areas (Spechler 2001).

Potential Combined Impact of Climate Change

Rainfall, temperature, and CO_2 concentrations do not change independently but interact with each other and are highly complex (Hatfield et al. 2011). To develop climate change adaptation strategies so that crop production can remain stable in a changing climate, it is important to sufficiently understand the complexity of natural systems and how these are affected by changing climatic factors (Boote et al. 2011). Wheeler et al. (1996) showed that a positive yield effect in wheat from 700 ppm elevated CO_2 in the UK could be offset by an increase in mean seasonal temperatures of 1^0C to 1.8^0C. It is important to understand the interactions before developing climate change adaptation strategies because, for example, adaptations to higher temperatures may be different from adapting to reduced rainfall (Ludwig and Asseng 2010, Tubiello et al. 2007). Another study by Allen et al. (2011) based on experiments with maize and sorghum, suggests that drought stress in C4 crop plants can be ameliorated at elevated CO_2 as a result of lower stomatal conductance and sustaining of intercellular CO_2 concentration. Furthermore the study suggests, that C4 crops may require less water under future higher atmospheric CO_2.

In livestock and poultry production, Reynolds et al. (2010) stated that changing climate would affect the following: (1) the suitability of land, (2) availability of land due to sea level rise, (3) water availability and quality, and (4) production efficiencies under drought conditions.

As local environmental conditions change, so too will the spread of livestock diseases in response to the changes in prevalence of the host species and the suitability of environmental conditions for pathogen transfer. Van Dijk et al. (2010) found clear evidence that climate change has already changed the overall abundance, seasonality, and spatial spread of endemic helminthes (parasitic worms in cattle) in the UK. Warming and changes in rainfall distribution may lead to changes in spatial or temporal distributions of those diseases sensitive to moisture such as anthrax, blackleg, *haemorrhagic septicaemia*, and vector-borne diseases (Hatfield et al. 2011). Pastureland response to climate change will likely be complex because, in addition to the main climate drivers, other plant and management factors might also influence the response (e.g., plant competition, perennial growth habits, seasonal productivity, and plant-animal interactions).

Climate Change Impact in the Southeast USA

A previous SE regional climate change assessment report summarized impacts of climate change on agriculture, forestry, air, and water quality (Ritschard et al. 2002). The effect of climate change on the crops studied in the report could be positive or negative, depending on location and crops. Dryland crops are expected to be more sensitive to climate change: a decline of 20% rainfall and an increase of 2°C temperature will cause yield losses from 10% to 15% by 2030 (Ritschard et al. 2002). Irrigated crop yields will decrease by 10%, except for rice, peanut, and soybean, which will increase 10% to 20% by 2030. The agriculture sector will likely be able to adapt to mild increase of temperatures of 1°C by 2030 provided rainfall increases. An increase in temperature will cause row crops growing in Alabama, north Florida, and southwest Georgia to shift north towards central Georgia, South Carolina, and North Carolina. Access to water for irrigation has been identified as the largest challenge to adapt to declining rainfall. Although some regions in the SE have access to shallow groundwater tables for irrigation, these areas are at risk of salt water intrusion from projected sea level rise (Ritschard et al. 2002). Also, competition for freshwater among the agricultural industry, urban communities, and ecological sectors will continue to increase. Recommended strategies to adapt to climate variability and change include improved seasonal forecasts, drought and heat stress resistant crops and livestock, adjustments of planting dates, and improved water management and fertilization practices to keep water reserves clean and available for the growing demands (Ritschard et al. 2002).

Hatfield et al. (2011) showed how future climate change likely will affect crops differently across the USA, due to different crops responses (e.g., C3 versus C4 plants), but also different base conditions (warmer in south versus cooler in north). For example, yields of maize and soybean likely will be less negatively affected in the Midwest than in SE, where increasing CO_2 (440 ppm) and temperatures (+0.8°C) will be more detrimental because of the fundamentally warmer climate in the South (Hatfield et al. 2011).

Higher temperatures will increase the atmospheric evaporative demand for water, thereby increasing evapotranspiration (ET). The effect of warmer temperatures on evaporative demand might be offset in part if warmer temperatures increase cloud cover. Higher atmospheric CO_2 is predicted to stimulate crop growth but also increase water use efficiency. Increasing temperature and CO_2 effects are of the same magnitude by 2040 in the USA (440 ppm, +0.8°C) but act in the opposite direction. The combined impacts of these effects will mean that the net changes to evapotranspiration likely will be minimal (Hatfield et al. 2011).

Climate changes will adversely affect the economic viability of livestock production systems. Surrounding environmental conditions directly affect mechanisms and rates of heat gain or loss by all animals. Lack of prior conditioning to extreme weather events (such as extreme heat, frost, and flooding) often results in catastrophic losses in the domestic livestock industry. In the central USA in 1992, 1995, 1997, 1999, 2005, and 2006, some intensive cattle feeding operations lost in excess of 100 head each during severe heat episodes (Hatfield et al. 2011). Economic losses from reduced cattle performance (morbidity affecting measures such as rate of weight gain, milk production per day, eggs per day) likely exceed those associated with cattle death losses by severalfold (Mader 2003). The risk potential associated with livestock production systems due to climate variability can be characterized by levels of vulnerability, as influenced by animal performance and environmental parameters (Hahn 1999). When combined performance level and environmental influences result in a low level of vulnerability, there is little risk. As performance levels (e.g., rate of weight gain, milk production per day, eggs per day) increase, the vulnerability of the animal increases and, when coupled with an adverse environment, the animal is at greater risk. Combining an adverse environment with high performance pushes the level of vulnerability and consequent risk to even higher levels. At very high performance levels typical of much of the highly efficient production in the SE, any environment other than near-optimal may increase animal vulnerability and risk.

The potential impacts of climatic change on overall performance of domestic animals can be estimated using defined relationships between climatic conditions and voluntary feed intake, climate data, and Global Climate Model (GCM) outputs. Because ingestion of feed is directly related to body heat production, any change in voluntary feed intake or energy density of the diet will change the amount of body heat produced by the animal (Mader et al. 1999). Ambient temperature has the greatest influence on voluntary feed intake. Body weight, body condition, and level of production affect the magnitude of voluntary feed intake and the level of ambient temperature at which changes to voluntary feed intake begin to be observed. Predicted climate outputs from GCM scenarios have been used to develop production and response models for growing confined swine and beef cattle, and milk-producing dairy cattle (Frank et al. 2001). The goal in the development of these models was to utilize climate projections, primarily average daily temperature, to estimate direct climate-induced changes in daily voluntary feed intake and subsequent performance across the entire country. The production response models were run for one current (pre-1986 as baseline) and two future climate scenarios: doubled CO_2 (~2040) and tripled CO_2 (~2090) levels. This database employed the output from two GCMs—the Canadian Global Coupled (CGC) Model, Version I, and the United Kingdom Meteorological Office/Hadley Center for Climate Prediction and Research model—for input to the livestock production and response models. Across the entire USA, production levels for livestock showed declines, including days to market swine, which increased 1.2% for the CGC and 0.9% for the Hadley model; days to market for beef, which increased 2.0% for the CGC and 0.7% for the Hadley model; and dairy milk production, which decreased 2.2% for CGC and 2.1% for the Hadley model. Swine and beef production were affected most in the south-central and SE USA. Dairy production was affected the most in the Midwest and Northeast. In the east-central USA, per animal milk production declined 388 kg (~4%) for a July through April production cycle, and 219 kg (~2.2%) for an October through July production cycle as a result of global warming. Swine growth rate in this same region was found to decline 26% during the summer months, but increased nearly 12% during the winter months as a result of climate changes. Between 1995 and 2010, the SE USA experienced a decline in milk production of about 37%. Approximately one-half of these summer domestic livestock production declines are offset by improvements in productivity during the winter.

Amundson et al. (2005) reported a decrease in pregnancy rates of cattle of 3.2% for each increase in average Temperature Heat Index (THI) above 70, and a decrease of 3.5% for each increase in average temperature above 23.4°C. These data were obtained from beef cows in a range or pasture management system. Minimum temperature had the greatest influence on the percent of cows getting pregnant. Clearly, increases in temperature or humidity have the potential to affect conception rates of domestic animals not adapted to those conditions.

A range of reviewed subregional and state-based assessments and impact studies predicting direct and indirect impacts on the agricultural sector in the SE region are summarized in the following sections. Examples of damages and losses associated with recent extreme events are used to illustrate current vulnerability to climate. Some opportunities for agriculture to contribute to mitigation are also highlighted.

Virginia. Increased storm surges and flooding are projected due to higher sea levels on 5,335 km of Virginia tidal shoreline. The state is highly susceptible to damage from hurricanes, storms, and water surges that are forecast to intensify and are likely to result in increasing economic damages and losses. Virginia can play an important role in reducing fossil carbon emissions as it has an abundance of required resources for biomass combustion, including mill and crop residues (Commonwealth of Virginia, ASP 2011).

North Carolina. In the last hundred years average temperatures increased by 0.67°C with a further 2.2°C projected for the next century (CIER 2008a). Such increase in global temperature likely will shrink North Carolina's booming $70.8 billion agricultural industry by nearly 23% by the end of the century (CIER 2008a). Between 1996 and 2006, 14 tropical storms and hurricanes caused more than $2.4 billion of damage to the state's agricultural Industry (CIER 2008a). The state's 2002 drought cost the industry $398 million and affected over 4,300 jobs (NCSL 2008). The Appalachian region livestock industry is projected to lose 10% of its yield through heat stress due to an increase of 5°C by the end of the century (CIER 2008a).

Tennessee. Temperature increases are predicted to negatively affect Tennessee soybean and corn yields and the industry (USDA-ERS 2010). Higher temperatures could impact negatively the lifespan of the Kentucky-bluegrass, an important turf grass (ASP 2011).

South Carolina. Agriculture accounts for 14.8% of South Carolina's GDP (ASP 2011). One-quarter of the state's 17.7 million hectares has been converted to farmland; and agriculture accounts for around $17 billion annually which correspond to about 8% of the state gross domestic product. Expected temperature increases are likely to hasten the maturation of plants, thus reducing total yield potential (SCSCO 2012). The US Environmental Protection Agency projects that South Carolina's soybean and wheat yields will fall by 42%, and its corn yields by 32%, with predicted rising temperatures by 1.7°C to 3.9°C between 2030 and 2100 (Carpio et al. 2008). Climate change will lower agricultural productivity in the long term for South Carolina due to increasing extreme weather events, pest infestations, and a northward shift of optimal production areas (von Lehe 2008).

Alabama. A study by Davenport (2007) suggested that in Alabama, traditional crops such as peach, apple, soybean, and wheat will suffer from climate change. In addition, more pesticides and herbicides will be required under any of the projected climate scenarios. However, increasingly favorable conditions are likely for cotton, corn, and new citrus crops. The Union of Concerned Scientists notes that 27% of the major roads, 9% of rail lines and 72% of ports within the region are built at or below sea level. Alabama's interconnectedness threatens its economy, inclusive of the agricultural sector (ASP 2011). Of the 70 natural disasters, related to extreme climate events, between 1980 and 2007 that caused $1 billion or more in damage nationally, at least 21 affected Alabama (Lott and Ross 2006).

Georgia. Analysis based on the 2007 IPCC projections suggests that by 2020, corn yields will drop by 15% and winter wheat yields will drop by 20% in parts of Georgia (IPCC 2007). However, soybean and peanut yields could increase as much 25% in northern Georgia and drop by 5% in the southern part of the state (CIER 2008b). The 2007 drought cost Georgia $1.3 billion in damages including crop losses of $83.8 million in hay, $160.1 million in cotton, $92.5 million in peanuts, and $63.1 million in corn (CIER 2008b).

Florida. Sea level rise, in combination with increased frequency and intensity of storms, projected increases in the number of major hurricanes, and associated seawater surges, is predicted to be the largest threat to Florida (see Chapter 2, Sections 2.4.5 and 2.4.6). For instance, aNatural Resources Defense Council report uses sea level rise projections of the 2007 IPCC Report to estimate that by 2060 16% of the Miami-Dade County will be inundated with water (IPCC 2007). Miami-Dade County produces more than $661 million annually in agricultural produce (2007), and is the second largest agricultural producing county in Florida (Hauserman 2007, Stanton and Ackerman 2007, USDA-ESR 2010).

Hurricanes are predicted to cost the state economy, including agriculture, $6 billion annually in 2025, increasing to $25 billion by 2050 (Hauserman 2007, Stanton and Ackerman 2007).

Florida's agricultural industries are predicted to be affected by higher temperatures, water scarcity, flooding of farmland that will cause crop losses and erosion, increased water demands, and increased costs for irrigation. Higher temperatures might lessen the likelihood of crop damaging winter freezes. By 2060, some scenarios project that floods will claim 10,400 ha of farmland, 1,800 ha of pasture, and 2,800 ha of Florida's citrus crop (Stanton and Ackerman 2007, Borisova et al. 2008). Preserving a sustainable citrus production in Florida could provide opportunities to expand the production of ethanol from citrus waste (USEIA 2010).

Mississippi. Warmer temperatures and less rainfall are expected to require additional irrigation to maintain the $4.8 billion agricultural industry in Mississippi (ERS, 2010, Wilbanks et al. 2010). Higher temperatures are also predicted to increase pests and weeds, and reports suggest that one of the most used and cost-effective herbicides, glyphosate, will be less effective under conditions of higher concentration of carbon dioxide (ASP 2011). The state's vulnerable aquaculture industry (see Chapter 9) will be under threat as a result of shrinking freshwater supplies, increasing salinization, warmer water temperatures, and contaminated runoff from high precipitation events (Twilley and Miller 2001). Opportunities exist for increased soybean-based biodiesel production, cellulosic ethanol made from crop residues, and renewable energy production from swine, poultry and dairy industries. Mississippi already has the nation's first methane producing system from poultry waste (ASP 2011).

Arkansas. The agricultural industry in Arkansas contributes $16.3 billion to the state's economy (UoA 2010).The impacts of climate change are predicted to lead to increased industry costs of production and reduced yields, causing a decrease in the sector's profitability according to an analysis of effects of 2009 weather conditions on crop production (Hignight et al. 2009). Twenty-two percent of the state's agricultural land lies in flood zones resulting in concerns over increased soil erosion(ASP 2011). Abnormal weather events, projected to increase in the future, caused an estimated loss of revenues close to $397 million in 2009—204 million for soybeans and $46 million for rice. Production levels of rice are expected to drop in the Mississippi Delta by 10% to 20% (Hignight 2009). Agriculture has great potential to help Arkansas reduce its carbon emissions through production of biodiesel and cellulosic ethanol using crop residues, which has the potential to replace 40% of the gasoline used in the state (ASP 2011, Cohen 2009).

Louisiana. The low-lying coast of Louisiana, including New Orleans, could be entirely under water by 2100 due to sea level rise (ASP 2011). The state currently loses wetlands at a rate of 6,200 ha annually (ASP 2011). Impacts of climate change include increased occurrences of storms, major hurricanes, and floods (Wilbanks et al. 2010) and also increased droughts in some regions (see Chapter 2, Section 2.4.3) that are expected to impact the state's agricultural industry (ASP 2011).

7.3 Adaptation to Climate Change and Variability in the Southeast USA

Climate change effects clearly will have impact on agriculture in the Southeast. Various types of adaptation can protect and even improve farm productivity. Adaptation has the potential to help farmers minimize negative effects or take advantage of positive effects of a changing climate. In most cases, adaptation to climate change in agriculture will occur locally, at the farm level, in response to and as preparation for local impacts of local or regional changes in rainfall and temperature and global changes in atmospheric CO_2 concentrations. Therefore, understanding the local impacts of regional climate change is a prerequisite for any adaptation strategy, since adaptations are devised at the local level in response to local conditions (Figure 7.2).

Most recent adaptations in agriculture in the SE USA relate to improved management in dealing with climate variability that includes frequent droughts, heat, frost, and high wind speeds. Recently, a better understanding of seasonal variability has emerged from climate-related agricultural research in the SE USA (Alexandrov and Hoogenboom 2001, Garcia y Garcia et al. 2006, Persson et al. 2011), the forecasting of seasonal climate (Bannayan and Hoogenboom 2008, Garcia y Garcia et al. 2010b, Olatinwo et al. 2010, Olatinwo et al. 2011, Royce et al. 2011), managing anticipated seasonal variability (Alexandrov and Hoogenboom 2001, Garcia y Garcia et al. 2006) and the management of climate-related pest and diseases (Boote et al. 2008). Studies on managing seasonal climate variability include research on farm-level risk management using irrigation (Lin et al. 2008), alternative crop insurance indices (Deng et al. 2008), optimizing crop insurance (Cabrera et al. 2006), spatial drought stress assessments (McNider et al. 2011), and the development of weather research and forecasting decision support tools (Olatinwo et al. 2011). For example, management tools for adaptation are available through AgroClimate. This widely-used climate-based decision support system, includes tools for seasonal forecast for much of the SE, including planting date scheduler, growing degree days and chill units tools, drought indices, and a host of other decision aids delivered via the Internet (www.agroclimate.org) (Fraisse et al. 2006).

Due to the relatively small changes in past climatic factors (rainfall, temperature, and CO_2), little adaptation has occurred that is exclusively related to historically experienced climate change. A number of researchers have studied the potential effects of

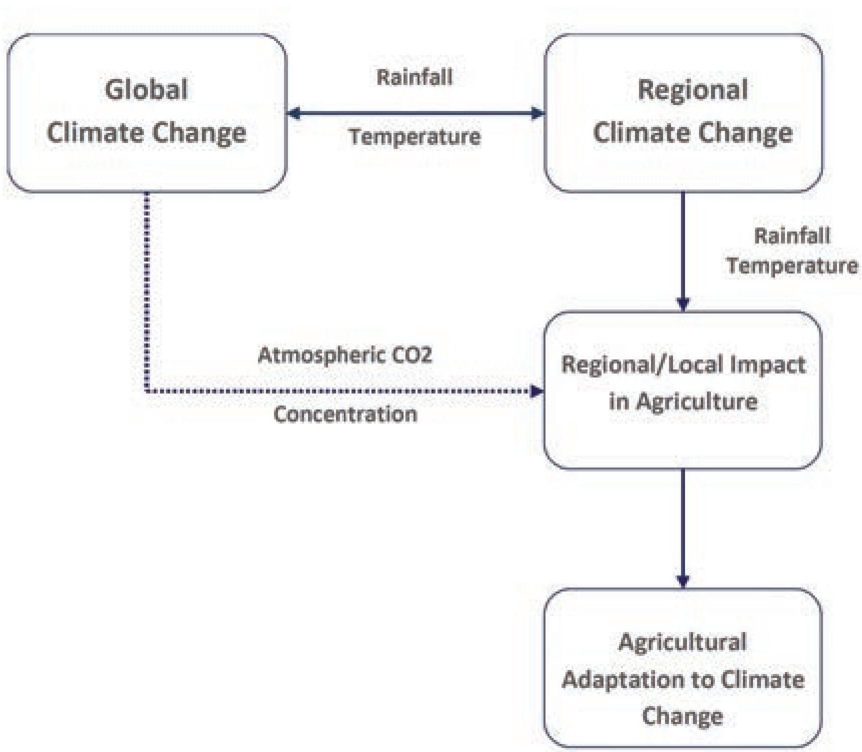


Figure 7.2 Relationship of global climate change, regional/local climate change, agricultural impact and agricultural adaptation to climate change.

changing climate and atmospheric CO_2 on agriculture (Bannayan et al. 2009, Ben-Asher et al. 2008, Garcia y Garcia et al. 2009, Garcia y Garcia et al. 2010a, Yoon et al. 2009) to prepare for climate change. Others have investigated these impacts on the future of agriculture assessing the potential for adaptation (Crane et al. 2011, Furman et al. 2011, Persson et al. 2011, White et al. 2011). For instance, alternative crops for ethanol production, as an important strategy for climate change mitigation, have been investigated in a number of studies (Persson et al. 2010a, Persson et al. 2009a, Persson et al. 2009b, Persson et al. 2010b).

Current Adaptation Strategies in Crop Production

Several possible adaptation strategies have been suggested to optimize crop production to local climate and to adapt to climate variability. Such methods will also assist in adapting crops to future climate change trends. Farmers in the SE have been testing a number of these new technologies, including sod-based rotation, conservation tillage, the usage of high biomass cover crops in combination with strip tillage and precision nutrient placement, optimum irrigation and fertilizing strategies, and decision support systems such as AgroClimate.

Sod-based rotation. A sod-based rotation is a four-year rotation that includes two years of bahia grass pasture/hay, followed by peanut, a winter cover crop, and cotton. The system has greater water-use efficiency as a result of increased soil organic matter and increased root activity at greater depths. The root mass produced by perennial grass is 20 mg/ha, compared with annual cover crops that produce only 3 to 4 mg/ha root mass. In addition, this system achieves greater efficiency of nutrient with less nitrate leached into ground water, greater soil cover for moderation of high temperature extremes, and reduced erosion. Other benefits include slower decomposition of crop residues that enhance opportunities for C sequestration and better yields at lower than conventional rates of fertilizer N, potentially mitigating greenhouse gas emissions (Wright et al. 2012).

Sustainable soil management strategies. Conservation tillage is one of the sustainable soil management strategies adopted in the SE. Conservation tillage is defined by USDA-NRCS as a system that leaves enough crop residues on the soil surface after planting to cover at least 30% of the soil area. Conservation tillage reduces climate risks through reduced runoff, increased water infiltration, increased plant-available water, reduced soil water evaporation, and reduced diurnal temperature fluctuations (Smith et al. 2011).

High biomass cover crops with strip tillage, and precision nutrient placement. The use of high biomass cover crops and limited tillage reduces impacts from weather extremes such as intense rainfall events, short-term spring/summer droughts, and extreme soil temperature during critical crop reproduction periods. Keeping the soil covered year round with crop residue, cover crops, or cash crops reduces soil erosion, improves water infiltration, reduces evaporative moisture loss, and moderates soil temperature. Precise nutrient placement improves nutrient efficiency during weather extremes.

Variable-rate irrigation. Variable-rate irrigation (VRI) is an innovative technology that retrofits existing center pivot systems and integrates GPS positioning with a control system that cycles individual sprinklers or groups of sprinklers on and off and varies travel speed to achieve desired irrigation rates within management zones. VRI reduces climate-related risks through reduction of total irrigation water volume required to grow field crops, exclusion of non-crop areas from water application; enhanced ability to tailor water application to varying crop needs across the field; better matching of irrigation application to site-specific soil types, textures, and topography reduction of nutrient leaching by application of optimal irrigation volumes; and reduction or elimination of runoff by better managing water application.

Micro-irrigation. Micro-irrigation is the slow, frequent application of water directly to relatively small areas adjacent to individual plants through emitters placed along a water delivery line, for example, drip irrigation. Micro-irrigation can help farmers adapt to climate changes through improving water use efficiency and reducing irrigation water volume required to grow crops, flexible irrigation based on the difference between potential and actual crop evapotranspiration, reduced nutrient leaching, optimal timing of nutrient applications, and application of fertilizer directly in the root zone. In addition, micro-irrigation is compatible with plastic mulch, which helps soil water conservation and protects fertilizer from leaching. Micro-irrigation via micro-sprinklers also provides freeze protection for small, high-value crops, such as strawberries. Information on these various methods is available through publications from IFAS (www.edis.ifas.ufl.edu).

Sensor-based, variable-rate nitrogen management. A sensor-based, variable-rate nitrogen application (SVNA) system for irrigated and dry land cotton reduce, production costs through the use of a nitrogen-rich calibration strip (NRCS) that guides mid-season nitrogen fertilization. The NRCS guidelines are adjusted for seasonal climate variability that arises in response to El Niño and La Niña events. Although the system will not mitigate risks from drought, excess rainfall, and temperature extremes, the technology can significantly reduce the nitrogen footprint for crop production to reduce greenhouse gas emissions.

AgroClimate: Information and tools for climate-smart agriculture. AgroClimate is a Web-based climate information system that includes seasonal forecasts and numerous management options for different crops/climate scenarios and tools that help producers in much of the SE plan for the season ahead. Users can also monitor variables of interest such as growing degree days, chill hours, disease risks for selected crops and drought conditions. Growers can use AgroClimate to reduce climate-related risks through tracking seasonal climate outlooks to better understand how climate conditions might affect crops, learn how El Niño and La Niña events affect the local climate, to explore how El Niño and La Niña phases affected crop production in much of SE USA, to help determine optimal planting dates for predicted climate, to select crops and varieties better suited for the expected climate, and to improve monitoring of disease risks for selected crops. In addition growers can monitor soil moisture conditions using several drought indices and be alerted via e-mail and mobile phones about detrimental soil conditions for specific crops (Fraisse et al. 2006). For more information and to use AgroClimate, go to www.agroclimate.org.

Livestock and poultry adaption strategies. Livestock production systems have adapted slowly over a long period of time to suit local environmental conditions, such as water and forage availability. In animal agriculture, adaptation technologies have been studied far less than mitigation options. Priorities include (1) use of species-rich mixtures, legumes, and better adapted forage species and cultivars adaptation in forage lands; (2) permanent pasture management by changes in grazing frequency to favor the maintenance of high-digestibility species and to increase tolerance to drought stress; (3) use of intercropping with legumes and use of C_3 and C_4 species of feed crop mixes; (4) integrated control options to reduce the spread and impacts of gastrointestinal parasites, especially in ruminant production systems; (5) provision of more shade or water in extensive grazing systems and development of improved technologies for reducing heat stress impacts in confined systems; (6) changes in livestock and poultry breed selection and selection to favor animals that are more tolerant of local conditions; and (7) development of improved tools to provide producers with warnings of when temperature heat indexes are nearing threshold levels so that producers can take action to avoid losses.

The Capacity for Agricultural Stakeholders to Adapt to Climate Change

Adaptive capacity is an emergent property that confers resilience to perturbation (shocks), giving ecological and human social systems the ability to reconfigure themselves with minimum loss of function. In human social systems, it is demonstrated by the stability of social relations, the maintenance of social capital and economic prosperity (Gunderson and Holling 2000, Folke et al. 2003, Yohe and Tol 2002). One past example of adaptive capacity in the SE USA was the ability of the citrus industry to relocate southward from its original location around Charleston, SC, to its current location in Central and South Florida, following a series of disastrous freezes starting in the late 19th century. Another case was the widespread adoption of zebu or Indian cattle breeds along the gulf coast that are more resistant to heat and tropical diseases than the traditional European cattle. In general, hardier, more heat-resistant varieties of fruits and vegetables have been developed and adopted for the subtropical SE USA. It must be emphasized, however, that these adaptations were purely technical and reactive.

The capacity for agricultural stakeholders to adapt proactively to climate change is determined by more than their access to appropriate technologies or management practices. For instance, social, political, and economic factors also shape adaptive responses. These include, but are not limited to, the ways in which agricultural stakeholders perceive the impacts and risks of long-term climate change, their access to and use of climate information; the ways in which they are actively connected within knowledge and community networks; and their capacity to address problems at household and farming system levels, in addition to those infrastructural, market, and policy barriers that limit options for adaptation.

A politicized struggle to shape public understanding of climate change in the USA has polarized the debate in the media. The scientific consensus is framed through elements of dread and uncertain risk, while climate change deniers portray climate change as natural, familiar, and improbable (Weber and Stern 2011, Leiserowitz et al. 2008). Within this context, many agricultural stakeholders in the SE USA may find it difficult to assess the risks that climate change presents (Ingram et al. 2012). Furthermore, because farmers manage many different types of risks on a day-to-day basis, the potential impacts of long-term climate change might not always motivate immediate concern (Ingram et al. 2012). Studies have shown that political ideologies also correlate strongly with belief in climate change as seen among organic farmers (Furman, et al. 2009) and African farmers in the southeastern states (Bartels, et al. 2012a, b). Another study demonstrated, for instance, that conservative white males are more likely to be climate skeptics (McCright 2010). In the SE, only one-eighth of the farm operators are women, with an average age from 56 to 58. The majority of farmers in the SE who are likely to make management decisions in the agricultural sector are older, more conservative, white men (USDA 2007).

The challenge of communicating about climate change with more skeptical audiences is being addressed within the SE Climate Consortium (SECC) by focusing initial discussions on climate-related issues that are of more urgent concern to growers. At state and local scales, governments are also engaged in cross-agency collaborations to communicate about issues that are linked directly (and indirectly) to managing climate-related risks. For instance, the Water and Agricultural Policy Division of the Florida Department of Agriculture and Community Services is engaging agricultural stakeholders around issues of water quality and quantity through best management practice programs. The manner in which scientists or government agency representatives begin to engage with farmers about climate change can influence their receptiveness to exploring adaptation options. By focusing on climate issues that resonate strongly with growers, researchers can open the door to future discussions about longer-term changes (Bartels et al. 2012a). For example, due to the strong influence of La Niña and El Niño on agricultural production in the SE USA, seasonal variability and extreme events are areas where scientists have the best potential to engage with farmers in implementing on-farm adaptation strategies (Ingram et al. 2012). In surveys conducted with row crop farmers, extension specialists, and researchers, respondents indicated that weather or seasonal forecasts were more useful to them than longer-term projections (Figure 7.3, Bartels et al. 2012a). This was also demonstrated in studies by Crane et al. (2010) and Furman et al. (2011). A large body of research and extension within the SECC has centered on providing farmers and extension professionals with seasonal climate forecasts and coproduction of decision support tools to reduce climate-related risks (Breuer et al. 2008, Breuer et al. 2009, Cabrera et al. 2008, Furman et al. 2009, Fraisse et al. 2009, Fraisse et al. 2006, Ingram et al. 2012). Approaches developed and knowledge gained from projects that have helped farmers manage risks from seasonal climate variability are now being applied to new projects to help farmers adapt to climate change.

Enhancing farmer use of climate information also requires an understanding of the social nature of risk management and information processes. For instance, social networks are important for processing information (Crane et al. 2010). Farmers discuss weather and climate at social gatherings, when doing business with buyers and brokers, or at meetings with extension agents (Crane et al. 2010, Furman et al. 2011). The

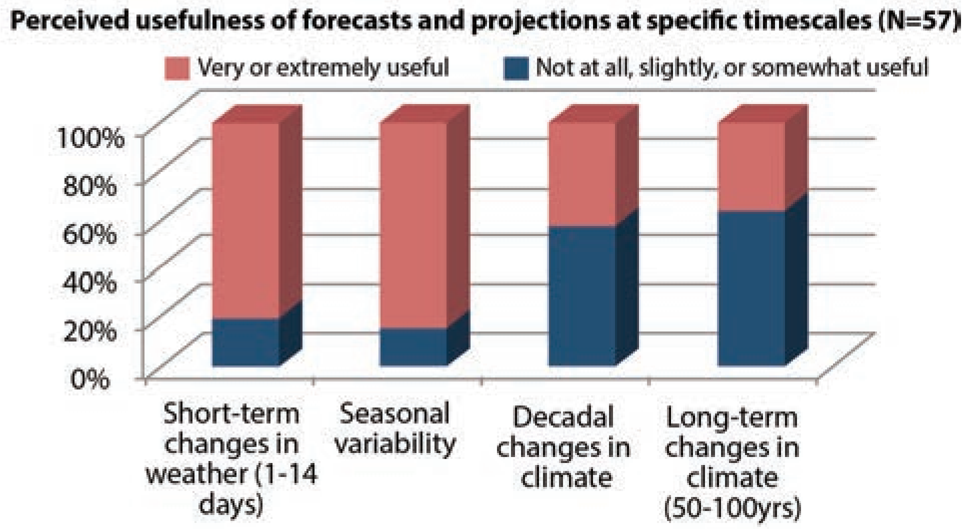


Figure 7.3 Perceived usefulness of forecasts and projections at specific timescales among row crop stakeholders (N=57) in the SE USA (Bartels et al. 2012a).

extension systems within the land-grant universities provide boundary organizations that link scientists to farmers for information diffusion and decision support. A survey of Florida extension agents found that between 2005 and 2009, knowledge and willingness to use and provide climate information to end users increased on average, and extension agents had refined their understanding of the types of climate information that are most useful (Breuer et al. 2010). These findings highlight the importance of receiving feedback from stakeholders about technologies. Such feedback can guide the development and dissemination of decision support tools that are accessible and relevant to the specific needs and goals of farmers. Valuable stakeholder input can be assessed further through interactive, participatory methods that explore farmers' perceptions, attitudes, long-term goals, and other cognitive and decision-making information before and during the development of decision support tools and systems (Breuer et al. 2008, Breuer et al. 2009, Cabrera et al. 2008, Fraisse et al. 2006). Fraisse et al. (2009) provide a framework for developing an extension program that combines climate variability and climate change (Figure 7.4).

Interactive venues in which farmers can exchange knowledge about adaptation technologies can enhance learning among all stakeholders. In this way, the thoughtful design of stakeholder engagement processes becomes a powerful social tool for improving adaptation decision support (Bartels et al. 2012b). A regional climate working group in the SE that includes farmers, extension agents, and researchers from Alabama, Florida, and Georgia meets biannually to foster knowledge exchange about climate and adaptation among scientists, farmers, and extension professionals. Historical timelines and storytelling have revealed the many ways in which growers have adapted to past changes and seasonal variability in climate. In assessing the barriers and opportunities for adapting farming systems these workshops reveal that farmers are familiar with several farm-and-field level management practices and planning decisions that can

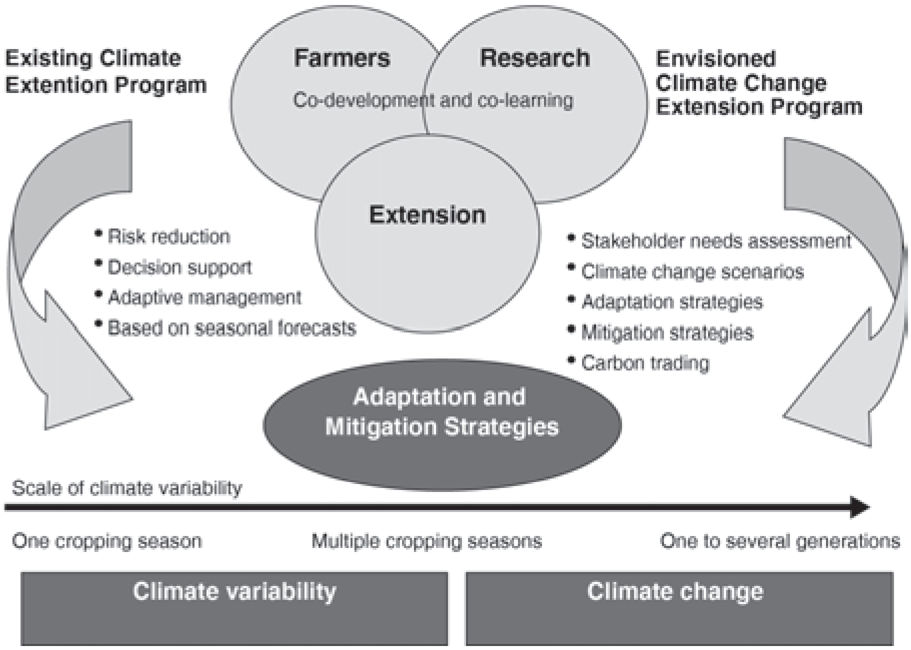


Figure 7.4 Framework for a combined climate variability and change extension program (Fraisse et al. 2009).

reduce climate-related risks. They are able to change crops or varieties, planting dates, tillage practices, or pesticide and irrigation schedules. However, they perceive a lack of control over other factors, such the federal farm bill, access to industrial infrastructure such as peanut shellers and cotton gins, and changes in commodity prices that drive planting decisions. One grower, for instance, reported that "as far as what crops were going to be grown 20 years from now, the farm bill probably impacts what farmers are gonna' grow more than anything." These findings point to the importance of moving discussions beyond farm-level decision making to embrace other scales of influence, for example, policy making circles that can influence the availability of potential adaptation options such as irrigation systems, crop insurance, or credit services (Bartels et al. 2012a).

Farmers constantly navigate and negotiate biophysical and socio-economic processes. Values, norms, meanings, and goals affect the way farmers perceive and respond to climate information. In addition, some livelihood systems are more flexible than others in terms of the ease with which farmers can integrate new technologies (Crane et al. 2010). For example, although awareness has grown among organic farmers in Georgia about the potential economic incentive offered by emerging markets for carbon credits, these farmers are not always able to implement practices that reduce emissions and sequester carbon. Smaller farms, including most organic farms, are easier to manage with manual tools than larger farms and new farmers might be less likely to afford the extra labor and costs required by strategies that seek to reduce carbon emissions (Furman et al. 2011). Farmers in central and northern Florida, who have more diversified and smaller operations, tend to place more importance on seasonal climate variability and are better positioned to respond to climate predictions (Breuer et al. 2010). Similarly, dryland farmers face very different adaptation challenges than do farmers who have irrigation systems. Therefore, to be effective, climate communication and education strategies must be designed to target specific commodity audiences, farming systems, and household types rather than a one-size-fits-all approach to adaptation (Bartels et al. 2012a, Furman et al. 2011, Crane et al. 2011). When viewing agriculture as a complex system of practices, climate information should be integrated gradually and experimented with over time. In this way, farmers will learn to employ these new technologies and adapt them to their own particular circumstances (Crane et al. 2010). For example, an Alabama extension professional and member of the row-crop climate working group reported that long term changes in agriculture are needed but that such changes are difficult. “It’s about like trying to turn a cruise ship, you know. You don’t turn a sharp left or a sharp right, ok, but you can start bending in one direction or another... I think that this kind of climate data and information can help make those minor shifts in one direction or another” (Bartels et al. 2012a).

7.4 Assessment and Research Needs

Climate change impact and adaption research needs in agriculture include general research needs relevant also to other agricultural regions and other sectors. However, some of the research needs are more specific to agriculture in the SE USA.

General Research Needs

Current climate change impact and adaption assessments are often local-, method- and assumption- specific and therefore not comparable. Standard assessment approaches and protocols (e.g. comparable baselines), multi-GCM climate change scenarios and multi-impact model applications to quantify the uncertainty of impact assessments with links to local, national and international trade and market models are urgently needed to better understand climate change impact and enable the development of appropriate adaptation strategies, as outlined in the Agriculture Model Intercomparison and Improvement Project-AgMIP (Rosenzweig et al. 2012).

The application of climate change impact models is also limited by the lack of suitable climate datasets for historical and projected climates. These climate datasets need to provide daily data that include maximum and minimum temperatures, precipitation, and solar radiation. To date, attempts to produce datasets through dynamical or statistical downscaling of global climate models (GCMs) have not been successful.

Mechanistic crop simulation models have been important tools in efforts to extrapolate how future climate will affect future crops. These mechanistic crop simulation models use knowledge gained from experiments conducted in fields, controlled-environments, across climate zones, rainfall regions, soil types, management regimes, and crops, in order to project how crops will perform under different climate change scenarios. Researchers have used these models to explore the impact of individual climate change components and the combined effects of climate change scenarios on crop production and externalities. These models allow testing of various management options and, to a lesser extent, varietal traits that can counteract the negative impacts of climate change and maximize potential benefits of climate change. While these models are simplifications of reality, they allow a first assessment of the complexity of climate change impact and adaption options in agriculture. However, there are a number of gaps in the global knowledge that apply to the SE USA that are needed to improve mechanistic crop models and their application in climate adaptation studies. These gaps include a better understanding of how combinations of various climate change factors affect crops, in particularly heat stress; how specific climate change factors affect plant-water relations; how climate change affects internal crop feedbacks such as sink-source relations; and how extreme events will affect crops. These needs are briefly discussed in the following paragraphs.

Temperature and CO_2. Effects of elevated CO_2 and temperature are often not considered in crop models although they may be significant. For example, reduction of transpiration canopy cooling as a result of elevated CO_2 and stomata closure can increase pollen sterility in rice (Ziska and Bunce 2007). As the frequency of extreme high temperatures (>32°C (89.6^{0}F) during the growing season increases, interactions with elevated CO_2 need to be understood and considered (Attri and Rathore 2003). Amthor (2001) indicated a reduction of yield with elevated CO_2 in combination with warming for wheat, compared with elevated CO_2 alone. Alonso and et al. (2008) found a higher photosynthetic temperature optimum in cereals under elevated CO_2. No such beneficial interactive effects were observed for rice, soybean, peanut, dry bean, or sorghum, although independent main effects of temperature or CO_2 were present (Boote et al. 2005, Hatfield et al. 2011).

Crop models need to be tested with data sets of interactive effects to ensure validity for climate change scenarios as suggested by Boote et al. (2010). Similarly, interaction effects of elevated CO_2 and flooded conditions; salinity (Ziska and Bunce 2007); and soil constraints, such as compactions, sub-soil toxicity, or transient waterlogging are unknown, but need to be considered (Probert and Keating 2000). Due to the interactive effects and feedbacks that emerge when climate factors are combined, experiments in which only single factors are manipulated are likely to be inadequate to fully predict the impacts of future climate change (Dermody 2006).

Warming, reduced water, and elevated CO_2. Studies have simulated elevated CO_2 and warming with reduced water supply, specific rainfall patterns, and a range of soil water holding capacities under various climate impact scenarios. Elevated CO_2 and increased temperatures will have different effects on physiological processes (Triboi et al. 2006), such as sink-source (or demand of grains for assimilates versus supply of assimilates from photosynthesis and remobilization) relationships of grain yield (Fischer 2008, Sinclair and Jamieson 2006). For example, wheat grain yield has been reported to be reduced under elevated CO_2 in sink-manipulated shoots (e.g., by removing growing grain from ears), implying that a high source-sink ratio might down-regulate photosynthetic capacity to an extent that more than offsets the stimulating effect of elevated CO_2 (Uddling et al. 2008). However, these models have never been tested with experimental data with such interactions as treatments even though the combined effects could be very different to the sum of single factor effects. For example, in one study, the net primary production response of grasslands to increased atmospheric CO_2, temperature, rainfall, and nitrogen deposition differed greatly from simple combinations of single factor responses (Shaw et al. 2002). In addition, simulation studies generally ignore the different response of genotypes to increasing CO_2 concentrations shown in some experiments (Manderscheid and Weigel 1997, Slafer and Rawson 1997). However, Boote et al. (2011) conducted model simulations of genetic improvements in soybeans and found certain traits gave a greater response under elevated CO_2 than under ambient CO_2 and that heat-tolerance traits for grain set were more beneficial under elevated temperature conditions. Such analysis gives plant breeders a chance to target genetics to adapt to future climate change. Linking crop models with the underlying genetic structure of crops (Hammer et al. 2006) might help identify and incorporate genetic traits that will help crops adapt to future climates. However, little is known about CO_2 acclimatization of crops and hence this is also absent from simulation studies.

Potassium and phosphorus. Most crop models consider nitrogen (N). Other nutrients such as potassium and phosphorus can also limit growth under elevated CO_2 conditions (Hungate et al. 2003, Ziska and Bunce 2007), but models do not usually consider them in climate impact studies. Both model simulations and field experiments indicate that response to CO_2 is less under N-limitation while response to CO_2 under water limitation is greater in field experiments and model simulations (Boote et al. 2010, Kimball 2010). Nutrients could also limit crop growth when climate change alters soil factors or restricts root growth needed for nutrient uptake (Brouder and Volenec 2008).

Yield quality. Climate factors often affect yield quality, such as protein composition and oil content (Kimball et al. 2001), but models do not simulate these effects as well as they simulate yield. Simulation studies on climate change impacts will require incorporating a better understanding of the physiology of yield quality into crop models.

Temperature thresholds. Changes in specific climate thresholds could become critical. For example, changes in minimum or maximum temperatures are likely to have greater importance than changes in mean temperatures for grain yields, so crop models may require modifications to respond appropriately to changes in minimum and maximum temperatures (Fischer 2007).

Modeling growth events. In developmental stages of growth, crops can be sensitive to various climate-related stresses. For example, cereals are highly sensitive to frost during flowering. Models still face challenges in representing and quantifying growth impacts from extreme events such as heat stress, frost, and flooding at specific growth stages.

New cultivars and farming systems. In addition to improved modeling capacities and adaptation options in agriculture, research is needed to investigate new cultivars and better adapted species for the projected climate change scenarios (Tester and Langridge 2010). In particular, crop varieties are needed that take advantage of elevated atmospheric CO_2 concentrations, resist heat stress and frost events, and are more water-use efficient. Also needed are drought-tolerant farming systems (Katsvairo et al. 2006) as well as methods for sequestering more carbon in soils (Lal 2004). For many agricultural regions, new crop varieties, cropping systems, and agricultural management strategies are needed to provide options to farmers to counterbalance climate changes (Boote 2011).

Livestock and poultry. Livestock and poultry production have many similar research needs to those of crops, though there has been less research to improve understanding of climate change effects on livestock and poultry production systems. Interactions exist among temperature, humidity, and other environmental factors which, in turn, influence energy exchange. Indices or measures that reflect these interactions remain ill-defined, but research to improve them is underway. Developing new breeds and genetic types, improving animal health, and enhancing water and soil would support adaptation measures over the long term. An improved understanding of climate change impacts on pastureland should be sought through comprehensive studies that include grazing regimes, mutualistic relationships (e.g., plant roots-nematodes; nitrogen-fixing organisms), as well as the balance of carbon, nutrients and water (Hatfield et al. 2011). Studies addressing the impacts of climate changes on parasites and pathogens that effect livestock and poultry are needed.

Seasonal forecast models. As rainfall in the SE USA is variable and likely to become more variable, skillful seasonal rainfall forecasts also will be crucial. Similar seasonal forecasting systems are needed for extreme events, including heat, frost, hurricanes, and tornados to improve planning and adaptation to seasonal climate variability and change.

Specific Research Needs for the SE USA

With its diversity and production of specialty crops, the SE USA has specific research needs unique to the region in addition to those mentioned in the previous section. Such research is essential for agriculture to remain socially, economically, and environmentally sustainable in light of a changing climate and growing population. Following are some of those needs.

Climate datasets and collaboration between agricultural and climate modelers. To be used in impact simulation models, especially agriculture and hydrology, GCM and downscaled outputs must be evaluated at a daily time-step. Climate modelers do not generally evaluate the performance of models based on daily data outputs; they generally analyze seasonal or annual averages. Appropriate application of models to conditions in the SE requires climate datasets that provide daily data including maximum and minimum temperatures, precipitation, and solar radiation.

Initial efforts to include daily information from SE regional climate models (RCMs) in crop simulation models were unsuccessful because the RCMs simulated small amounts of rainfall daily rather than as discrete storm-related events (Jagtap 2005, pers. comm.). Efforts to use statistically downscaled general circulation models outputs for the SE also failed because the datasets included freeze events during summer months (Baigorria 2011, pers. comm.), a condition that does not currently exist and is not projected to occur in the future. Clearly, enhanced collaboration between climate and agricultural simulation modelers would benefit both parties (Rosenzweig et al.

2012) and would help identify anomalous events, such as a freeze during the summer, thereby helping climate scientists improve their methods.

Integrated, participatory, systems research approaches. Traditional agricultural research has followed a linear approach from research scientist to extension agent to farmer. To address the complex issues of sustainability in the face of changing and variable climate, research should follow a new paradigm—one that emphasizes the integration of research, teaching, and extension; invites the participation of decision makers throughout the research process; and assembles the diverse elements of agriculture through a systems approach (e.g., Breuer et al. 2009 and 2010, Bartels et al. 2012a, Roncoli 2006). Plant and livestock breeding and management research also are important elements to the overall agricultural research portfolio regarding climate change, but they should be incorporated into integrated approaches to assure that they contribute to agricultural sustainability. There is also a need for specific research in integrated climate impact and adaptation assessment in agriculture for Puerto Rico and the Virgin Islands as part of the SE, which is currently lacking.

Water and land resource policies. Population increases in the SE have led the nation for several decades and are likely to continue. As a result, urban sprawl and water demands from municipal, energy, and other sectors will increasingly compete with agricultural uses. Initial research shows that there is a strong interaction between changes in agricultural land use/land cover and regional climate. Policy research will be essential to balance these competing demands for land and water resources. Research on water resource issues should evaluate agricultural competitiveness in the SE both for its ability to meet food, fiber, and fuel needs of the region as well as its contributions to the national and global production (Marcus and Kiebzak 2008).

Mitigation and adaptation technologies and systems. Researchers are working with farmers in the SE to develop and assess technologies to mitigate and adapt to climate variability and change. Additional, albeit similar, research is needed to identify, develop and incorporate adaptive technologies into agricultural systems. These technologies should be evaluated based on their carbon, energy, water, and nutrient balances as well as life cycle, risk, and economic analysis, though such analyses are rarely applied to agricultural research and development.

7.5 References

Alexandrov, V.A. and G. Hoogenboom. 2001. Climate variation and crop production in Georgia, USA, during the twentieth century. *Climate Research* 17 (1): 33-43.

Allen Jr., L.H., V.G. Krakani, J.C. Vu, K.J. Boote. 2011. Elevated CO_2 increases water use efficiency by sustaining photosynthesis of water-limited maize and sorgum. *Journal of Plant Physiology* 168 (16): 1909-1918.

Alonso, A., P. Perez, R. Morcuende, R. Martinez-Carrasco. 2008. Future CO_2 concentrations, though not warmer temperatures, enhance wheat photosynthesis temperature responses. *Physiologia Plantarum* 132 (1): 102-112.

Amani, I., R.A. Fischer, M.P. Reynolds. 1996. Canopy temperature depression association with yield of irrigated spring wheat cultivars in a hot climate. *Journal of Agronomy and Crop Science* 76 (20): 119-129.

Amundson, J.L., T.L. Mader, R.J. Rasby, Q.S. Hu. 2005. Temperature and temperature-humidity index effects on pregnancy rate in beef cattle. *Proceedings 17th Intl. Congress on Biometeorology*, September 2005. Dettscher Wetterdienst, Offenbach, Germany.

Amthor, J.S. 2001. Effects of atmospheric CO_2 concentration on wheat yield: Review of results from experiments using various approaches to control CO_2 concentration. *Field Crops Research* 73 (1): 1-34.

Anderson, G., I. FilleryI, F. Dunin, P. Dolling, S. Asseng. 1998. Nitrogen and water flows under pasture-wheat and lupin-wheat rotations in deep sands in Western Australia. 2. Drainage and nitrate leaching. *Australian Journal of Agricultural Research* 49 (30): 345-362.

Angus, J., R. Cunningham, M. Moncur, D. Mackenzie. 1981. Phasic development in field crops 1. Thermal response in the seedling phase. *Field Crops Research,* 3 (1980): 365-378.

Arkansas Farm Bureau. Flooding to cost Arkansas agriculture over $500 million. *The Delta Farm Press* May 10, 2011.

ASP. 2011. Pay now, pay later, American security project—Arkansas, Louisiana, Mississippi, Kentucky, Tennessee, Virginia, North Carolina, South Carolina, Alabama, Georgia, and Florida. Accessed September 10, 2012. http://americansecurityproject.org/issues/climate-energy-and-security/climate-change/pay-now-pay-later/

Attri, S. and L. Rathore. 2003. Simulation of impact of projected climate change on wheat in India. *International Journal of Climatology* 23 (6): 693-705.

Baethgen, W.E., H. Meinke, A. Gimenez. 2003. Adaptation of agricultural production systems to climate variability and climate change: Lessons learned and proposed research approach. Paper presented at ClimateAdaptation.net conference Insights and Tools for Adaptation: Learning from Climate Variability, Washington, DC, November 18-20, 2003.

Baker, J.T., K.J. Boote, L.H. Allen. 1995. Potential climate change effects on rice: Carbon dioxide and temperature. In *Climate Change and Agriculture: Analysis of Potential International Impacts*, ed. C. Rosenzweig, J.W. Jones, L.H. Allen. ASA Spec. Pub. No. 59, ASA-CSSA-SSSA, Madison, WI, USA.

Bannayan, M. and G. Hoogenboom. 2008. Weather analogue: A tool for real-time prediction of daily weather data realizations based on a modified *k*-nearest neighbor approach. *Environmental Modelling & Software* 23 (6): 703-713.

Bannayan, M., C.M. Tojo Soler, A. Garcia y. Garcia, L.C. Guerra, G. Hoogenboom. 2009. Interactive effects of elevated [CO_2] and temperature on growth and development of a short- and long-season peanut cultivar. *Climatic Change* 93 (3-4): 389-406.

Bartels, W., C.A. Furman, F. Royce, B. Ortiz, D. Zierden, C. Fraisse. 2012a. Developing a learning community: Lessons from a climate working group for agriculture in the southeast USA. In *SECC & FCI Technical Report 12-001.* Albany, GA: Southeast Climate Consortium and Federation of Southern Cooperatives/Land Assistance Fund.

Bartels, W., C.A. Furman, F. Royce. 2012b. Agricultural adapatation to climate variability and change among African growers in the southeast USA. In *Southeast Climate Consortium Technical Report Series: 12-002.* Albany, GA: Southeast Climate Consortium and Federation of Southern Cooperatives/Land Assistance Fund.

Ben-Asher, J., A.G.Y. Garcia, G. Hoogenboom. 2008. Effect of high temperature on photosynthesis and transpiration of sweet corn (*Zea mays* L. var. *rugosa*). *Photosynthetica* 46 (4): 595-603.

Boote, K.J. 2011. Improving soybean cultivars for adaptation to climate change and climate variability. In *Crop adaptation to climate change,* ed. S.S. Yadav, R.J. Redden, J.L. Hatfield, H. Lotze-Campen, and A.E. Hall, 370-395. West Sussex, United Kingdom: Wiley-Blackwell.

Boote, K.J., A.M.H. Ibrahim, R. Lafitte, R. McCulley, C. Messina, S.C. Murray, J.E. Specht, S. Taylor, M.E. Westgate, K. Glasener, C.G. Bijl, J.H. Giese. 2011. Position statement on crop adaptation to climate change. *Crop Science* 51 (6): 2337-2343.

Boote, K.J., L.H. Allen Jr., P.V. Prasad, J.W. Jones. 2010. Testing effects of climate change in crop models. In *Handbook of climate change and agroecosystems: Impacts, adaptation, and mitigation*, ed. D. Hillel and C. Rosenzweig, 109-129. London, United Kingdom: Imperial College Press.

Boote, K.J., L.H. Allen Jr., P.V. Prasad, J.T. Baker, R.W. Gesch, A.M. Synder, D. Pan, J.M. Thomas. 2005. Elevated temperature and CO_2 impact pollination, reproductive growth and yield of globally important crops. *Journal of Agricultural Meteorology* 60 (5): 469-474.

Boote, K.J., J.W. Jones, G. Hoogenboom. 2008. Crop simulation models as tools for agro-advisories for weather and disease effects on production. *Journal of Agrometeorology (Indian)* 10 (Special Issue Part 1): 9-17.

Borisova, T., N.E. Breuer, R. Carriker. 2008. Economic impacts of climate change on Florida: Estimates from two studies. *EDIS and University of Florida-IFAS,* No. FE787.

Breuer, N.E., V.E. Cabrera, K.T. Ingram, K. Broad, P.E. Hildebrand. 2008. AgClimate: A case study in participatory decision support system development. *Climatic Change* 87 (3-4): 385-403.

Breuer, N.E., C.W. Fraisse, V.E. Cabrera. 2010. The cooperative extension service as a boundary organization for diffusion of climate forecasts: A 5-Year study. *Journal of Extension* 48 (4): 4RIB7.

Breuer, N.E., C.W. Fraisse, P.E. Hildebrand. 2009. Molding the pipeline into a loop: the participatory process of developing AgroClimate, a decision support system for climate risk reduction in agriculture. *Journal of Service Climatology* 3 (1): 1-12.

Brouder, S. and J. Volenec. 2008. Impact of climate change on crop nutrient and water use efficiencies. *Physiologia Plantarum* 133 (4): 705-724.

Cabrera, V.E., N.E. Breuer, P.E. Hildebrand. 2008. Participatory modeling of North Florida dairy farm systems: A method for building climate variability into farm models. *Climatic Change* 89 (3): 395-409.

Cabrera, V.E, C.W. Fraisse, D. Letson, G. Podesta, J. Novak. 2006. Impact of climate information on reducing farm risk by optimizing crop insurance strategy. *Transactions of the ASABE* 49 (4): 1223-1233.

Calderini, D., R. Savin, L. Abeledo, M. Reynolds, G. Slafer. 2001. The importance of the period immediately preceding anthesis for grain weight determination in wheat. *Euphytica* 119 (1-2): 199-204.

Carpio, C.E., D.W. Hughes, O. Isengildina, T.N. Hasing, M. Scott, D. Lamie, S. Zapata, D. Swindall. 2008. Comphrehensive assessment of the South Carolina agribusiness cluster. Accessed 17 September 2012. http://www.clemson.edu/public/ciecd/focus_areas/research/files/Complete%20Report%20MarketSearchJuly2909.pdf

CIER (Center for Integrative Environmental Research). 2008a. Economic impact of climate change on North Carolina. College Park, MD: University of Maryland.

CIER (Center for Integrative Environmental Research). 2008b. Economic impact of climate change on Georgia. College Park, MD: University of Maryland.

Cohen, M.R. 2009. *A clean energy economy for Arkansas: Analysis of the rural economic development potential of renewable resources.* New York, NY: Natural Resources Defense Council.

http://www.nrdc.org/energy/cleanar/files/cleanar.pdf

Crane, T., C. Roncoli, N.E. Breuer, K. Broad, J. Paz, C. Fraisse, K. Ingram, D. Zierden, G. Hoogenboom. 2010. Forecast skill and farmers' skills: Seasonal climate forecasts and agricultural risk management in the southeastern United States. *Weather Climate Society* 2 (1): 44-59.

Crane, T.A., C. Roncoli, G. Hoogenboom. 2011. Adaptation to climate change and climate variability: The importance of understanding agriculture as performance. *NJAS-Wageningen Journal of Life Sciences* 57 (3-4): 179-185.

Commonwealth of Virginia, Department of Mines, Minerals and Energy. Accessed 10 September 2012. http://www.dmme.virginia.gov/

Davenport, L. 2007. Climate change and its potential effect on Alabama's plant life. Paper presented at Alabama Environmental Education Consortium conference Climate Change and Alabama: Prospects and Options, Birmingham, AL, November 4, 2006.

Deng, X.H., B.J. Barnett, G. Hoogenboom, Y.Z. Yu, A. Garcia y Garcia. 2008. Alternative crop insurance indexes. *Journal of Agricultural and Applied Economics* 40 (1): 223-237.

Dermody, O. 2006. Mucking through multifactor experiments; design and analysis of multifactor studies in global change research. *New Phytologist* 172 (4): 598-600.

Dracup, M., P. Gregory, R. Belford. 1993. Restricted growth of lupin and wheat roots in the sandy: A horizon of a yellow duplex soil. *Australian Journal of Agricultural Research* 44 (6): 1273-1290.

Drake, B., M. Gonzalez-Meler, S. Long. 1997. More efficient plants: A consequence of rising atmospheric CO_2? *Annual Review of Plant Physiology and Plant Molecular Biology* 48 (1): 609-639.

Easterling, W. 2007. Climate change and the adequacy of food and timber in the 21st century. *Proceedings of the National Academy of Sciences of the United States of America* 104 (50): 19679-19679.

ERS (Economic Research Service). 2010. *USDA state fact sheets: Mississippi*. Washington, DC: USDA (United States Department of Agriculture).

Farquhar, G.D., D.R. Dubbe, K. Raschke. 1978. Gain of the feedback loop involving carbon dioxide and stomata. *Plant Physiology* 62 (30): 406-412.

Ferris, R., R. Ellis, T. Wheeler, P. Hadley. 1998. Effect of high temperature stress at anthesis on grain yield and biomass of field-grown crops of wheat. *Annals of Botany* 82 (5): 631-639.

Fischer, R. 1979. Growth and water limitation to dryland wheat yield in Australia: A physiological framework. *Journal of the Australian Institute of Agricultural Science* 45 (2): 83-94.

Fischer, R. 2007. Understanding the physiological basis of yield potential in wheat. *Journal of Agricultural Science* 145 (2): 99-113.

Fischer, R. 2008. The importance of grain or kernel number in wheat: A reply to Sinclair and Jamieson. *Field Crops Research* 105 (1-2): 15-21.

Folke, C., J. Colding, and F. Berkes. 2003. Synthesis: Building resilience and adaptive capacity in social-ecological systems. 352–387. In Navigating social-ecological systems: Building resilience for complexity and change, ed. F. Berkes et al. Cambridge Univ. Press, Cambridge, UK.

Folland, C., N. Rayner, S. Brown, T. Smith, S. Shen, D. Parker, I. Macadam, P. Jones, R. Jones, N. Nicholls, D. Sexton. 2001. Global temperature change and its uncertainties since 1861. *Geophysical Research Letters* 28 (13): 2621-2624.

Fraisse, C.W., N.E. Breuer, D. Zierden, K.T. Ingram. 2009. From climate variability to climate change: Challenges and opportunities to extension. *Journal of Extension* 47 (2): 2FEA9.

Fraisse, C., N. Breuer, D. Zierden, J. Bellow, J. Paz, V. Cabrera, A. Garcia, K. Ingram, U. Hatch, G. Hoogenboom, J. Jones, J. O'Brien. 2006. AgClimate: A climate forecast information system for agricultural risk management in the southeastern USA. *Computers and Electronics in Agriculture* 53 (1): 13-27.

Frank, K.L., T.L. Mader, J.A. Harrington, G.L. Hahn, M.S. Davis. 2001. Climate change effects on livestock production in the Great Plains. *Proceedings 6th International Livestock Environment Symposium*, American Society of Agricultural Engineers, St. Joseph, MI: 351-358.

Furman, C., C. Roncoli, T. Crane, J. Paz, G. Hoogenboom. 2009. Managing risk in climate variation among Georgia organic farmers. In *Southeast Climate Consortium Technical Report Series: 09-003*. Gainesville, FL: Southeast Climate Consortium.

Furman, C., C. Roncoli, T. Crane, G. Hoogenboom. 2011. Beyond the "fit": Introducing climate forecasts among organic farmers in Georgia (United States). *Climatic Change* 109 (3): 791-799.

Garcia, R., S. Long, G. Wall, C. Osborne, B. Kimball, G. Nie, P. Pinter, R. Lamorte, F. Wechsung. 1998. Photosynthesis and conductance of spring-wheat leaves: Field response to continuous free-air atmospheric CO_2 enrichment. *Plant, Cell and Environment* 21 (7): 659-669.

Garcia y Garcia, A., L.C. Guerra, G. Hoogenboom. 2009. Water use and water use efficiency of sweet corn under different weather conditions and soil moisture regimes. *Agricultural Water Management* 96 (10): 1369-1376.

Garcia y Garcia, A., G. Hoogenboom, L.C. Guerra, J.O. Paz, C.W. Fraisse. 2006. Analysis of the inter-annual variation of peanut yield in Georgia using a dynamic crop simulation model. *Transactions of the ASABE* 49 (6): 2005-2015.

Garcia y Garcia, A., T. Persson, L.C. Guerra, G. Hoogenboom. 2010a. Response of soybean genotypes to different irrigation regimes in a humid region of the southeastern USA. *Agricultural Water Management* 97 (7): 981-987.

Garcia y Garcia, A., T. Persson, J.O. Paz, C. Fraisse, G. Hoogenboom. 2010b. ENSO-based climate variability affects water use efficiency of rainfed cotton grown in the southeastern USA. *Agriculture, Ecosystems & Environment* 139 (4): 629-635.

Goudriaan, J. and H.H. Van Laar. 1994. *Modelling potential crop growth processes: Textbook with Exercises.* Dordrecht, The Netherlands: Kluwer Academic Publishers.

GRACEnet. "A Unified Response to Climate Change". Accessed September 17, 2012. http://www.ars.usda.gov/is/AR/archive/nov09/gracenet1109.htm.

Gunderson, L.H. and C.S. Holling, editors. Panarchy: Understanding Transformations in Human and Natural Systems. Island Press, Washington.

Hahn, G.L. 1999. Dynamic responses of cattle to thermal heat loads. *Journal of Animal Science* 77, 10-20.

Hammer, G., M. Cooper, F. Tardieu, S. Welch, B. Walsh, F. van Eeuwijk, S. Chapman, D. Podlich. 2006. Models for navigating biological complexity in breeding improved crop plants. *Trends in Plant Science* 11 (12): 587-593.

Hatfield, J.L., K.J. Boote, B.A. Kimball, R.C. Izaurralde, D. Ort, A. Thomson, D.W. Wolfe. 2011. Climate impacts on agriculture: Implications for crop production. *Agronomy Journal* 103 (2): 351-370.

Hauserman, J. 2007. The bottom line in the sand. *St. Petersburg Times*, January 28.

Hayhoe, K., C.P. Wake, T.G. Huntington, L.F. Luo, M.D. Schwartz, J. Sheffield, E. Wood, B. Anderson, J. Bradbury, A. DeGaetano, T.J. Troy, D. Wolfe. 2007. Past and future changes in climate and hydrological indicators in the US northeast. *Climate Dynamics* 28 (4): 381-407.

Hayhoe, K., C.P. Wake, T.G. Huntington, L.F. Luo, M.D. Schwartz, J. Sheffield, E. Wood, B. Anderson, J. Bradbury, A. DeGaetano, T.J. Troy, D. Wolfe. 2007. Past and future changes in climate and hydrological indicators in the US northeast. *Climate Dynamics* 28 (4): 381-407.

Hignight, J.A., S. Stiles, E.J. Wailes, B. Watkins, W.P. Miller. 2009. Final estimates of Arkansas crop losses from poor harvest conditions in 2009–December 10, 2009. In *Staff Papers No. 56391 from University of Arkansas Department of Agricultural Economics and Agribusiness.* Fayetteville, AR: University of Arkansas.

Hungate, B., J. Dukes, M. Shaw, Y. Luo, C. Field. 2003. Nitrogen and climate change. *Science* 302 (5650): 1512-1513.

Ingram, K.T., J.W. Jones, J.J. O'Brien, M.C. Roncoli, C. Fraisse, N.E. Breuer, W.L. Bartels, D. Zierden, D. Letson. 2012. Vulnerability and adaptability of agricultural systems in the southeast USA to climate variability and climate change. In *Climate change in the Midwest: Impacts, risks, vulnerability and adaptation*, ed. S.C. Pryor. Bloomington, IN Indiana University Press.

IPCC (Intergovernmental Panel on Climate Change). 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel* *on Climate Change*, ed. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller, 749-844. New York and United Kingdom: Cambridge University Press.

Izquierdo, N., L. Aguirrezábal, F. Andrade, V. Pereyra. 2002. Night temperature affects fatty acid composition in sunflower oil depending on the hybrid and the phenological stage. *Field Crops Research* 77 (2-3): 115-126.

Jiang, D., X. Fan, T. Dai, W. Cao. 2008. Nitrogen fertiliser rate and post-anthesis waterlogging effects on carbohydrate and nitrogen dynamics in wheat. *Plant and Soil* 304 (1-2): 301-314.

Kang, S., F. Zhang, X. Hu, J. Zhang. 2002. Benefits of CO_2 enrichment on crop plants are modified by soil water status. *Plant and Soil* 238 (1): 69-77.

Katsvairo, T., J. Rich, R. Dunn. 2006. Perennial grass rotation: An effective and challenging tactic for nematode management with many other positive effects. *Pest Management Science* 62 (9): 793-796.

Kimball, B., C. Morris, P. Pinter, G. Wall, D. Hunsaker, F. Adamsen, R. LaMorte, S. Leavitt, T. Thompson, A. Matthias, T. Brooks. 2001. Elevated CO_2, drought and soil nitrogen effects on wheat grain quality. *New Phytologist* 150 (2): 295-303.

Kimball, B.A. 2010. Lessons from FACE: CO_2 effects and interactions with water, nitrogen and temperature. In *Handbook of climate change and agroecosystems–Impacts, adaptation, and mitigation,* ed. D. Hillel and C. Rosenzweig, 87-107. London: Imperial College Press.

Klinedinst, P.L., D.A. Wilhite, G.L. Hahn, K.G. Hubbard. 1993. The potential effects of climate change on summer season dairy cattle milk production and reproduction. *Climatic Change* 23: 21-36.

Lal, R. 2004. Soil carbon sequestration to mitigate climate change. *Geoderma* 123 (1-2): 1-22.

Lal, R., J.A. Delgado, P.M. Groffman, N. Millar, C. Dell, A. Rotz. 2011. Management to mitigate and adapt to climate change. *Journal of Soil and Water Conservation* 66 (4): 276-285.

Lawlor, D.W. and R.A.C. Mitchell. 2000. Crop ecosystems responses to climatic change: Wheat. In *Climate change and global crop productivity*, ed. K. Raja Reddy and H.F. Hodges, 57-80. Wallingford, United Kingdom: CABI Publishing.

Leiserowitz, A., E. Maibach, C. Roser-Renouf. 2008. *Global warming's "Six Americas": An audience segmentation*. New Haven, CT: Yale Project on Climate Change.

Lin, S., J.D. Mullen, G. Hoogenboom, S.S. Lin. 2008. Farm-level risk management using irrigation and weather derivatives. *Journal of Agricultural and Applied Economics* 40 (2): 485-492.

Lobell, D. 2007. Changes in diurnal temperature range and national cereal yields. *Agricultural and Forest Meteorology* 145 (3-4): 229-238.

Lobell, D. and C. Field. 2007. Global scale climate-crop yield relationships and the impacts of recent warming. *Environmental Research Letter,* 2 (1).

Long, S.P., E.A. Ainsworth, A.D.B. Leakey, J. Nosberger, D.R. Ort. 2006. Food for thought: Lower-than-expected crop yield stimulation with rising CO_2 concentrations. *Science* 312 (5782): 1918-1921.

Lott, N. and T. Ross. 2006. Tracking and evaluating U.S. billion dollar weather disasters, 1980-2005. National Oceanic and Atmospheric Administration National Climatic Data Center. Accessed 17 September 2012. http://www1.ncdc.noaa.gov/pub/data/papers/200686ams1.2nlfree.pdf

Lu, Z., J.W. Radin, E.L. Turcotte, R. Percy, E. Zeiger. 1994. High yields in advanced lines of Pima cotton are associated with higher stomatal conductance, reduced leaf area and lower leaf temperature. *Physiologia Plantarum* 92 (2): 266-272.

Ludwig, F. and S. Asseng. 2010. Adaptation of wheat systems to climate change through the introduction of plant traits related to early vigor and flowering time. *Agricultural Systems* 103: 127-136.

Luscombe R. As Florida Keys residents confront rising sea levels, what lessons? *The Christian Science Monitor* March 4, 2010.

Ma, H., J. Zhu, Z. Xie, G. Liu, Q. Zeng, Y. Han. 2007. Responses of rice and winter wheat to free-air CO_2 enrichment (China FACE) at rice/wheat rotation system. *Plant and Soil* 294 (1-2): 137-146.

Mader, T.L. 2003. Environmental stress in confined beef cattle. *Journal of Animal Science* 81: 110-119.

Mader, T.L., J.M. Gaughan, B.A. Young. 1999. Feedlot diet roughage level of Hereford cattle exposed to excessive heat load. *Professional Animal Scientist* 15: 53-62.

Manderscheid, R. and H. Weigel. 1997. Photosynthetic and growth responses of old and modern spring wheat cultivars to atmospheric CO2 enrichment. *Agriculture, Ecosystems & Environment* 64 (1): 65-73.

Manderscheid, R. and H. Weigel. 2007. Drought stress effects on wheat are mitigated by atmospheric CO2 enrichment. *Agronomy for Sustainable Development* 27 (2): 79-87.

Marcus, R.R. and S. Kiebzak. 2008. The role of water doctrines in enhancing opportunities for sustainable agriculture in Alabama. *Journal of the American Water Resources Association (JAWRA)* 44 (6): 1578-1590.

McCright, A. 2010. The effects of gender on climate change knowledge and concern in the American public. *Population and Environment* 32 (1): 66-87.

McNider, R.T., J.R. Christy, D. Moss, K. Doty, C. Handyside, A. Limaye, A. Garcia y Garcia, G. Hoogenboom. 2011. A real-time gridded crop model for assessing spatial drought stress on crops in the southeastern United States. *Journal of Applied Meteorology and Climatology* 50 (7): 1459-1475.

Menzel, A., T. Sparks, N. Estrella, E. Koch, A. Aasa, R. Ahas, K. Alm-Kubler, P. Bissolli, O. Braslavska, A. Briede, F. Chmielewski, Z. Crepinsek, Y. Curnel, A. Dahl, C. Defila, A. Donnelly, Y. Filella, K. Jatcza, F. Mage, A. Mestre, O. Nordli, J. Penuelas, P. Pirinen, V. Remisova, H. Scheifinger, M. Striz, A. Susnik, A. Van Vliet, F. Wielgolaski, S. Zach, A. Zust. 2006. European phenological response to climate change matches the warming pattern. *Global Change Biology* 12 (10): 1969-1976.

Morison, J. 1985. Sensitivity of stomata and water-use efficiency of high CO2. *Plant Cell and Environment* 8 (6): 467-474.

NCSL (National Conference of State Legislators). 2008. Assessing the Cost of Climate Change. Accessed 10 September 2012. http://www.ncsl.org/issues-research/env-res/climate-change-publications.aspx

Nicholls, N. 1997. Increased Australian wheat yield due to recent climate trends. *Nature* 387 (4): 484-485.

Nickerson, C., R. Ebel, A. Borchers, F. Carriazo. 2011. Major uses of land in the United States, 2007, EIB-89, US Department of Agriculture, Economic Research Service, December 2011.

Olatinwo, R.O., J.O. Paz, R.C. Kemerait Jr., A.K. Culbreath, G. Hoogenboom. 2010. El Nino-Southern Oscillation (ENSO): Impact on tomato spotted wilt intensity in peanut and the implication on yield. *Crop Protection* 29 (5): 448-453.

Olatinwo, R.O., T. Prabha, J.O. Paz, D.G. Riley, G. Hoogenboom. 2011. The Weather Research and Forecasting (WRF) model: Application in prediction of TSWV-vectors populations. Journal of Applied Entomology 135 (1-2): 81-90.

Peng, S., J. Huang, J. Sheehy, R. Laza, R. Visperas, X. Zhong, G. Centeno, G. Khush, K. Cassman. 2004a. Rice yields decline with higher night temperature from global warming. Proceedings of the National Academy of Sciences of the United States of America 101 (27): 9971-9975.

Peng, S., R.C. Laza, R.M. Visperas, G.S. Khush, P. Virk, D. Zhu. 2004b. Rice: progress in breaking yield ceiling. In *New directions for a diverse plant: Proceedings of the 4th International Crop Science Congress*, ed. T. Fischer, N. Turner, J. Angus, L. McIntyre, M. Robertson, A. Borrell, D. Lloyd. Gosford, Australia: The Regional Institute Ltd.

Persson, T., A. Garcia y Garcia, J.O. Paz, C.W. Fraisse, G. Hoogenboom. 2010a. Reduction in greenhouse gas emissions due to the use of bio-ethanol from wheat grain and straw produced in the south-eastern USA. *The Journal of Agricultural Science* 148 (5): 511-527.

Persson, T., A. Garcia y Garcia, J. Paz, J. Jones, G. Hoogenboom. 2009a. Maize ethanol feedstock production and net energy value as affected by climate variability and crop management practices. *Agricultural Systems* 100 (1-3): 11-21.

Persson, T., A. Garcia y Garcia, J.O. Paz, J.W. Jones, G. Hoogenboom. 2009b. Net energy value of maize ethanol as a response to different climate and soil conditions in the southeastern USA. *Biomass and Bioenergy* 33 (8): 1055-1064.

Persson, T., A. Garcia y Garcia, J.O. Paz, B.V. Ortiz, G. Hoogenboom. 2010b. Simulating the production potential and net energy yield of maize-ethanol in the southeastern USA. *European Journal of Agronomy* 32 (4): 272-279.

Persson, T., B.V. Ortiz, D.I. Bransby, W. Wu, G. Hoogenboom. 2011. Determining the impact of climate and soil variability on switchgrass (*Panicum virgatum* L.) production in the southeastern USA; A simulation study. *Biofuels, Bioproducts and Biorefining* 5 (5): 505-518.

Prasad, P.V.V., L.H. Allen Jr., K.J. Boote. 2005. Crop responses to elevated carbon dioxide and interaction with temperature: Grain legumes. *Journal of Crop Improvement* 13 (1-2): 113-155.

Probert, M. and B. Keating. 2000. What soil constraints should be included in crop and forest models? *Agriculture, Ecosystems & Environment* 82 (1-3): 273-281.

Radin, J.W., Z. Lu, R.G. Percy, E. Zeiger. 1994. Genetic variability for stomatal conductance in Pima cotton and its relation to improvements of heat adaptation. *Proceedings of the National Academy of Science of the United States of America* 91 (15): 7217-7221.

Randall, P. and H. Moss. 1990. Some effect of temperature regime during grain filling on wheat quality. *Australian Journal of Agricultural Research* 41 (4): 603-617.

Reynolds, C., L. Crompton, J. Mills. 2010. Livestock and climate change impacts in developing world. *Outlook in Agriculture* 39: 245-248.

Ritschard, R., J. O'Brien, J. Cruise, U. Hatch, J. Jones, J. Shrikant, S. McNulty, B. Abt, B. Murray, J. Cruise. 2002. *Preparing for a changing climate: The potential consequences of climate variability and change—Southeast.* Washington, DC: US Global Change Research Program.

Roncoli, C. 2006. Ethnographic and participatory approaches to research on farmers' responses to climate predictions. *Climate Research* 33 (1): 81-99.

Rogers, G., P. Milham, M. Gillings, J. Conroy. 1996. Sink strength may be the key to growth and nitrogen responses in N-deficient wheat at elevated CO_2. *Australian Journal of Plant Physiology* 23 (3): 253-264.

Rosenzweig, C., J.W. Jones, J.L. Hatfield, A.C. Ruane, K.J. Boote, P. Thorburn, J.M. Antle, G.C. Nelson, C. Porter, S. Janssen, S. Asseng, B. Basso, F. Ewert, D. Wallach, G. Baigorria, J.M. Winter. 2012. The agricultural model intercomparison and improvement project (AgMIP): Protocols and pilot studies. *Agricultural Forestry and Meteorology* (in press).

Royce, F.S., C.W. Fraisse, G.A. Baigorria. 2011. ENSO classification indices and summer crop yields in the southeastern USA. *Agricultural and Forest Meteorology* 151 (7): 817-826.

Sadras, V. and J. Monzon. 2006. Modelled wheat phenology captures rising temperature trends: Shortened time to flowering and maturity in Australia and Argentina. *Field Crops Research* 99 (2-3): 136-146.

Sadras, V. and D. Rodriguez. 2007. The limit to wheat water-use efficiency in eastern Australia. II. Influence of rainfall patterns. *Australian Journal of Agricultural Research* 58 (7): 657-669.

Schaible, G.D. 2004. Irrigation, Water Conservation, and Farm Size in the Western United States. *Amber Waves* 2 (3): 8.

Shaw, M., E. Zavaleta, N. Chiariello, E. Cleland, H. Mooney, C. Field. 2002. Grassland responses to global environmental changes suppressed by elevated CO_2. *Science* 298 (5600): 1987-1990.

Sheehy, J.E., P.L. Mitchell, L.H. Allen, A.B. Ferrer. 2006a. Mathematical consequences of using various empirical expressions of crop yield as a function of temperature. *Field Crops Research* 98 (2-3): 216-221.

Sheehy, J.E., P.L. Mitchell, A.B. Ferrer. 2006b. Decline in rice grain yields with temperature: Models and correlations can give different estimates. *Field Crops Research* 98 (2-3): 151-156.

Shepherd, J.M. 2011. Carbon, climate change, and controversy. *Animal Frontiers* 1: 5-13.

Sinclair, T. and P. Jamieson. 2006. Grain number, wheat yield, and bottling beer: An analysis. *Field Crops Research* 98 (1): 60-67.

Slafer, G. and H. Rawson. 1997. CO_2 effects on phasic development, leaf number and rate of leaf appearance in wheat. *Annals of Botany* 79 (1): 75-81.

Smith, A.R., N.B. Smith, W.D. Shurley. 2011. Crop Comparison Tool, December Update. Extension Agricultural and Applied Economics Department, The University of Georgia. Accessed 12 September 2012. http://www.ces.uga.edu/Agriculture/agecon/printedbudgets.htm

SCSCO (South Carolina State Climatology Office). "The Impact of Climate Change on South Carolina". Accessed 17 September 2012. http://www.dnr.sc.gov/climate/sco/Publications/climate_change_impacts.php

Spechler, R.M. 2001. The relation between structure and saltwater intrusion in the Floridan aquifer system, Northeastern Florida. In *US Geological Survey Karst Interest Group Proceedings, Water-Resources Investigations Report 01-4011*, ed. E.L. Kuniansky, 25-29. St. Petersburg, FL: US Geological Survey.

Stanton, E. and F. Ackerman. 2007. *Florida and climate change: The cost of inaction*. Medford, MA: Global Development and Environment Institute, Tufts University.

Tester, M. and P. Langridge. 2010. Breeding technologies to increase crop production in a changing world. *Science* 327 (5967): 818-822.

Triboi, E., P. Martre, C. Girousse, C. Ravel, A. Triboi-Blondel. 2006. Unravelling environmental and genetic relationships between grain yield and nitrogen concentration for wheat. *European Journal of Agronomy* 25 (2): 108-118.

Triboi, E., P. Martre, A. Triboi-Blondel. 2003. Environmentally-induced changes in protein composition in developing grains of wheat are related to changes in total protein content. *Journal of Experimental Botany* 54 (388): 1731-1742.

Tubiello, F., J. Soussana, S. Howden. 2007. Crop and pasture response to climate change. *Proceedings of the National Academy of Sciences of the United States of America* 104 (50): 19686-19690.

Twilley, R. and R. Miller. 2001. Mississippi: State findings from confronting climate change in the Gulf Coast Region: Prospects for sustaining our ecological heritage. In *Confronting climate change in the Gulf Coast Region: Prospects for sustaining out ecological heritage,* ed. R.R. Twilley, E.J. Barron, H.L. Gholz, M.A. Harwell, R.L. Miller, D.J. Reed, J.B. Rose, E.H. Siemann, R.G. Wetzel, and R.J. Zimmerman. Cambridge, MA: UCS Publications.

Uddling, J., J. Gelang-Alfredsson, P. Karlsson, G. Sellden, H. Pleijel. 2008. Source-sink balance of wheat determines responsiveness of grain production to increased [CO_2] and water supply. *Agriculture, Ecosystems & Environment* 127 (3-4): 215-222.

UoA (University of Arkansas). 2010. *Economic impact of Arkansas agriculture*. Little Rock, AR: Department of Agriculture, University of Arkansas. Accessed 12 September 2012. http://arkansasagnews.uark.edu/Economic_Impact-2010.pdf

USDA-NASS (United States Department of Agriculture, National Agricultural Statistics Service). 2012. Agricultural Census. Accessed 10 September 2012. http://www.nass.usda.gov/

USDA-ERS (United States Department of Agriculture, Economic Research Service). 2010. States-Fact-Sheets. Accessed 10 September 2012. http://www.ers.usda.gov/data-products/state-fact-sheets.aspx

USDA (United States Department of Agriculture). 2007. Census of Agriculture. Accessed 10 September 2012. http://www.agcensus.usda.gov/Publications/2007/Full_Report/

USEIA (US Energy Information Admistration). 2010. State energy profile: Florida 2010.

Van Dijk, J., N. D. Sargison, F. Kenyon, P. J. Skuce. 2010. Climate change and infectious disease: helminthological challenges to farmed ruminants in temperate regions. *Animal* 4 377-392.

Van Herwaarden, A., J. Angus, R. Richards, G. Farquhar. 1998. 'Haying-off', the negative grain yield response of dryland wheat to nitrogen fertiliser II. Carbohydrate and protein dynamics. *Australian Journal of Agricultural Research* 49 (7): 1083-1093.

Von Lehe, A. 2008. Climate change and South Carolina's economy. *Environmental Law Journal* 16 (2): 358-390.

Wall, G.W. 2001. Elevated atmospheric CO_2 alleviates drought stress in wheat. *Agriculture, Ecosystems & Environment* 87 (3): 261-271.

Weber, E. and P. Stern. 2011. Public understanding of climate change in the United States. *American Psychologist* 66 (4): 315-328.

Wheeler, T.R., G.R. Batts, R.H. Ellis, P. Hadley, J.I.L. Morison. 1996. Growth and yield of winter wheat (*Triticum aestivum*) crops in response to CO_2 and temperature. *The Journal of Agricultural Science* 127 (1): 37-48.

White, J.W., G. Hoogenboom, B.A. Kimball, G.W. Wall. 2011. Methodologies for simulating impacts of climate change on crop production. *Field Crops Research* 124 (3): 357-368.

Wilbanks, T., K. Ebi, G. Hoogenboom, P. Kirshen. 2010. Climate change impacts in the southeastern United States. Discussion paper prepared for Office of Air and Radiation and US Environmental Protection Agency. Boulder, CO: Stratus Consulting Inc.

Wright D.L., J.J. Marois, C. Mackowiak, D. Zhao, G. Anguelov, C. Lamb. 2012. Sod-based/Livestock/Row Crop Integration: An Improved Conservation Farming System. In Conservation Tillage Systems: Production, Profitability and Stewardship. Sustainable Agriculture Research and Education (SARE) outreach office, USDA, Beltsville, MD.

Wrigley, C., C. Blumentha, P. Gras, E. Barlow. 1994. Temperature-variation during grain filling and changes in wheat-grain quality. *Australian Journal of Plant Physiology* 21 (6): 875-885.

Wu, D., G. Wang, Y.Bai, J. Liao. 2004. Effects of elevated CO_2 concentration on growth, water use, yield and grain quality of wheat under two soil water levels. *Agriculture, Ecosystems & Environment* 104 (3): 493-507.

Yang, X., E. Lin, S. Ma, H. Ju, L. Guo, W. Xiong, Y. Li, Y. Xu. 2007. Adaptation of agriculture to warming in northeast China. *Climatic Change* 84 (1): 45-58.

Yohe, G., and R.S.J. Tol. 2002. Indicators for social and economic coping capacity—moving toward a working definition of adaptive capacity. *Global Environmental Change* 12: 25-40.

Yoon, S.T., G. Hoogenboom, I. Flitcroft, M. Bannayan. 2009. Growth and development of cotton (*Gossypium hirsutum* L.) in response to CO_2 enrichment under two different temperature regimes. *Environmental and Experimental Botany* 67 (1): 178-187.

Zhao, H., T. Dai, D. Jiang, W. Cao. 2008. Effects of high temperature on key enzymes involved in starch and protein formation in grains of two wheat cultivars. *Journal of Agronomy and Crop Science* 194 (1): 47-54.

Ziska, L. and J. Bunce. 2007. Predicting the impact of changing CO_2 on crop yields: Some thoughts on food. *New Phytologist* 175 (4): 607-618.

Chapter 8

Forests and Climate Change in the Southeast USA

CONTRIBUTING AUTHORS

Steven McNulty (steve_mcnulty@ncsu.edu; Eastern Forest Environmental Threat Assessment Center, USDA Forest Service, Raleigh, North Carolina)

Peter Caldwell (Eastern Forest Environmental Threat Assessment Center, USDA Forest Service, Raleigh, North Carolina)

Thomas W. Doyle (National Wetlands Research Center, US Geological Survey, Lafayette, Louisiana)

Kurt Johnsen (Southern Institute of Forest Ecosystems Biology, USDA Forest Service, Research Triangle Park, North Carolina)

Yongqiang Liu (Center of Forest Science Disturbance, USDA Forest Service, Athens, Georgia)

Jacqueline Mohan (Odum School of Ecology, University of Georgia, Athens, Georgia)

Jeff Prestemon (Forest Economics Unit, USDA Forest Service, Research Triangle Park, North Carolina)

Ge Sun (Eastern Forest Environmental Threat Assessment Center, USDA Forest Service, Raleigh, North Carolina)

The forests of the southeastern USA have seen many changes over the past 200 years. From cutting of the virgin forest in the 19th century to the expansion and later contraction of farming and the rise of plantation forestry in the 20th century, the structure and function of southern forests continues to evolve. Climate change represents another factor that is changing Southeast (SE) forests and forestry practices. Current and continued projected warming likely will increase the risk of wildfire, wind, insect, and disease damage to southeastern forests. Increased air temperatures also likely will lead to decreased forest water yield, even as the population of the SE USA continues to expand. Conflicts between maximizing forest carbon sequestration as a mitigation strategy for climate change and need for water likely will continue well into the 21st century. However, scientists are actively working with land managers to address these issues. Although the form of SE forests will continue to change due to old and new pressures, forest managers are becoming increasingly better prepared to cope with these challenges. This chapter examines some of the pressing issues and management options associated with global change in the SE USA.

Key Findings

- Warming air temperatures likely will increase regional drying through increased forest water use via evapotranspiration (ET) regardless of changes in precipitation, and this drying will likely increase wildfire risk across SE USA forests.
- Longer growing seasons will likely increase the risk of insect outbreak and very likely will expand the northern range of some species, such as the southern pine beetle.
- Under most scenarios, increasing temperatures and decreasing precipitation will result in a greater uptake of soil water by forests and lead to reductions in streamflow.
- Despite climate and land use changes, forests in the southeastern USA will likely continue to provide a sink of atmospheric carbon dioxide (CO_2).
- The potential savannafication of the SE, in which forests are converted into more open woodlands due to a combination of hotter and drier conditions, could be one of the most profound potential climate change impacts in the USA

8.1 Historical Perspective

The forests of the Southeast (SE) USA have seen extensive change during the past century. Currently, 60% of the SE landscape is forested (Wear and Greis 2002). In 1860, about 43% of the SE land area was reported as under cultivation, but a substantial part of the farm holdings that remained in forest were used for grazing livestock (Smith and Darr 2009). Timberland continued to decline until the early 1920s due to the continued expansion of settlements. Significant changes in agriculture took place after 1920 that resulted in abandonment of large areas of crop and pasture lands. Some of the abandoned land was planted with trees, but most of the land reverted naturally to forest, leading to increases in timberland acreage (Wear et al. 2007). By the late 1950s and early 1960s, decline of timberland began again in the SE, caused primarily by the clearing of forests for soybean and other crop production. Much of this timberland reduction occurred in bottomland hardwood forest areas of the Mississippi Delta.

Throughout the 1970s, timberland was cleared for agricultural use and for an expanding export market. The decade beginning in 1982 marked a slowing of forest cover loss with the National Resources Inventory reporting roughly a half million-acre loss (less than 1%) in forestland in the SE (Wear et al. 2007). That trend has continued into the 21st century as softwood pulp prices have fallen by 50% since 1998, and the forest products industry divested approximately 75% of its timberland holdings (Butler and Wear, In Press). Although market prices will likely continue to be a driving factor in forest land area, other ecosystem services such as climate change, wildlife protection, drinking water supply, and recreation may increasingly influence the distribution and composition of SE forests (Wear and Greis 2002).

8.2 Southeastern Forest Types

The southeastern USA is not comprised of a single forest type, but of many. This assessment of forests and climate change focuses on six distinct forest areas within the SE: the Atlantic and East Gulf Coastal Plain, Piedmont, Appalachian/Cumberland, Mid-South, Coastal, and the Mississippi Alluvial Valley. Current inventory data shows that more than 30 million hectares of upland hardwood forests dominate the SE, followed by more than 15 million hectares of planted pine, approximately 13 million hectares of natural pine and bottomland hardwoods, and more than 3 million hectares oak-pine forest types (Butler and Wear 2012). These forest ecosystems provide a multitude of goods and services including clean water and air, wildlife habitat, recreation and aesthetics, timber and fiber production, and CO_2 sequestration. This chapter reviews current and future stresses on services provided by SE forests, and examines how forest management could be used to cope, adapt, or mitigate negative impacts.

Atlantic and East Gulf Coastal Plain. Historically, most of the southeastern Coastal Plain was dominated by fire-dependent longleaf pine (*Pinus palustris*) savannas (Christensen 2000). However, upland closed-canopied forests occur in mesic areas protected from frequent fire or where fire suppression has occurred. Notable examples of old-growth mesophytic beech-magnolia forests are present in the Apalachicola National Forest of the Florida panhandle. Other Coastal Plain broadleaved forests include those dominated by southern oak species such as swamp chestnut oak (*Quercus michauxii*), cherry bark oak (*Quercus pogoda*), and live oak (*Quercus virginiana*), as well as hickories (*Carya spp.*) and loblolly pine (*Pinus taed*a). American holly (*Ilex opaca*), spice bush (*Lindera benzoin*), and pawpaw (*Asimina triloba*) are common in the understory and subcanopy (Christensen 2000).

The distribution of current and potential future droughts and associated fire risk varies as does the potential impacts on trees species. Several dendrochronological analyses of Coastal Plain longleaf pine trees demonstrate the impact of growing season drought severity in relationship to reduced tree growth rates, as well as positive impacts of warmer winter temperatures (Bhuta et al. 2009, Henderson and Grissins-Mayer 2009). Less climatic research has been conducted in closed-canopied upland forests, but increasing fire frequencies in these Coastal Plain forests, due to ongoing and potential future droughts, may be a major impact on the distribution of some forests of this region (Wade et al. 2000). However, a recent study by Gruhn and White (2011) examined the northward range expansion of southern magnolia by comparing establishment success with climatic and topographic variables. Although minimum winter temperatures and the number of frost-free days were important determinants of establishment success, precipitation was not.

In addition to drought and fire, Coastal Plain forests and other ecosystems are also particularly vulnerable to hurricanes. Hurricane Isabel in September 2003 damaged 15% of trees, particularly canopy trees, in a maturing hardwood forest of the Virginia Coastal Plain (Prengaman et al. 2008). Hurricane Isabel was only a Category 2 storm, so increased frequencies of Category 4 and 5 hurricanes as a consequence of climate change likely will have even more profound effects (Webster et al. 2005, Knutson et al. 2011). Hurricane Katrina is an example of the damage caused by a strong hurricane (MIFI 2005).

Southern Appalachians. These forests cover much of the high elevation areas of the north-central southern region that includes eastern Tennessee and Kentucky, western North Carolina and Virginia, and northern Georgia. The southern Appalachian forests are some of the most diverse in North America (Clark et al. 2011). Both unique species and commercially important species can be found within the region. The diversity of these forests is controlled by regional and local weather patterns that can be highly variable due to the mountainous terrain (Clark et al. 2011). As with other mountain systems, the high elevation forests of the southern Appalachian ecosystems are at particular risk from a warming climate. A 3^{o}C increase in July temperature would raise climate-elevation bands by about 480m, resulting in the extirpation of the rare red spruce-Fraser fir (*Picea rubens* and *Abies fraseri*) alpine forests growing at the highest elevations in North Carolina and harboring federally threatened animal species, including the North Carolina flying squirrel (Delcourt and Delcourt 1998). Many of the mid-elevation "cove" forests, which are currently dominated by mesic, fire-intolerant tree species, are extremely diverse in terms of canopy trees, spring ephemeral wildflowers, and amphibians. Since the early 1980s this region has warmed and precipitation variability has increased. If these trends continue, they could lead to substantial change in the structure and function of future southern Appalachian forests.

In addition to determining biodiversity, climate variability also controls forest growth. For example, the annual growth rate of five dominant oak species can be severely affected by growing season drought intensity (Speer et al. 2009). During drought years, observed oak forests showed diminished productivity and accumulated 40% less carbon compared to a year of average precipitation (Noormets et al. 2008). If projected temperature increases are accompanied by decreased growing season precipitation, the combined changes may reduce the competitiveness of oaks in the southern Appalachians and elsewhere in the SE (Ibáñez et al. 2008).

Wildfires also shape the structure and function of forests within the southern Appalachians. A recent study suggested that fires occurred fairly frequently over the past 4,000 years in a variety of southern Appalachian forest types including those now dominated by mesic hardwoods, including tulip poplar (*Liriodendron tulipifera*) (Fesenmyer and Christiansen 2010). These researchers found that fire return intervals appear to have been of centuries-scale duration in the time period 4,000 to 1,000 years before present, and were likely often severe. Fires became more frequent approximately 1,000 years ago and were thus likely less severe due to less accumulated fuels build-up. The increased frequency of fire coincided with the occupation by Woodland Tradition Native Americans. If drought and drought-induced fires become more common in the southern Appalachians, fire-tolerant oak and hickory species may become more abundant over less-tolerant tulip poplar, maple (*Acer spp.*), basswood (*Tilia americana*), birch (*Betula* spp.) and magnolia (*Magnolia* spp.) species, potentially reducing diversity in currently highly-diverse mesic forests (Fesenmyer and Christiansen 2010).

Piedmont. The Piedmont region lays southeast of the Appalachian region and stretches from east-central Alabama through central Georgia, northwestern South Carolina, and central North Carolina and Virginia. These forests are dominated by a mixture of pine and deciduous species (Figure 8.1) of high commercial importance (Van Lear et al. 2004). Dale et al. (2010) used ecosystem models and an ensemble of general circulation model (GCM) scenarios to project that in the southeastern Piedmont and Appalachians, southern mixed hardwoods and pine forests on the Piedmont were the most susceptible to changes induced by warmer, and particularly drier, climates. Under the driest of the three climate scenarios considered by Dale et al. (2010), a southern mixed forest transitioned from very high tree species diversity with 14 commonly co-dominant species to very low forest diversity, dominated by loblolly pine, southern red oak (*Quercus falcata*), and Shumard's oak (*Quercus shumardii*). Dale et al. (2010) also found that the less-diverse forests may be more susceptible to insect and pathogen pests, and that hickory (*Carya spp.*) species tended to increase in relative importance under the climate change scenarios considered. Conversely, under those projections the biomass of chestnut (*Quercus prinus*) and black oaks (*Quercus velutina*) tended to decline across Tennessee, as the hickories appeared to be better able to grow in the warmer, drier climate relative to the oak species.

Research from the Duke Free-Air CO_2 Enrichment (FACE) experiment and the Oak Ridge FACE experiment in the southern Appalachians suggests that an approximate doubling of atmospheric CO_2 increases the productivity of the canopy loblolly pine and sweet gum (*Liquidambar styraciflua)* trees by 23% to 27% (DeLucia et al. 2005, Norby et al. 2005). However, when examining the juvenile tree species most likely to comprise the future forests, elevated CO_2 conditions favored the population biomass growth of less productive, shade-tolerant tree species southern sugar maple (*Acer saccharum*), red maple (*Acer rubrum*), and black cherry (*Prunus serotina*) as well as woody vines such as poison ivy (*Toxicodendron radicans*) (Mohan et al. 2006, 2007, and 2008) and exotic Japanese honeysuckle (*Lonicera japonica*) (Belote et al. 2004). So, increased atmospheric CO_2 levels may benefit a variety of species, but it is unclear from these few studies how elevated CO_2 levels coupled with other potential stresses may affect the composition of future forests as a whole.

Coastal wetland forests. Coastal wetland forests exist in the transition between the Coastal Plain and maritime ecosystems and are responsive to changes in climate and freshwater outflow resulting from varying patterns and frequencies of freeze, drought, storm, sea level, and runoff events. Because saltmarshes and mangroves thrive in the

Figure 8.1 Mixed conifer and deciduous Piedmont forest in the southeastern USA.

intertidal zone between land and sea, these systems are expected to undergo the most severe changes from marine effects, such as sea level rise and salinity. They are also affected by freshwater drainage effects (e.g., flooding, elevated nutrient loading, and pollutant discharge), and by extreme climate events (e.g., freezing air temperatures, drought, and hurricanes) (Michener et al. 1997, Erwin 2009). For example, mangroves (*Rhizophora* spp.) are halophytes that thrive along tropical coastlines reaching latitudinal limits along the northern Gulf Coast in Texas, Louisiana, and Florida. Historical lapses in freeze events and extreme drought events may account for the northward establishment of red mangrove, which are cold sensitive (Montagna et al. 2009). Warming sea and surface temperatures under predicted climate change scenarios will likely increase the frequency and severity of drought episodes in western parts of the Southeast (Caldwell et al. 2012), while decreasing the periodicity of hard freezes that cause dieback of frost-intolerant tropical plant species (Montagna et al. 2009). Mangrove populations have persisted in fringe populations along subtropical coastal settings of Texas, Louisiana, and Florida but have been undergoing recent expansion in latitudes above the tropical Everglades region, where mangroves traditionally have dominated the coastal land margin (Michot et al. 2010, Doyle et al. 2010). Local populations of black mangrove *(Avicennia germinans)* in coastal Louisiana have expanded in area, density, and stature since the last damaging freeze two decades ago (Michot et al. 2010). If the period between severe freeze events lengthens under climate changes, mangrove expansion is expected to succeed landward and poleward along the northern Gulf Coast changing the proportion of saltmarsh area (Krauss et al. 2008). Mangroves have the added benefit of possessing unique root structures that may help stabilize coastal areas from erosion (McKee et al. 2007, Cherry et al. 2009). A shift from saltmarsh dominated coastlands to mangrove dominated shores, due to climatic changes, may also lead to shifts in fish species present (Ley et al. 1999), and reductions in some bird populations (e.g., brown pelican, *Pelecanus occidentalis*) (Visser et al. 2005).

Climate change poses some immediate and long-term threats to the health, function, and biodiversity of tidal wetlands along the coastal margin of the SE USA. Tidal forests of the Gulf Coast and elsewhere have been undergoing dieback and retreat from sea-level rise during the 20th century (Montagna et al. 2009). This trend is expected to continue or be exacerbated under projected increases of global sea level rise (Montagna et al. 2009). Coastal ecosystems of the western Gulf of Mexico are even more vulnerable due to the high rates of land subsidence that drive relative sea level rates that equal or exceed high Intergovernmental Panel on Climate Change (IPCC) projections for accelerated global sea level rise expected with climate warming during the 20th century (Doyle et al. 2007 and 2010). In all coastal counties and region-wide, sea level rise of any rate or origin, relative or eustatic, is expected to cause widespread loss or retreat of coastal forests as dictated by local environmental settings (Doyle et al. 2010). Mangrove forests that dominate tropical shores of southern Florida are expected to migrate inland with increasing sea level and increase the proportion of forested habitat in coastal areas.

Mississippi Alluvial Plain and adjacent regions. The Mississippi Alluvial Plain (MAP) forests, which extend up north to southern Illinois and Kentucky, west to Tennessee; and into the western Gulf Coastal Plain, are similar to those of the Atlantic and Eastern Gulf Coastal Plain forests but can include different levels of nutrients and soil types. Alfisol soils, which are more fertile than highly-weathered clay Ultisol soils or sandy Entisols, are common along the alluvial plain of the Mississippi River as well locations in Alabama (Christensen 2000). Seasonal temperature variations increase away from the coast and frost-free growing season durations decline appreciably from south to north. Although covered more extensively in Natural Ecosystems (Chapter 11), the freshwater swamp forests of the MAP in Louisiana are particularly threatened by a combination of drought and intrusion of saltwater triggered by drought conditions (Hoeppner 2008). Drought also has been linked to increased fire frequency and size in Mississippi, particularly in counties dominated by pines in the southern part of the state (Grala and Cook 2010). The importance of drought for this region is underscored by paleo-ecological work examining extended drought impacts during the mid- to late-Holocene period including the Medieval Warm Period (approximately 800 to 1200 CE) that characterized much of the Northern Hemisphere. During these times, vegetation loss was severe enough to coincide with the formation of low mounds and dunelike features that characterize much of the currently forested regions in the south-central USA today (Seifert et al. 2009).

8.3 Changes in Forest Type Across the South

The forests of the SE USA are currently highly diverse but they are not necessarily stable under a changing climate (for discussion of projected changes see Chapter 2). The potential savannafication of the SE, in which forests are converted into more open woodlands due to a combination of hotter and drier conditions, could be one of the most profound potential climate change impacts in the USA. Predictions for the SE include emergence of savanna ecosystems (Hansen et al. 2001, Bachelet et al. 2001), with expansion of Coastal Plain species into the Piedmont and Appalachians (Iverson et al. 2008). However, the SE is also expected to have future climates and vegetation compositions that are currently not found within the region (Williams and Jackson 2007). The combination of future climate, soils, and land cover may not resemble anyplace currently within vegetation dispersal distances (Williams and Jackson 2007). Current Coastal Plain climates are most similar to those expected for the Piedmont, but this region differs in soils, hydrology, and historical fire frequencies (Christensen 2000). Clay soils of the southeastern mountains and Piedmont are more similar to each other than those of the sandy Coastal Plain, and it is unclear how species may shift distributions in response to changes in SE climates.

Climate envelope models use the climate where a species occurs today to predict where suitable climates will likely occur in the future. However, climate envelop models themselves do not predict the future locations of tree species, as they do not account for rates of migration, habitat fragmentation, and other issues (Iverson et al. 2008). Genetic evidence suggests late Quaternary and early Holocene migration of trees species following the last ice age likely occurred at much slower rates than what would be required to keep pace with current and future climate change (McLachlan et al. 2005, Anderson et al. 2006, Mohan et al. 2009). Molecular work using chloroplast DNA suggests these paleo-rates were much less than 100 m per year, yet current global temperatures are shifting poleward at rates exceeding 1 km per year (McLachlan et al. 2005, Anderson et al. 2006). Migration rates of plant populations depend largely on rare long-distance seed dispersal events (LDD) which may not be frequent enough to result in the rapid migrations needed to keep track with species' current climates. Successful seedling recruitment and colonization after LDD is further limited by successful germination, growth, and survival (Ibáñez et al. 2007, Mohan et al. 2009). Recent work suggests that 59% of the 92 tree species examined were exhibiting range contractions at both the northern and southern boundaries (Zhu et al. 2011). Only 21% of eastern temperate tree species were shifting ranges northward, and 16% were shifting ranges southward (Zhu et al. 2011). This is in contrast to the expectation that juvenile trees of the eastern USA may currently be expanding northward in response to warming over the last several decades (Zhu et al. 2011).

Climate effects on canopy tree mortality rates are highlighted in work by Lines et al. (2010). Using data from across the eastern USA they found that tree mortality was six to nine times lower in areas with an intermediate temperature range (8°C to 10°C) compared to those areas with higher or lower temperatures. Mortality increased with increasing temperatures for species that currently exist in a range where average annual air temperature ranges between 10°C to 15°C. Areas with mean annual temperatures of more than 15°C, which currently includes much of the southeastern Piedmont and most of the Coastal Plain, exhibited much higher rates of tree mortality, suggesting that overall tree survivorship may decline with warmer temperatures. Therefore, northern parts of the SE may also see sharp increases in forest decline with increasing annual temperatures associated with regional warming. Conversely, historical tree mortality was minimized at intermediate amounts of annual precipitation, but mortality rates increases were much greater where annual precipitation was lowest. Therefore, future shifts in precipitation patterns within the region could also impact forest mortality.

8.4 Current and Projected Forest Stresses

Expansion and contraction in forest range and survivorship are often not directly a function of climate or climate change, but indirectly a function of climate impacts on other stressors such as insect populations and wildfire. Drought may weaken a forest, but it may be another biotic or abiotic factor that is the actual cause of death (McNulty and Boggs 2010). Forests in the southeastern USA are characterized by frequent natural disturbances such as fire, wind and ice storms, drought, insects and disease (Dale et al. 2001). Under a changing climate, many of these disturbances are projected to continue and may be amplified by climate change, and a series of disturbances may be required to significantly impact forest mortality. The major types of disturbance across the southeastern USA are outlined in the following sections.

Wildfires

The SE contains some of most productive forest land in the USA (Wear et al. 2007). As forest productivity increases so does fuel for wildfire. The combination of favorable climate and abundant fuel loads create a high fire-return rate of three to five years (Stanturf et al. 2002). The SE leads the nation in number of wildfires per year. The region averaged approximately 45,000 fires per year from 1997 through 2003 (Gramley 2005). Climate change may increase the frequency and intensity of wildfires (Blate et al. 2009).

Wildfires can lead to severe environmental consequences. Emissions from wildfires are an important source of atmospheric carbon. Furthermore, smoke particles are a source of atmospheric aerosols, which affect atmospheric radiative transfer through scattering and absorbing solar radiation and through modifying cloud microphysics (Charlson et al. 1992). These processes can further modify clouds and precipitation and atmospheric circulation (Ackerman et al. 2000, Liu 2005a and 2005b). In addition, wildfires release large amounts of particulate matter (PM) and other air pollutants that can degrade air quality (Riebau and Fox 2001). Wildland fires contribute an estimated 15% of total PM and 8% of CO_2 emissions over the southeastern USA (Barnard and Sabo 2003).

Weather and climate are determinants for wildfires along with fuel properties and topography (Pyne et al. 1996). Fire activities vary from one fire season to another. Fire weather and climate influence wildfire behavior and account for fire variability at various time scales. Under warm and dry conditions, fire seasons become longer and fires ignite more easily and spread more quickly. There is evidence that wildfires, especially catastrophic wildfires, have increased in recent decades in both the USA and other parts of the world (Piñol et al. 1998, Westerling et al. 2006). Among the converging factors were extreme weather events such as extended drought and climate change (Goldhammer and Price 1998, Stocks et al. 2002). Many climate models have projected significant climate change by the end of this century due to the greenhouse effect (IPCC 2007), including an overall increase in temperature worldwide and a drying trend in many subtropical and mid-latitude regions. Thus, wildfires likely will increase in these regions. Fire potential will increase significantly in several global geographic regions, including some areas in the USA (Liu et al. 2009).

Climate change may have various impacts on fires in the SE. Temperature is projected to increase across the South and would contribute to increased fire frequency and intensity, total burned area and longer fire seasons. In addition, temperature change can indirectly impact fires by changing fuel conditions. Increased temperature will reduce fuel moisture due to increased evaporation and, therefore, increase the threat of wildfires. The impact of climate change on fuel loading is more complex. Increased air temperature can increase fuel loading if the growing time is lengthened and there is sufficient soil moisture for tree growth. However, if increased air temperature also reduces soil moisture, tree productivity and fuel loading could *decrease* despite the extended length of the growing season.

The contributions of precipitation and humidity are also complex. Projections for precipitation are less certain than those for air temperature. Projected precipitation change often shows no clear trends even over large areas, including the southeastern USA (McNulty et al. 2012). Model agreement over projected precipitation decrease is higher in many subtropical and mid-latitude ecosystems outside the SE. This reduced precipitation would reduce fuel moisture and therefore increase fire potential in these regions. However, precipitation reduction would reduce available water for plant growth, leading to less fuel and therefore lower fire potential. Nevertheless, most GCMs also project more frequent precipitation anomalies such as drought that in turn could increase fire risk.

Hurricanes

Hurricanes, which are tropical cyclones with sustained winds equal to or greater than 119 km per hour, can cause massive economic damage to forests (see chapter 2 for more detail on future hurricane projections). In 2005, Hurricane Katrina heavily damaged forests along the Louisiana and Mississippi Gulf coasts (Chambers et al. 2007, and Stanturf et al. 2007). McNulty (2002) estimated that a single Category 3, 4, or 5 hurricane can destroy the equivalent of 10% of the annual carbon sequestered in the USA. Owing to its size, intensity and trajectory, Hurricane Katrina may have had 6 to 14 times that impact (Chambers et al. 2007). In 2005, winds from Hurricane Katrina damaged 22 million m^3 of timber estimated at a value of $1.4 billion to $2.4 billion dollars. Impacts are not limited to loss of wood volume and quality; ecosystem services provided by these forests also can also be impaired.

There are four main factors that determine the extent and severity of wind damage on forests: climate, soils, topography, and stand conditions (Wilson 2004). Hurricanes obviously represent an extreme climatic event. Trees growing in soil conditions that restrict root growth and depth are consistently more prone to uprooting. Variation in wind-throw along topographical gradients is more complicated and is often confused with damage due to species type and soil variation. There are many stand attributes that help determine tree susceptibility to wind-throw. These include height to diameter ratios, height, spacing, recent thinning, and impacts of previous disturbance on creating exposed edges that contain trees more vulnerable to wind-throw. Tree species composition may also impact the degree of damage from hurricanes. Therefore, stand composition and stocking levels represent stand attributes that can be manipulated by forest managers to reduce hurricane impacts.

Some evidence suggests that longleaf pine (*Pinus palustris*) might also be more tolerant to high winds than either slash pine (*P. elliottii*) or loblolly pine (*P. taeda*). In a study of the Hobcaw Forest, in coastal South Carolina after Hurricane Hugo, Gresham et al. (1991) reported that longleaf pine suffered less damage than loblolly pine. It was noted that species native to the Coastal Plain may be adapted better to the disturbance regimes found there. For example, longleaf pine, baldcypress (*Taxodium distichum*), and live oak (*Quercus virginiana*) suffered less damage than forest species with broad distribution ranges Gresham et al. (1991).

Johnsen et al. (2009) found that following hurricane Katrina, longleaf pine suffered less mortality (7%) than loblolly pine (26%). In addition to being potentially more resistant to wind-throw, longleaf pine is also more drought and fire resistant than the commonly planted loblolly pine (Landers et al. 1995). Wind damage increases with tree size, but the frequency and severity varies with species, site, wind parameters, and stand characteristics, specifically canopy evenness and age distribution, making it difficult to distinguish those tree species that appear to be more or less susceptible to wind damage (Gresham et al. 1991). The southeastern USA Coastal Plain is highly prone to hurricane events (Stanturf et al. 2007), and intense hurricanes occur two out of every three years across the region (McNulty 2002). Similar to historical natural fire regimes, the selection pressure of frequent high velocity winds has been a driving factor in forest composition.

Insects

Many types of insects damage southeastern forests, but the southern pine beetle (*Dendroctonus frontalis Zimm*.) is the most commercially destructive. Southern pine beetles caused more than $900 million in damage to SE pine forests between 1960 and 1990. Higher winter air temperatures are expected to increase over-wintering beetle larva survival rate, and higher annual air temperatures are expected to allow the beetles to produce more generations per year (Ayres and Lombardero 2000). Both of these factors could increase beetle populations. Other climate changes may work to reduce 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 (McNulty et al. 1998). However, severe drought stress reduces resin production and greatly increases the susceptibility of trees to beetle infestation (McNulty and Boggs 2010).

In addition to length and timing of the breeding season, other factors will likely impact the amount of insect caused damage under future climate conditions including the minimum winter air temperature and the prompt removal and destruction of infected timber (Rodriguez 1966). However, another factor closely linked to climate change may also impact insect success. Although it is one of the principle drivers of rising global air temperatures, CO_2 also increases forest productivity. Gan (2004) used an ecosystem model in conjunction with climate scenarios to predict that climate change would increase forest production by more than 7% during this century. The increase in productivity was a function of increased air temperature, longer growing season, and elevated atmospheric CO_2. However, southern pine beetle damage is also projected to increase by 4 to 7 times current levels, which would cause damage estimated at $500 to $800 million year per year (Gan 2004).

Potentially, some of the challenging impacts of climate change will be those conditions for which we have not considered or prepared for, such as previously unobserved combinations of environmental conditions that interact in new and unique ways. This concern is not unique to science. One such event occurred in the high elevations red spruce (*Picea rubens*, Sarg.) forests of western North Carolina. From 1999 until 2002, the area around Mt. Mitchell was in a period of extended heat wave and drought (McNulty and Boggs 2010). This southerly section of the Appalachian Mountains received some of the highest rates of acidic deposition in the eastern USA and contain remnant species present from the last glaciation, such as red spruce or hemlock that may be most at risk of extirpation. In 2001 some of the red spruce stands in the area began to die in large numbers while other stands of red spruce survived within the area (Figure 8.2). An examination of the sites found that stands with predominantly live trees and sites with predominantly dead trees had very different site characteristics. The sites with predominantly dead trees had much faster growth rates and higher soil nitrogen concentrations prior to the drought, compared to the historically slower growth rates and lower soil nitrogen concentrations from sites that largely survived the drought. In addition to the drought, there were signs that all the sites were attacked by southern pine beetles, a species that does not normally inhabit high elevation areas (Williams and Liebhold 2002). All the trees were attacked, but the trees that survived successfully repelled the phloem eating beetles. These were the trees from the poorer quality (i.e., lower soil nitrogen content) sites. Conversely, the trees that were unable to repel the beetles came from the higher quality (i.e., high soil nitrogen content) sites. The authors suggested that those factors that allowed stands to have the most vigorous growth under average climatic conditions also made these stands the most susceptible to mortality once those conditions changed. In combination, insects, drought, and nitrogen deposition ultimately combined to cause the observed forest mortality. If any one of these factors were not present, the trees may not have died. While in retrospect, the mechanisms for decline seem clear, forest managers have historically not been taught to consider vigorous forest stands as unhealthy. However, under a changing climate the definition of forest health, resilience, and resistance may need to be reevaluated (Thompson et al. 2009).

Elevated Atmospheric CO_2

Although CO_2 is not considered a disturbance factor for forests, atmospheric CO_2 could impact forest structure and function. Atmospheric carbon dioxide (CO_2) levels have increased nearly 35% since preindustrial times, from about 280 ppm to more than 380 ppm (IPCC 2007). Depending on the growth and emissions scenario used, atmospheric CO_2 may rise as high as 850 ppm by 2100 (IPCC 2007).

Figure 8.2 Red spruce (*Picea rubens Sarg.*) mortality in western North Carolina due to a combination of drought, southern pine beetles, and acid rain.

While carbon dioxide is the primary driver of anthropogenic climate change, it is also the basis of plant photosynthesis. Given that plant photosynthesis is not saturated at current CO_2 levels, anthropogenic increases in CO_2 will almost certainly lead to higher rates of photosynthesis if sufficient soil nutrients are available to support the elevated CO_2 induced growth (Oren et al. 2001). However, greater photosynthesis may not translate to significantly greater forest productivity and plant carbon storage, and gains in productivity may not be sustainable over the long term (Norby et al. 2010).

8.5 Ecosystem Services

Southeastern forests have been a major source of ecosystem goods and services for thousands of years (Anderson and Sassaman 1996). Current changes in demographics and climate may change the value of and need for some ecosystem services, but an overall reliance on southeastern ecosystems for societal and economic purposes will remain. In addition to goods and services such as timber and protection of water supplies, southeastern forests are considered important sinks for atmospheric CO_2, and part of a strategy to slow global warming. These services are outlined in the next section.

Forest Productivity and Carbon Sequestration

Large areas in the SE are actively managed for wood production at varying levels of intensity. For example, site preparation; weed control; fertilization; stocking, such as planting density and thinning; and genetic improvement can all impact forest productivity. Attention is being focused on the role forests play in sequestering some of the anthropogenic carbon inputs to the atmosphere in biomass and soils, while conserving existing carbon stocks through informed resource management (Blate et al. 2009).

The role of southeastern forests in providing a steady supply of timber and fiber is of particular importance in meeting current and future timber and fiber needs across the USA because forest harvests have substantially decreased across the other regions. As a whole, the South's forest sector produces approximately 60% of the total wood production in the USA (Prestemon and Abt 2002).

Climate change has the potential to impact forest productivity and carbon sequestration. Increases in forest carbon sequestration (a result of forests storing carbon in soils and woody tissues) can slow down the rate of atmospheric CO_2 increase and therefore help to slow down global warming. Southeastern forests also have been estimated to account for 36% of the carbon sequestered in the conterminous United States (Turner et al. 1995). Han et al. (2007) estimated that each year forests in the SE sequester 13% of regional greenhouse emissions in soils and long-lived forest products, such as lumber. Southeastern forests also contain about 30% of the nation's carbon stock (Mickler et al. 2004) and play a prominent role in the regional and global carbon cycle (Turner et al. 1995).

Forest Water Resources

When compared with other land uses, managed and unmanaged forests provide the cleanest and most stable water supplies for drinking water, recreation, power generation, aquatic habitat, and groundwater recharge. Large acres of forestland in the Appalachians and Piedmont are the headwaters of many river systems in the SE (Sun et al. 2011). These watersheds provide a disproportionately higher amount of the regional water supply than the Coastal Plain because these forests occupy areas with relatively high precipitation and low evapotranspiration (Brown et al. 2008).

The impacts of climate change on forest structure and functions are likely to result in negative consequences on water quantity and quality of forested watersheds through altering key hydrologic fluxes including precipitation and evapotranspiration, and the biogeochemical processes (Sun et al. 2011). An increase in air temperature means an increase in energy availability and atmospheric water demand. Thus for the humid southeastern USA, water shortages are expected to increase. For example, Walter et al. (2004) concluded ecosystem ET has been increasing at a rate of 10.4 mm per decade across six major basins that cover a majority of the watersheds in the USA. As more water is evapotranspired form the soil, less water will flow through the soil, and into streams and rivers. There will also be less water recharging shallow aquifers as tree water use (i.e., ET) increases with increasing air temperature (see Chapter 10. for more details on how forests use and yield water).

Shifts in tree species due to changes in climate, fire regime, and invasive species are likely to increase ecosystem transpiration rates and alter the carbon and nutrient balances. An increase in frequency of high intensity storm events will increase rainfall erosivity thus the potential for increased soil erosion and sedimentation (Marion et al. In press). An example of this increased soil erosion potential was forecast for the

Uwharrie National Forest where severe soil erosion was predicted to increase significantly under future climate changes (Figure 8.3).

Ecosystem model simulations and multiple watershed vegetation manipulation experiments suggest that activities that do not result in a forest type conversion or a coppice stand structure will not substantially alter streamflow responses to extreme precipitation events (Ford et al. 2011). However, based on forest conversion experiment studies, the conversion of deciduous forests (either naturally or by forest management) to pine monocultures in the Appalachians substantially altered the streamflow response to extreme annual precipitation. The pine increased soil permeability and rain fall absorption, but the pines also use more soil water than do the hardwoods. Thus, forest management may reduce flood risk but also exacerbate drought. Tradeoff between managing forests for opposite extremes should be carefully considered by water resource managers for contingency land use planning (Ford et al. 2011).

Increased frequency of heavy rainfall events will likely impact forest communities and increase flood occurrence. If there is an increase spring and summer droughts, it likely will make forest vegetation vulnerable to stresses due to high ET demands in the Coastal Plain region. Forests can also modulate regional climate by controlling energy and water transfers between the atmosphere and forested land-surface (Liu 2011). Forest restoration, afforestation, or both are expected to play important roles in mitigating the impacts of climate change on water resources in these regions.

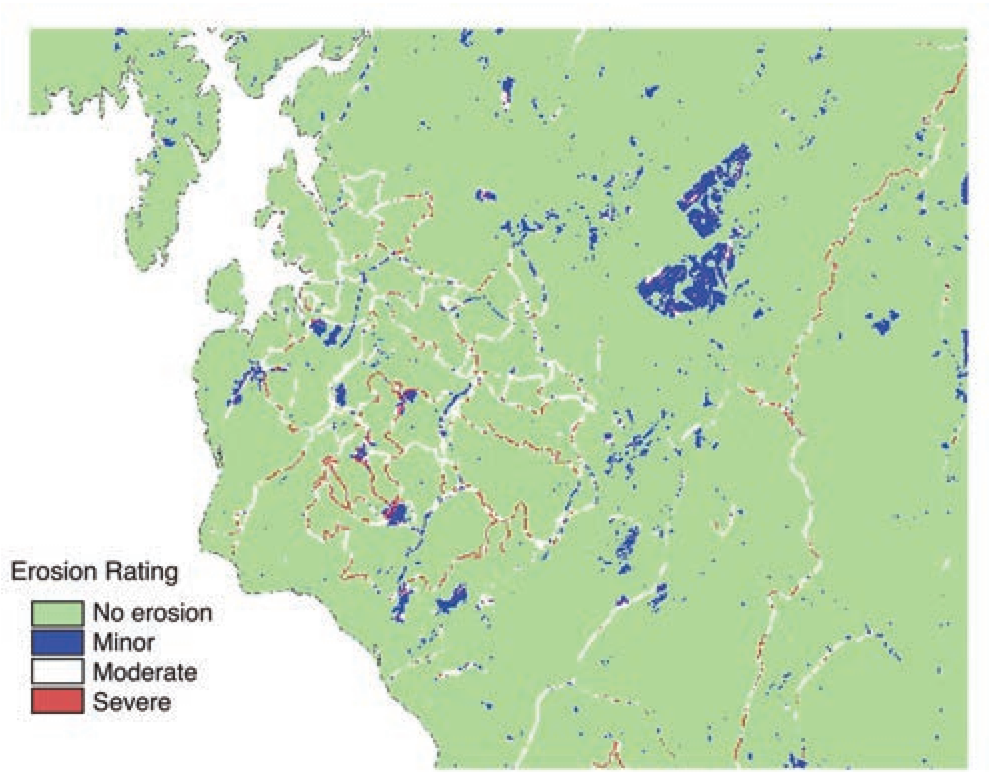


Figure 8.3 Revised Universal Soil Loss Equation predictions of soil erosion areas within the Uwharrie National Forest by 2030.

Regional modeling with a monthly scale water supply and demand model called the Water Supply Stress Index (WaSSI) suggests ecosystem water stress across the eastern USA will likely increase in the next 50 years, especially during the summer and fall seasons, due to increase water demand and reduced water yield (Caldwell et al. 2011).

8.6 Adaptation and Mitigation Options

In general, the biological productivity of SE forests likely will be enhanced by atmospheric carbon enrichment, as long as precipitation does not decline or air temperature does not increase soil moisture stress to a level that would offset potential CO_2 benefits on productivity. Use of forest resources is also anticipated to adapt to changes in productivity (de Steiger and McNulty 1998). For instance, a northward shift in forest productivity (Figure 8.4) is projected to lead to relative increases in the proportion of regional timber harvests that come from the northern reaches of the region. This may compensate for harvest reduction in the southeastern parts, which are projected to be more negatively affected by the biophysical effects of climate change. In addition, landowners are projected to switch land between forestry and agricultural in places and at times where the change in relative productivity warrants it.

There are a variety of other adaptation strategies to address climate trends and extremes. Potential adaptation strategies include genetic and silvicultural system improvements that increase water use efficiency or water availability. Increasing

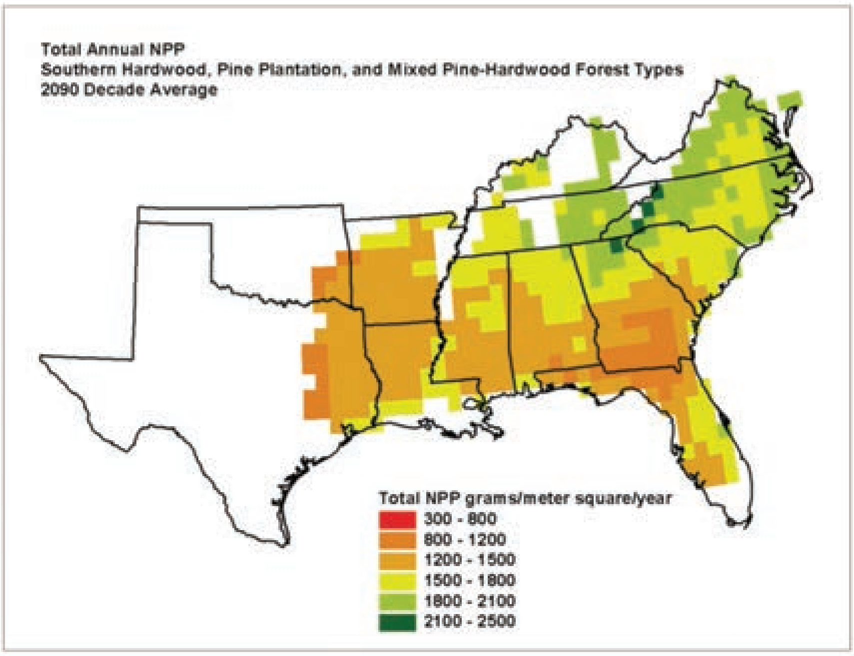


Figure 8.4 Forest model predictions of increased carbon sequestration (measured at net primary productivity, NPP) in the northern sections of the southern USA due to increasing air temperature by the end of this century.

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 may prove important in this region (Dale et al. 2001). Timber productivity associated with increased temperature, growing season length, and CO_2 enrichment may be further enhanced by improved genetics, bioengineering, use of marginal agricultural land for tree production, and more intensive forest management (Schmidtling et al. 2004, Oren et al. 2004). Reduction of air pollutants, such as ozone and nitrogen oxides, may also be an important strategy for increasing forest productivity due to the potential for synergistic stress impacts (McNulty and Boggs 2010, Figure 8.5).

Increased use of fertilizers may increase forest productivity and carbon sequestration in an effort to partially mitigate greenhouse gas emissions. More than 400,000 ha of pine plantations are now fertilized each year with nitrogen which increases forest productivity (Albaugh et al. 2007). Fertilization can also decrease carbon losses by reducing soil respiration, and thus increasing forest carbon sequestration (Butnor et al. 2003). Other management tools that directly impact carbon sequestration include species selection, modification of initial planting density, and rotation length and thinning.

The effects of silvicultural treatments, such as planting density, thinning and rotation length, on carbon sequestration were analyzed by simulating carbon flux under

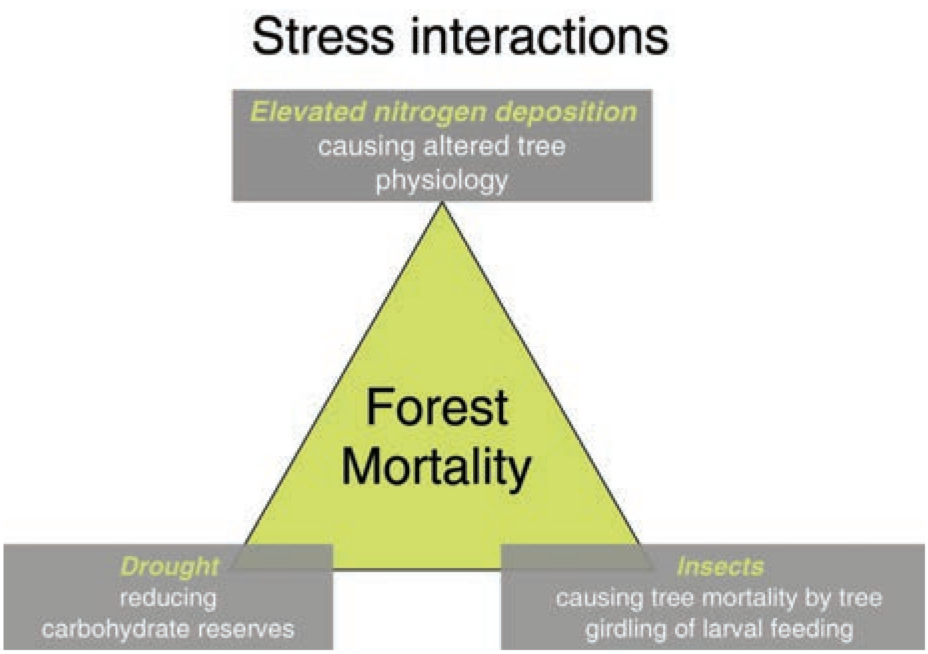


Figure 8.5 Interactions of climate (e.g., drought), biological (e.g., insects) and abiotic (e.g., fire or acid rain) can combine to cause forest mortality. The interactive stresses may be related (e.g., drought and fire) or unrelated (e.g., drought and acid rain). Any single stress may not have caused the mortality, but as climate change continues the potential for more frequent, more severe, and synergistic stress increases.

different climate and management scenarios for loblolly pine and slash pine plantations established in the southeastern USA Lower Coastal Plain (Gonzalez-Benecke et al. 2010 and 2011). Increasing the rotation length increased carbon stock in both species. Canadell and Raupach (2008) cited longer harvesting cycles as a major management strategy for increasing forest carbon stocks.

Improved understanding of climate change impacts and adaptation options are only useful if this information can be conveyed to the land manager. New web-based models and tools are being developed to allow for easier, more site specific climate change assessments. For example, the web-based Distrib/Shift forest species distribution model gives users the ability to examine which tree and bird species will likely become more and less dominant in that area over the coming years and decades (Iverson et al. 2011). Similarly, the web-based WaSSI (Water Supply Stress Index) hydrologic model gives land managers the ability to examine the impacts of climate, population and land use change on water supply and demand on their watersheds. Finally, Web-based tools like TACCIMO (Template for Assessing Climate Change Impacts and Management Options) allow the user to search scientifically reviewed literature on climate change impacts for their area, and then to further use TACCIMO to search for management options to address or adapt to these changes. Significantly improved graphic user interfaces (Figure 8.6), data storage, and internet access speeds have greatly improved the application of these tools.

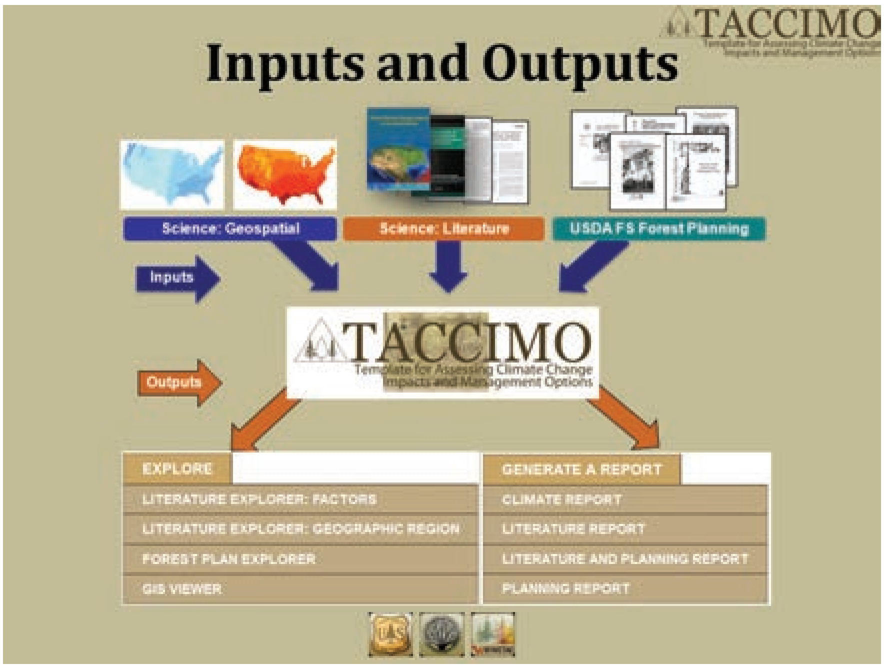


Figure 8.6 Web-based tools such as TACCIMO (Template for Assessing Climate Change Impacts and Management Options) are increasingly being used to easily translate scientific knowledge into the hands of the land manager.

8.7 Conclusions

Southeastern forests are as diverse as the cultures that exist within them. The wide range of tree, plant, and animal species make the region both resistant and susceptible to change. Some species will not be able to adapt to rapidly changing climatic conditions; other species will fill vacated niches that develop. Protecting the overall integrity of the ecosystem will be less of a challenge than protecting all of the parts. Several independent studies suggest that remnant species present from the last glaciation, such as red spruce or hemlock may be most at risk of extirpation. If changes result in warmer, drier conditions in some parts of the SE, conditions could favor more drought-tolerant species such as oaks and long-leaf pine.

8.8 References

Ackerman, A.S., O.B. Toon, D.E. Stevens, A.J. Heyms, V. Ramanathan, E.J.Welton. 2000. Reduction of tropical cloudiness by soot. *Science*, 288 (5468): 1042-1047.

Albaugh, T.J., H.L. Allen, T.R. Fox. 2007. Historical patterns of forest fertilization in the Southeast United States from 1969 to 2004. Southern Journal of Applied Forestry, 31 (3): 129-137.

Anderson, D.G., K.E. Sassaman. 1996. *The Paleoindian and early archaic southeast*. Tuscaloosa, AL: University of Alabama Press.

Anderson, L.L., F.S. Hu, D.M. Nelson, R.J. Petit, K.N. Paige. 2006. Ice-age endurance: DNA evidence of a white spruce refugium in Alaska. *Proceedings of the National Academy of Sciences of the United States of America* 103 (33): 12447-12450.

Ayres, M. and M. Lombardero. 2000. Assessing the consequences of global change for forest disturbance from herbivores and pathogens. *The Science of the Total Environment* 262 (3): 263–286.

Bachelet, D., R.P. Nielson, J.M. Lenihan, R.J. Drapek. 2001. Climate change effects on vegetation distribution and carbon budget in the United States. *Ecosystems* 4 (3): 164-185.

Barnard, W. and E. Sabo. 2003. Draft report: Review of 1999 NEI version 2 final and recommendations for developing the 2002 VISTAS inventory for regional haze modeling: Area and point sources. Herndon, VA: MACTEC.

Belote, R.T., J.F. Weltzin, R.J. Norby. 2004. Response of an understory plant community to elevated [CO_2] depends on differential responses of dominant invasive species and is mediated by soil water availability. *New Phytologist* 161 (3): 827-835.

Bhuta, A.A.R., L.M. Kennedy, N. Pederson. 2009. Climate-radial growth relationships of northern latitudinal range margin longleaf pine (*Pinus palustris Mill.*) in the Atlantic Coastal Plain of southeastern Virginia. *Tree-Ring Research* 65 (2): 105-115.

Blate, G.M., L.A. Joyce, J.S. Littell, S.G. McNulty, C.I. Millar, S.C. Moser, R.P. Neilson, K. O'Halloran, D.L. Peterson. 2009. Adapting to climate change in United States national forests. *Unasylva* (231/232), 60:57-62.

Butler, B.J. and D.N. Wear. 2012. Forest ownership dynamics of southern forests. In *Southern Forests Futures Project*, ed. D. Wear and J. Greis. USDA Forest Service Southern Research Station General Technical Report. (In press).

Brown, T.C., M.T. Hobbins, J.A. Ramirez. 2008. Spatial distribution of water supply in the conterminous United States. *Journal of the American Water Resources Association* 44 (6): 1474–1487.

Butnor, J.R., K.H. Johnsen, R. Oren, G.G. Katul. 2003. Reduction of forest floor respiration by fertilization on both carbon dioxide-enriched and reference 17-year-old loblolly pine stands. *Global Change Biology* 9: 849–861.

Caldwell, P., G. Sun, S. McNulty, E. Cohen, J.M. Myers. 2011. Modeling impacts of environmental change on ecosystem services across the conterminous United States. In *Proceedings of the 4th Interagency Conference on Research in the Watersheds: Observing, Studying, and Managing for Change*, ed. C.N. Medley, G. Patterson, and M.J. Parker, 63-69. Reston, VA: US Geological Survey.

Caldwell, P.V., G. Sun, S.G. McNulty, E.C. Cohen, J.A. Moore Myers. 2012. Impacts of impervious cover, water withdrawals, and climate change on river flows in the conterminous US. Hydrology and Earth System Sciences Discussion 9:4263-4304.

Canadell, J.G. and M.R. Raupach. 2008. Managing Forests for Climate Change Mitigation. *Science* 320: 1456-1457.

Chambers, J.Q., J.I. Fisher, H. Zeng, E.L. Chapman, D.B. Baker, G.C. Hurtt. 2007. Hurricane Katrina's carbon footprint on U.S. Gulf Coast forests. *Science* 318 (5853): 1107.

Charlson, R.J., S.E. Schwartz, J.M. Hales, R.D. Cess, J.A. Coakley Jr., J.E. Hansen, D.J. Hoffman. 1992. Climate forcing by anthropogenic sulfate aerosols. *Science* 255 (5043): 423-430.

Cherry, J.A., K.L. McKee, J.B. Grace. 2009. Elevated CO_2 enhances biological contributions to elevation change in coastal wetlands by offsetting stressors associated with sea-level rise. *Journal of Ecology* 97 (1): 67-77.

Christensen, N.L. 2000. Vegetation of the Southeastern Coastal Plain. In *North American terrestrial vegetation*, ed. M.G. Barbour and W.D. Billings, 397-448. Cambridge, UK: Cambridge University Press.

Clark, J.S., D.M. Bell, M.H. Hersh, L. Nichols. 2011. Climate change vulnerability of forest biodiversity: Climate and competition tracking of demographic rates. *Global Change Biology* 17 (5): 1834-1849.

Dale, V.H., L.A. Joyce, S.G. McNulty, R.P. Neilson, M.P. Ayres, M.D. Flannigan, P.J. Hanson, L.C. Irland, A.E. Lugo, C.J. Peterson, D. Simberloff, F.J. Swanson, B.J. Stocks, B.M. Wotton. 2001. Climate change and forest disturbances. *BioScience* 59 (9): 723-734.

Dale, V.H., M.L. Tharp, K.O. Lannom, D.G. Hodges. 2010. Modeling transient response of forests to climate change. *Science of the Total Environment* 408 (8): 1888-1901.

de Steiguer, J.E. and S.G. McNulty, 1998. An integrated assessment of climate change on timber markets of the southern United States. In The productivity and sustainability of southern forest ecosystems in a changing environment, ed. R.A. Mickler and S.A. Fox. Springer-Verlag: New York.

Delcourt, P.A. and H.R. Delcourt. 1998. Paleoecological insights on conservation of biodiversity: A focus on species, ecosystems, and landscapes. *Ecological Applications* 8 (4): 921-934.

DeLucia, E.H., D.J. Moore, R.J. Norby. 2005. Contrasting responses of forest ecosystems to rising atmospheric CO_2: Implications for the global C cycle. *Global Biogeochemical Cycles* 19, GB3006; doi: 10.1029/2004GB002346.

Doyle, T.W., C.P. O'Neil, M.P.V. Melder, A.S. From, M.M. Palta. 2007. Tidal freshwater swamps of the southeastern United States: Effects of land use, hurricanes, sea-level rise, and climate change. In *Ecology of tidal freshwater forested wetlands of the southeastern United States*, ed. W.H. Conner, T.W. Doyle, and K.W. Krauss, 1-28. Dordrecht, The Netherlands: Springer Netherlands.

Doyle, T.W., K.W. Krauss, W.H. Conner, A.S. From. 2010. Predicting the retreat and migration of tidal forests along the northern Gulf of Mexico under sea-level rise. *Forest Ecology and Management* 259 (4): 770-777.

Erwin, Kevin L. 2009. Wetlands and global climate change: the role of wetland restoration in a changing world. *Wetlands Ecology and Management* 17:71-84.

Fesenmyer, K.A. and N.L. Christensen. 2010. Reconstructing Holocene fire history in a southern Appalachian forest using soil charcoal. *Ecology* 91 (3): 662-670.

Ford, C.R., S.H. Laseter, W.T. Swank, J.M. Vose. 2011. Can forest management be used to sustain water-based ecosystem services in the face of climate change? *Ecological Applications* 21 (6): 2049-2067.

Gan, J. 2004. Risk and damage of southern pine beetle outbreaks under global climate change. *Forest Ecology and Management* 191 (1-3): 61-71.

Goldenberg, S.B., C.W. Landsea, A.M. Mestas-Nunez, W.M. Gray. 2001. The recent increase in Atlantic hurricane activity: Causes and implications. *Science* 293 (5529): 474-479.

Goldhammer, J.G. and C. Price. 1998. Potential impacts of climate change on fire regimes in the tropics based on Magicc and a GISS GCM-derived lightning model. *Climatic Change* 39 (2-3): 273-296.

Gonzalez-Benecke, C.A., T.A. Martin, W.P. Cropper Jr., R. Bracho. 2010. Forest management effects on in situ and ex situ slash pine forest carbon balance. *Forest Ecology and Management* 260 (5): 795-805.

Gonzalez-Benecke, C.A., T.A. Martin, E.J. Jokela, R. De La Torre. 2011. A flexible hybrid model of life cycle carbon balance for loblolly pine (*Pinus taeda* L.) management systems. *Forests* 2 (3): 749-776.

Grala, K. and W.H. Cook III. 2010. Spatial and temporal characteristics of wildfires in Mississippi, USA. *International Journal of Wildland Fire* 19 (1): 14-28.

Gramley, M. 2005. Fire in the South: A Report by the Southern Group of State Foresters. Winder GA: Southern Group of State Foresters. http://216.226.177.78/PDFs/fire_in_the_south.pdf

Gresham, C.A., T.M. Williams, D.J. Lipscomb. 1991. Hurricane Hugo wind damage to southeastern U.S. coastal forest tree species. *Biotropica* 23 (4): 420-426.

Gruhn, J.A. and P.S. White. 2011. *Magnolia grandiflora L.* range expansion: A case study in a North Carolina Piedmont forest. *Southeastern Naturalist* 10(2): 275-288.

Han, F., M. Plodinec, Y. Su, D. Monts, and Z. Li. 2007. Terrestrial carbon pools in southeast and south-central United States. *Climate Change* 84: 191-202.

Hansen, A.J., R.P. Neilson, V.H. Dale, C. Flather, L. Iverson, D.J. Currie, P. Bartlein. 2001. Global change in forests: Responses of species, communities, and biomes. *BioScience* 51 (9): 765-779.

Henderson, J.P. and H.D. Grissins-Mayer. 2009. Climate-tree growth relationships of longleaf pine (*Pinus palustris* Mill.) in the Southeastern Coastal Plain, USA. *Dendrochronologia* 27 (1): 31-43.

Hoeppner, S.S. 2008. Swamp ecology in a dynamic coastal landscape: An investigation through field study and simulation modeling. Department of Oceanography and Coastal Sciences, Louisiana State University.

Ibáñez, I., J.S. Clark, S. LaDeau, J.H.R. Lambers. 2007. Exploiting temporal variability to understand tree recruitment response to climate change. *Ecological Monographs* 77 (2): 163-177.

Ibáñez, I., J.S. Clark, M.C. Dietze. 2008. Evaluating the sources of potential migrant species: Implications under climate change. *Ecological Applications* 18 (7): 1664-1678.

IPCC (Intergovernmental Panel on Climate Change). 2007. *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. Core Writing Team, R.K. Pachauri, and A. Reisinger. Geneva, Switzerland: IPCC.

Iverson, L.R., A.M. Prasad, S.N. Matthews, M. Peters. 2008. Estimating potential habitat for 134 eastern USA tree species under six climate scenarios. *Forest Ecology and Management* 254 (3): 390-406.

Johnsen, K.H., J.R. Butnor, J.S. Kush, R.C. Schmidtling, C.D. Nelson. 2009. Hurricane Katrina winds damaged longleaf pine less than loblolly pine. *Southern Journal of Applied Forestry* 33 (4): 178-181.

Krauss, K.W., C.M. Lovelock, K.L. McKee, L. López-Hoffman, S.M.L. Ewe, W.P. Sousa. 2008. Environmental drivers in mangrove establishment and early development: A review. *Aquatic Botany* 89 (2): 105-127.

Landers, J.L., D.H. van Lear, W.D. Boyer. 1995. The longleaf pine forests of the southeast: Requiem or renaissance? *Journal of Forestry* 93 (11): 39-44.

Ley, J.A., C.C. McIvor, C. Montague. 1999. Fishes in mangrove prop-root habitats of northeastern Florida Bay: Distinct assemblages across an estuarine gradient. *Estuarine, Coastal and Shelf Science* 48 (6): 701-723.

Lines, E.R., D.A. Coomes, D.W. Purves. 2010. Influences of forest structure, climate and species composition on tree mortality across the eastern U.S. *PLOS ONE*, 5 (10): 1-12.

Liu, Y. 2005a. Atmospheric response and feedback to radiative forcing from biomass burning in tropical South America. *Agricultural and Forest Meteorology* 133 (1-4): 40-53.

Liu, Y. 2005b. Enhancement of the 1988 northern U.S. drought due to wildfires. *Geophysical Research Letters* 32, L10806; doi: 10.1029/2005GL022411

Liu Y., J. Stanturf, S. Goodrick. 2009. Trends in global wildfire potential in a changing climate. *Forest Ecology and Management* 259 (4): 685-697.

Liu, Y. 2011. A numerical study on hydrological impacts of forest restoration in the southern United States. *Ecohydrology* 4 (2): 299-314.

Marion, D. and G. Sun et al. In Press. Water quantity and quality under climate change in the southern U.S. In *Climate Change Adaptation and Mitigation Management Options (CCAMMO) Project*, ed. J.M. Vose. Raleigh, NC: USDA Forest Service.

McKee, K.L., D.R. Cahoon, I.C. Feller. 2007. Caribbean mangroves adjust to rising sea level through biotic controls on change in soil elevation. *Global Ecology and Biogeography* 16 (5): 545-556.

McLachlan, J.S., J.S. Clark, P.S. Manos. 2005. Molecular indicators of tree migration capacity under rapid climate change. *Ecology* 86 (8): 2088-2098.

McNulty, S.G., P.L. Lorio Jr., M.P. Ayres, J.D. Reeve. 1998. Predictions of southern pine beetle populations using a forest ecosystem model. In The productivity and sustainability of southern forest ecosystems in a changing environment, ed. R.A. Mickler and S.A. Fox, 617-634. New York, USA: Springer-Verlag, New York, Inc.

McNulty, S.G. 2002. Hurricane impacts on USA forest carbon sequestration. *Environmental Pollution* 116 (Suppl. 1): S17-S24.

McNulty, S.G. and J.L. Boggs. 2010. A conceptual framework: Redefining forest soil's critical acid loads under a changing climate. *Environmental Pollution* 158 (6): 2053-2058.

McNulty, S., J.M. Myers, P. Caldwell, G. Sun. 2012. Chapter 3: Climate change. In *Southern forest futures project*, ed. D. Wear and J. Greis, 67-122. Raleigh, NC: USDA Forest Service.

Michener, W.K., E.R. Blood, K.L. Bildstein, M.M. Brinson, and L.R. Gardner. 1997. Climate change, hurricanes, and tropical storms, and rising sea level in coastal wetlands. *Ecological Applications* 7:770–801.

Michot, T.C., R.H. Day, C.J. Wells. 2010. Increase in black mangrove abundance in coastal Louisiana. In Louisiana natural resources news: Newsletter of the Louisiana Association of Professional Biologists. Lafayette, LA: National Wetlands Research Center.

Mickler, R.A., J.E. Smith, L.S. Heath. 2004. Forest carbon trends in the Southern United States. In Gen. Tech. Rep. SRS 75. Asheville, NC: US Department of Agriculture, Forest Service, Southern Research Station, chapter 33, 383-394.

MIFI (Mississippi Institute for Forest Inventory). 2005. Mississippi Forest Recovery Task Force: Timber Damage from Katrina. Available at http://www.msforestry.net/home/mfa-publications.html (Note this is a restricted site and you must register to access information.)

Mohan, J.E., L.H. Ziska, W.H. Schlesinger, R.B.Thomas, R.C. Sicher, K. George, J.S. Clark. 2006. Biomass and toxicity responses of poison ivy (*Toxicodendron radicans*) to elevated atmospheric CO_2. *Proceedings of the National Academy of Sciences of the United States of America* 103 (24): 9086-9089.

Mohan, J.E., J.S. Clark, W.H. Schlesinger. 2007. Long-term CO_2 enrichment of a forest ecosystem: Implications for forest regeneration and succession. *Ecological Applications* 17 (4): 1198-1212.

Mohan, J.E., L.H. Ziska, W.H. Schlesinger, R.B. Thomas, R.C. Sicher, K. George, J.S. Clark. 2008. Biomass and toxicity responses of poison ivy (*Toxicodendron radicans*) to elevated atmospheric CO_2: Reply. *Ecology* 89 (2): 585-587.

Mohan, J.E., R. Cox, L. Iverson. 2009. Northeastern forest composition and carbon dynamics in a future, warmer world. *Canadian Journal of Forest Research* 39 (2): 213-230.

Montagna, P.A., J. Brenner, J. Gibeaut, S. Morehead. 2009. Coastal impacts. In The impact of global warming on Texas, ed. J. Schmandt, J. Clarkson and G.R. North. Austin TX: University of Texas Press.

Noormets, A., S.G. McNulty, J.L. DeForest, G. Sun, Q. Li, J. Chen. 2008. Drought during canopy development has lasting effects on annual carbon balance in a deciduous temperate forest. *New Phytologist* 179 (3): 818-828.

Norby, R.J., E.H. DeLucia, B. Gielen, C. Calfapietra, C.P. Giardina, J.S. King, J. Ledford, H.R. McCarthy, D.J.P. Moore, R. Ceulemans, P. De Angelis, A.C. Finzi, D.F. Karnosky, M.E. Kubiske, M. Lukac, K.S. Pregitzer, G.E. Scarascia-Mugnozza, W.H. Schlesinger, R. Oren. 2005. Forest response to elevated CO_2 is conserved across a broad range of productivity. *Proceedings of the National Academy of Sciences of the United States of America* 102 (50): 18052-18056.

Norby, R.J., J.M. Warren, C.M. Iversen, B.E. Medlyn, R.E. McMurtrie. 2010. CO_2 enhancement of forest productivity constrained by limited nitrogen availability. *Proceedings of the National Academy of Sciences of the United States of America* 107 (45): 19368-19373.

O'Gorman, P.A. and T. Schneider. 2009. The physical basis for increases in precipitation extremes in simulations of 21st-century climate change. *Proceedings of the National Academy of Sciences of the United States of America* 106 (35): 14773-14777.

Oren R., D.S. Ellsworth, K.H. Johnsen, K. Liu, N. Phillips, B.E. Ewers, C. Maier, R. Karina, V.R. Schäfer, G. Hendrey, S.G. McNulty, G.G. Katul. 2001. Soil fertility limits carbon sequestration by forest ecosystems in CO2-enriched atmosphere. *Nature* 411: 469-472.

Piñol, J., J. Terradas, F. Lloret. 1998. Climate warming, wildfire hazard, and wildfire occurrence in coastal eastern Spain. *Climatic Change* 38 (3): 345-357.

Prengaman, K.A., J.R.G. Kribel, S. Ware. 2008. Effects of Hurricane Isabel on a maturing hardwood forest in the Virginia Coastal Plain. *The Journal of the Torrey Botanical Society* 135 (3): 360-366.

Prestemon, J.P. and R.C. Abt. 2002. Timber products supply and demand. In *The Southern Forest Resource Assessment*, ed. D.N. Wear and J.G. Greis. USDA Forest Service, General Technical Report SRS-53, Asheville, North Carolina.

Pyne, S.J., P.L. Andrews, R.D. Laven. 1996. *Introduction to wildland fire*. New York, NY: John Wiley & Sons, Inc.

Riebau, A.R. and D. Fox. 2001. The new smoke management. *International Journal of Wildland Fire* 10 (4): 415-427.

Rodriguez L.R. 1966. El combate directo de Dendroctonus frontalis Zimm. por derribo, descortezamiento y quema de la corteza de los arboles infestados [Direct control of Dendroctonus frontalis Zimm. by destroying, debarking, and burning infested trees]. *Bosques* 3 (6):8- 11.

Schmidtling, R.C., T.L. Robison, S.E. McKeand, R.J. Rousseau, H.L. Allen, B. Goldfarb 2004. The role of genetics and tree improvement in southern forest productivity. In General Technical Report SRS 75. Asheville, NC: US Department of Agriculture, Forest Service, Southern Research Station, Chapter 10.

Seifert, C.L., R.T. Cox, S.L. Forman, T.L. Foti, T.A. Wasklewicz, A.T. McColgan. 2009. Relict nebkhas (pimple mounds) record prolonged late Holocene drought in the forested region of south-central United States. *Quaternary Research* 71 (3): 329-339.

Smith, W.B. and D. Darr. 2009. *U.S. forest resource facts and historical trends*. Washington, DC: U.S. Department of Agriculture: Forest Service.

Speer, J.H., H.D. Grissino-Mayer, K.H. Orvis, C.H. Greenberg. 2009. Climate response of five oak species in the eastern deciduous forests of the southern Appalachian Mountains, USA. *Canadian Journal of Forest Research* 39 (3): 507-518.

Stanturf, J.A., D.D. Wade, T.A. Waldrop, D.K. Kennard, G.L. Achtemeier. 2002. Fires in southern forest landscapes. In *The southern forest resource assessment, general technical report SRS-53*, ed. D.M. Wear and J. Greis, 607-630. Asheville, NC: USDA Forest Service.

Stanturf, J.A., S.L. Goodrick, K.W. Outcalt. 2007. Disturbance and coastal forests: A strategic approach to forest management in hurricane impact zones. *Forest Ecology and Management* 250 (1-2): 119-135.

Stocks, B.J., J.A. Mason, J.B. Todd. 2002. Large forest fires in Canada, 1959-1997. *Journal of Geophysical Research* 107, 8149; doi: 10.1029/2001JD000484.

Sun, G., P. Caldwell, A. Noormets, E. Cohen, S.G. McNulty, E. Treasure, J.C. Domec, Q. Mu, J. Xiao, R. John, J. Chen. 2011. Upscaling key ecosystem functions across the conterminous United States by a water-centric ecosystem model. *Journal of Geophysical Research* 116, G00J05; doi: 10.1029/2010JG001573.

Thompson, I., B. Mackey, S. McNulty, A. Mosseler. 2009. Forest resilience, biodiversity, and climate change: A synthesis of the biodiversity/resilience/stability relationship in forest ecosystems, technical series no. 43. Montreal, Quebec, Canada: Secretariat of the Convention on Biological Diversity.

Turner, D.P., G.J. Koerper, M.E. Harmon, J.J. Lee. 1995a. A carbon budget for forests of the conterminous United States. *Ecological Applications* 5: 421-436.

Van Lear, D.H., R.A. Harper, P.R. Kapeluck, W.D. Carroll. 2004. History of Piedmont forests: Implications for current pine management. In *Proceedings of the 12th biennial southern silvicultural research conference, general technical report SRS-71*, ed. K.F. Connor, 127-131. Asheville, NC: US Department of Agriculture.

Visser, J.M., W.G. Vermillion, D.E. Evers, R.G. Linscombe, C.E. Sasser. 2005. Nesting habitat requirements of the brown pelican and their management implications. *Journal of Coastal Research* 21 (2): e27-e35.

Wade, D.D., B.L. Brock, P.H. Brose, J.B. Grace, G.A. Hoch, and W.A. Patterson. 2000. Chapter 4:53-96 Fire in eastern ecosystems. In J.K. Brown and J.K. Smith (eds.) Wildland Fire in Ecosystems: Effects of Fire on Flora. Genenral Technical Report RMRS-GTR-42-Vol. 2. Ogden, UT: US Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Walter, M.T., D.S. Wilks, J.Y. Parlange, R.L. Schneider. 2004. Increasing evapotranspiration from the conterminous United States. *Journal of Hydrometeorology* 5 (3): 405-408.

Wear, D.N. and J.G. Greis. 2002. *Southern forest resource assessment, general technical report SRS–53*. Asheville, NC: US Department of Agriculture.

Wear, D.N., D.R. Carter, J. Prestemon. 2007. The U.S. South's timber sector in 2005: A prospective analysis of recent change. Asheville, NC: US Department of Agriculture. GTR-SRS 099.

Webster, P.J., G.J. Holland, J.A. Curry, H.R. Chang. 2005. Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science* 309 (5742): 1844-1846.

Westerling, A.L., H.G. Hidalgo, D.R. Cayan, T.W. Swetnam. 2006. Warming and earlier spring increase Western U.S. wildfire activity. *Science* 313 (5789): 940-943.

Williams, D. and A. Liebhold. 2002. Climate change and the outbreak ranges of two North American bark beetles. *Agricultural and Forest Entomology* 4 (2): 87-99.

Williams, J.W and S.T Jackson. 2007. Novel climates, no-analog communities, and ecological surprises. *Frontiers in Ecology and the Environment* 5 (9): 475–482.

Wilson, J. 2004. Vulnerability to wind damage in managed landscapes of the coastal Pacific Northwest. *Forest Ecology and Management* 191 (1-3): 341-351.

Zhu, K., C.W. Woodall, J.S. Clark. 2011. Failure to migrate: Lack of tree range expansion in response to climate change. *Global Climate Change* 18 (3): 1042-1052.

Chapter 9

Effects of Climate Change on Fisheries and Aquaculture in the Southeast USA

LEAD AUTHOR

Julie A. Anderson (janderson@agcenter.lsu.edu; Louisiana State University Agricultural Center and Louisiana Sea Grant, Baton Rouge, Louisiana)

CONTRIBUTING AUTHORS

Shirley M. Baker (University of Florida, IFAS School of Forest Resources and Conservation; Gainesville, Florida)

Gary L. Graham (Texas Sea Grant Program, Texas A&M University; Palacios, Texas)

Michael G. Haby (Texas Sea Grant Program, Texas A&M University; Corpus Christi, Texas)

Steven G. Hall (Louisiana State University and Louisiana State University Agricultural Center; Baton Rouge, Louisiana)

LaDon Swann (Mississippi-Alabama Sea Grant Consortium; Auburn, Alabama)

William C. Walton (Auburn University and Alabama Cooperative Extension System; Dauphin Island, Alabama)

Charles A. Wilson (Louisiana Sea Grant College Program and Louisiana State University; Baton Rouge, Louisiana)

In the Southeast (SE), commercial fishing, recreational fishing, and aquaculture sectors are diverse and widespread. They provide a large economic benefit as well as providing sources of food, baitfish, and ornamental organisms for the rest of the nation. Many of the species and infrastructure are likely to be heavily affected by climate change as has already been seen throughout the region.

Key Findings

- As land loss continues from sea level rise, subsidence, and coastal inundation, vital habitat for juvenile estuarine finfish and crustacean shellfish is lost; fisheries production will also decrease.
- Most fish species have a fairly narrow range of optimum temperatures. Depending on the species, the area occupied may expand, shrink, or be relocated with changes in ocean temperatures. Extinctions are predicted to occur where dispersal ability is limited or suitable northward habitat is unavailable (e.g., Gulf of Mexico).
- Chronic exposure to hypoxia and fluctuating oxygen concentrations impairs reproduction, immune responses, and growth. Hypoxic events are predicted to increase from increased run-off, droughts, and increased temperatures.
- Severe tropical storms negatively affect fishery species through increased pollution run-off, direct storm damage, flooding, saltwater intrusion from storm surge, and habitat loss. In addition, the fishing and aquaculture industries can be devastated by the damage and loss of infrastructure including boats, docks, marinas, equipment, processing plants, and distribution centers.
- The potential effects of climate changes on molluscan shellfish fishing and aquaculture are significant and complex. Changes in distribution could occur on decadal time periods based on multiple parameters including temperature, ocean pH and local acidification, sea level rise, and saltwater intrusion.
- Warming water temperatures may lead to an increase in foodborne and waterborne pathogens associated with molluscan shellfish harvest and consumption.
- Designing adequate mitigation and adaptation strategies for fisheries management will require continued monitoring, research, and predictive modeling. Existing practices such as more efficient gear technology, direct marketing, monitoring, diversified effort, and carbon sequestration options support adaptation or mitigation, but they are not all widely adopted.

9.1 Background

This chapter covers major fishery and aquaculture systems in the Southeast (SE) region beginning with the value and importance of existing systems, the predicted effect from climate change, and adaptions currently underway or that may be taken in the future. Information includes the research needs necessary to increase societal resiliency to climate change. Not all fisheries and sectors in the region are discussed; those highlighted are known to be vulnerable to climate change. Many of the ecosystem impacts are covered more thoroughly in the natural ecosystem chapter. Some of these gaps in coverage are addressed in the research needs portion, and these topics should be included in future assessments.

Commercial Fishing

Commercial fishing in the SE consists of freshwater fisheries in reservoirs, lakes, and river systems for sport fish (Florida Fish and Wildlife Conservation Commission, personal communication). Commercial fishing for marine species using seines, hook-and-line, cast nets, gill nets, tongs, and other gear types is conducted in state and federally managed waters. Primary commercial marine species include blue crab, stone crab, crawfish, shrimp, scallops, oysters, clams, menhaden, flounder, groupers, mackerels, mullets, red snapper, striped bass, and tunas.

Commercial fishing is a major economic enterprise in the SE and specifically in the Gulf of Mexico. Commercial fishing in the SE has been valued at $787 million in dockside sales with more than 800,000 metric tons landed in 2010 (National Marine Fisheries Service 2010). According to the National Ocean Service (NOS 2011), five of the top ten ports by poundage are in Louisiana (three), Virginia (one), and Mississippi (one) for a combined 1,765 million pounds annually. Louisiana and Virginia also each has one of the top ten ports by value. Gulf of Mexico coastal wetlands produce an annual shellfish harvest worth $474 million (NOS 2011). These areas are expected to be heavily affected by climate change in the SE (NOS 2011).

In the Caribbean, Puerto Rico and the US Virgin Islands landed 2,745 tons of marine finfish, crustaceans, and molluscs in 2010. Most of these fisheries are divided between trap/pots, line, net, hand collection, and spearfishing (FAO 2012). The small nature of the fishery operations and boats makes them susceptible to damage from tropical storms (Norri and Taylor 2011).

Recreational Fishing

Primary marine recreational species in the SE are striped bass, bluefish, black sea bass, spotted seatrout, yellowfin tuna, dolphin fish, red grouper, red snapper, yellowtail snapper, sheephead, flounder, Spanish mackerel, and Atlantic croaker. The most sought after freshwater recreational species are largemouth bass, sunfishes, trout, and catfish. Recreational fishing occurs in most natural bodies of water and many constructed impoundments. The SE has thousands of kilometers of rivers and streams and thousands of hectares of natural lakes and constructed impoundments.

The combined marine and freshwater recreational fishing industry in the USA was valued at $42 billion in 2006 (US Fish and Wildlife Service of Interior et al. 2006). Total marine fishing trip and durable equipment expenditures across the Mid-Atlantic, South Atlantic, and Gulf of Mexico regions in 2009 totaled approximately $19 billion (National Marine Fisheries Service 2010). Florida has the largest freshwater fishing industry of any state. Combined, the saltwater and freshwater sectors contributed more than $6.1 billion to that state's economy in 2006 (Florida Fish and Wildlife Conservation Commission 2011).

Aquaculture

The most recent estimate of farm-gate sales of freshwater and marine aquaculture in the 11 states of the SE region is approximately $740 million (Census of USDA 2005). The primary food species farmed in the SE include clams, crawfish, oysters, soft-shell crawfish and crabs, alligators, catfish, striped bass, tilapia, and trout. The production of food organisms is the most common form of aquaculture practiced in the USA. However, all SE states also have bait farms, sometimes known as minnow or crawfish farms. Species of fish and crustaceans produced include golden shiners, fathead minnows, shrimp, goldfish, suckers, and crawfish.

In addition to those species already mentioned, more than 800 species of ornamental fish are cultured for the aquarium trade, primarily in Florida (Hill and Yanong 2010). The ornamental fish, aquatic plant, and snail industry may be divided into two types: tropical and cool-water species. The tropical fish and aquatic plant industry originated in South Florida where annual temperatures are similar to those of the plant or animal's native range. Other varieties of ornamental fish cultured are the goldfish and the koi carp, which are cool-water species. In addition to growing ornamental fish, some farmers grow fish for use as "feeders" for larger aquarium fish. In addition, raising aquaculture products for educational and research biological supply houses covers a broad range of organisms from algae to turtles. Louisiana also has a thriving pet turtle aquaculture industry.

The production of sportfish to stock the farm, city, and county ponds and lakes in the SE is another aquaculture sector. Many combinations of fish are suitable for stocking in ponds and lakes. Some of the more commonly cultured species are largemouth bass, bluegill, redear sunfish, hybrid sunfish, channel catfish, bullhead, trout, crappie, walleye, yellow perch, fathead minnow, bluntnose minnow, and golden shiner. In the Caribbean, Puerto Rico, and the US Virgin Islands aquaculture includes freshwater ornamental fish, tilapia, pacu, prawns, and Pangasius. In 2010, Puerto Rice produced 17 tons of aquaculture species, and the US Virgin Islands produced 10 tons (FAO 2012).

Production methods. When describing aquatic production systems, names of systems refer to the type of water-holding facility in which the organisms are grown. Several kinds of water facilities are used for growing fish in the SE, including ponds, cages, raceways, and recirculating systems (Swann 1992). The most common production system in use is the earthen pond and may include simple small farm ponds in addition to those specifically designed and built for aquaculture. Cage culture of fish uses existing water resources, lakes or ponds, with the fish enclosed in cages or baskets, which allows water to pass freely between the fish and the water body. A raceway production facility requires large quantities of inexpensive high quality water. The water is normally obtained from a spring or stream and is passed through the raceways using gravity. Recirculating raceway facilities reduces water consumption.

9.2 Climate Change Effects

The metabolism of fish, crustaceans, and bivalves is influenced by a variety of water quality parameters including temperature, salinity and pH. Aquatic organisms have evolved to adapt to daily fluctuations in these parameters (Willmer et al. 2000); however, future climate variation of temperature, for example, may have a significant influence on the metabolism of these organisms. Most freshwater and marine fish, crustaceans, and bivalves are non-thermoregulating ectotherms; they are unable to regulate their body temperature and, therefore, their internal temperatures match the environment. On an acute time scale, the metabolic rate of ectotherms increases approximately exponentially with temperature (Willmer et al. 2000). For example, the metabolic rate of a clam may double with every 7°C to 10°C increase in water temperature. This increase in metabolic rate has important implications for energy use, growth efficiency, and upper lethal limits (Gosling 2003). Temperature, photoperiod, and in the case of marine organisms, salinity also regulate reproduction. Many of these factors are linked, and altering temperature at different times of year (photoperiod) could drastically affect spawning, mating, and growth of many species (Munro et al. 1990).

Observed changes in species distributions begin at the base of the food web: primary producers. Long-term studies begun in 1958 indicate that climate change has altered primary production in the North Atlantic Ocean. Phytoplankton abundance has increased in the cooler regions (north of 55°N) and decreased in warmer regions (south of 50°N) (Richardson and Schoeman 2004, Sarmiento et al. 2005). Although both regions have experienced warming, reductions in primary productivity in the southern region of the North Atlantic Ocean are due to a warming-induced reduction in vertical mixing and the resulting nutrient limitation (Richardson and Schoeman 2004, Sarmiento et al. 2005).

Impacts on phytoplankton have likely influenced other parts of ecosystems through the food web. The planktonic phases of fish life cycles are particularly vulnerable to impacts of unsuitable or insufficient food. Therefore climate-induced changes in productivity may alter the distribution and phenology of fish larvae and, ultimately, recruitment and production of fish stocks through impacts on growth, survival, and reproduction (Beaugrand et al. 2002 and 2003). More data on the effects of climate change on primary productivity in the Mid-Atlantic Ocean and the Gulf of Mexico are necessary to assess these potential impacts on stock distributions.

Finfish and Crustacean Shellfish

Fisheries for finfish and crustacean shellfish (i.e. crabs, shrimp, etc.) face many potential impacts from climate change. Below is a summary of how different threats from climate change may impact these fisheries.

Wetland loss and sea level rise. Sea level rise will be a significant aspect of climate change effects. Currently, the Southeast Atlantic and Florida experience a relative increase of 2.5 mm per year while Louisiana has relative sea level rise rates of 9.5 mm per year. Climate change could increase global mean sea level rise 20 cm to 200 cm over the next 100 years (see Chapter 2, Section 2.3.8). Currently Louisiana's wetland loss represents about 90% of coastal wetland loss nationally, yet Louisiana has still seen a 6.4% per year increase in marine commercial landings since 1930. However, this increase is most likely due to the increasing land-water interface as a result of land loss. As large land masses are splintered, the total interface area increases due to the combined interface area of all the smaller pieces. However, continued erosion, subsidence, and sea level rise eventually result in the total loss of these splintered islands and reduced length of interface. Fisheries production will likely decrease as land loss continues and the scale tips to shrinking land-water interface, vital habitat for juvenile estuarine finfish and crustacean shellfish such as shrimp (Caffey and Schexnayder 2002, Browder et al. 1985).

While well-documented in Louisiana, all the SE coastal states face these threats. Menhaden, for example, depend on coastal wetlands or estuaries for part of their life cycle because they spawn all along the USA Atlantic coast and Gulf of Mexico in different months at different locations. After two months in the ocean the larvae are carried into the bays and estuaries by ocean currents, and from there they move into the rivers for several months before migrating back to the ocean. Most mature at two to three years and can live to age ten. Changes in ocean currents could disrupt larval transport into bays and estuaries. Additionally, salt water intrusion, coastal inundation, and land loss due to sea level rise in the Gulf of Mexico states may increase nursery habitat while sea level associated with global warming could flood nursery habitats in northern areas of the region, such as the Carolinas and Virginia, where spawning occurs in protected bays rather than on the shelf. Warmer ocean temperatures could also change menhaden adult migration patterns and spawning locations. In addition to being a fishery species, menhaden are an important food fish for many larger fish, and their reduced abundance and distribution would likely affect the populations of fish that prey on them (Aubrey and Emery 1993, Houde and Rutherford 1993, Jones 1994).

Temperature. A number of researchers have hypothesized the effects of climate change on fishes. Effects range from simple extension of native ranges migrating northward in response to the gradual warming of water to total year class failure (i.e., no survival to juveniles) and disappearance of populations due to interruption of reproductive cycles and offset of timing between predator and prey. Most fish species have a fairly narrow range of optimum temperatures related to specific basic metabolism per species, and in addition the food organisms have their own optimum temperature ranges. Depending on the species, the area it occupies may expand, shrink, or be relocated with changes in ocean temperatures. Warmer temperatures in estuaries would be associated with lower dissolved oxygen levels for larvae (Aubrey and Emery 1993, Houde and Rutherford 1993, Jones 1994). Research indicates that within and near oxygen-depleted waters, finfish and mobile macroinvertebrates, such as crustacean shellfish, experience negative effects that range from mortality to altered trophic interactions. Chronic exposure to hypoxia and fluctuating oxygen concentrations impairs reproduction, immune responses, and growth (Breitburg et al. 2009).

Changes in species distributions occur much more rapidly in the marine environment than in terrestrial systems (Rosenzweig et al. 2007), and there are many examples of distribution changes and migration phenology associated with climate change (Ware and Tanasichuk 1989, Sims et al. 2004, Perry et al. 2005, Pörtner and Knust 2007). For example, a number of tropical and subtropical fish species have shifted northwards along the continental slope of England, at rates matching plankton shifts of 50 km per year (Quero et al. 1998, Stebbing et al. 2002). The southern boundary of one North Sea species, the blue whiting (*Micromesistius poutassou*), has moved by as much as 816 km (ICES 2004, Perry et al. 2005). It should be noted that not all species move northward at the same rate or at all. These disconnected shifts of species in a system may have unpredictable consequences on, for example, trophic interactions of predators and prey (Murawski 1993, Edwards and Richardson 2004). Extinctions are predicted to occur where dispersal ability is limited or suitable northward habitat is unavailable (Thomas et al. 2004). Local extinctions have already occurred at the edges of some current fish ranges (Friedland et al. 2003). These species shifts and extinctions in other parts of the world suggest that similar changes in distribution could be occurring in the SE USA; more research is needed in this area.

Shifts in fish stock distributions are likely having social and economic consequences (Brander 2010). One economic impact of distributional shifts in some fishery species is the displacement of fishing pressure to other species. For example, as cod fisheries have declined due to fishing pressure, landings of shrimp, crab, and lobsters have risen (Parsons and Lear 2001). In fact, northern shrimp (*Pandalus borealis*) and lobster (*Homarus americanus*) populations have actually increased, possibly as a result of increased water temperatures and subsequent improvements in recruitment (Parsons and Colbourne 2000, Mann and Drinkwater 1994).

Storm severity. Recent modeling studies suggest that the frequency of major hurricanes (Categories 3 to 5) likely will increase in the future, while the overall number of tropical cyclones will likely decrease (See Chapter 2.4.6). An increase in tropical storm activity could have large impacts on the fishing and aquaculture industries. Many fished and cultured species are negatively affected by severe tropical storms through increased pollution run-off, direct storm damage, flooding, saltwater intrusion from storm surge, and habitat loss. In addition the fishing and aquaculture industries can be devastated by the damage and loss of infrastructure including boats, docks, marinas, equipment, processing plants, and distribution centers. These types of losses have already been documented throughout the SE after major storms (Figure 9.1).

Molluscan Shellfish

Molluscan shellfish include bivalves such as clams, oysters, scallops, and mussels that are fished or cultured for human consumption. These species are predominately sessile, or immobile, and face different effects from climate change than finfish and crustacean shellfish. Clams and oysters are of particular importance in the SE. For example, shellfish aquaculture products sold in 2005 from SE states were valued at $42 million—Louisiana and Florida were the largest contributors (USDA 2005). The effects of climate change on molluscan shellfish fisheries and aquaculture are expected to be complex; some potential aspects are considered in the following sections.

Climate change is expected to affect the reproduction, health, and distribution of commercially harvested bivalve species within the Gulf of Mexico, as expected in other coastal marine systems (Harley et al. 2006, Hollowed et al. 2011). The potential effects of increased water temperature on molluscan shellfish fishing and aquaculture, in particular, are significant, potentially complex and highly variable (Allison et al. 2011). Bivalve ranges shift locally on a seasonal basis as freshwater flows ebb and flow. However, larger changes in range could occur on longer time periods based on multiple parameters. Among these are temperature, ocean pH and local acidification, and sea

Figure 9.1 A fishing vessel lies on its side near a wholesale fishing dock in St. Bernard Parish, Louisiana, after Hurricane Katrina. Adjacent infrastructure also suffered massive damage. Photo by Paula Ouder. Courtesy of Louisiana Sea Grant College Program.

level rise that may move coastal estuaries inland. Here the potential aspects of climate change that could influence molluscan shellfish are considered.

Increases in water temperature. Warmer water temperatures are expected to have effects on the physiology of species, leading to possible impacts on metabolism, reproduction, and species distribution in both marine and estuarine environments (Fields et al. 1993, Lubchenco et al. 1993). North Atlantic sea-surface temperatures are expected to show the greatest increases–up to 3°C by the end of the 21st century in the area eastward across the subtropics from South Florida and the Bahamas, and smaller increases across the Caribbean Sea and Gulf of Mexico (see Chapter 2, Section 2.4.7). Increased temperatures may allow tropically distributed species, including nonindigenous species such as the green mussel, *Perna viridis*, (currently established in Florida) to expand their ranges northward. Additionally, warming water temperatures may lead to an increase in foodborne and waterborne pathogens associated with molluscan shellfish harvest and consumption (Rose et al. 2001). Moreover, increased water temperatures may be associated with an increase in hypoxia events, which pose a significant threat to commercially harvested shellfish in the coastal waters of the Gulf of Mexico (Fogelson et al. 2011, Vaquer-Sunyer and Duarte 2008).

Sea level rise. Sea level rise is expected to have the greatest impacts on fisheries and aquaculture in areas of shallow water, such as Louisiana and much of the Gulf Coast, as estuarine locations could shift significantly. Blum and Roberts (2009) suggest the loss of tens of thousands of square kilometers of delta surface area in Louisiana alone. Rises in sea level may affect the distribution of established oyster reefs as well as the productivity and accessibility of privately leased oyster beds and clam farms.

Freshwater inputs and increased precipitation. Increased precipitation, predicted for parts of the SE is likely to increase freshwater inputs to estuarine and coastal areas, decreasing salinity. On the other hand, diversion of freshwater sources for human and agricultural uses may reduce freshwater inputs and increase salinity. Studies of El Niño-Southern Oscillation (ENSO) events support observations that salinity is a major factor affecting distribution of molluscan shellfish, and any changes in salinity are predicted to have significant consequences (Soniat et al 2006, Kim et al. 1999). Soniat et al. (2006) found that the oyster pathogen, *Perkinsus marinus* or Dermo, was associated with ENSO-driven increases in salinity. Conversely, Kim et al. (1999) suggested that ENSO-driven cycles can lead to increased levels of contaminants, such as pesticides and trace metals, and decreasing salinity with increased freshwater input. Studies of ENSO events can provide a model of what precipitation changes from climate change could mean to the region.

Ocean acidification. The effect of increased CO_2 concentrations in water and the resulting lower pH decreases the saturation state of calcium carbonate and leads to decreased calcification in marine organisms (Raven et al. 2005). Therefore, ocean acidification is expected to have major effects on molluscan shellfish fisheries and aquaculture and has already been linked to failures of shellfish spawning at Pacific coast hatcheries in the USA (Porter 2007, Kraines and Suzuki et al. 1996, Miller et al. 2009). Estuarine waters are less buffered than marine waters and are more susceptible to ocean acidification (Waldbusser et al. 2011). Experimental studies of larval growth and survival have indicated that predicted levels of acidification ($p$$CO_2$ up to 560 and 800 μatm) would lead to decreased growth and survival (Miller et al. 2009, Parker et al. 2009, Talmage and Gobler 2010). Miller et al. (2009) studied the Atlantic oyster (*Crassostrea virginica*) and found modest decreases in shell area and calcium content in specimens treated with two expected future CO_2 concentrations (up to approximately three times preindustrial CO_2 levels), compared to controls. However, oysters were able to continue to accrue some new shell, even in situations with limited amounts of aragonite, the most soluble form of calcium carbonate (Miller et al. 2009).

Severity of storms. The potential increase in the severity of tropical storms in the western Atlantic (Emmanuel et al. 2008), should such increase occur, could have devastating effects on both molluscan shellfish fisheries and aquaculture, as evidenced by the catastrophic effects of recent hurricanes within the Gulf of Mexico. Not only are animals directly affected, but fisheries and aquaculture infrastructure can be completely destroyed. The depression of oyster harvests in the northern Gulf of Mexico by Hurricane Katrina is one well-documented example of the effect of severe storms (NMFS Statistics Office, personal communication). Research is needed to assess the potential impacts of increased storm frequency and severity on molluscan fisheries and aquaculture.

Freshwater Fisheries and Aquaculture

All aquaculture species may face harmful effects from climate change. Increased temperatures may result in hypoxia in outdoor systems (see sea surface temperature, Chapter 2, Section 2.4.7). Outdoor systems near the coast face threats from sea level rise and inundation. All four types of facilities will face challenges due to climate change. Ponds will face threats from extreme temperatures, drought, and flooding and those near the coast will have the additional threats from saltwater intrusion and sea level rise. Drought and increased temperatures, which reduce dissolved oxygen levels, will likely threaten cage production because they increase the need for circulation to compensate. Both raceways and recirculating systems will need to contend with conflicting water uses which may reduce water availability for these facilities. Crawfish and alligators are important fishery and aquaculture species in the SE facing negative impacts by climate change. Sea level rise, reduced rainfall, or seasonal flooding would all have effects.

Although crawfish are fairly tolerant to saltwater, saltwater intrusion will negatively affect production. Tolerance to salinity is directly proportional to crawfish size. Salinity affects crawfish reproduction at much lower concentrations but the effect of continuous exposure to low salinity on crawfish reproduction is not fully known. If salinities higher than 3 ppt occur through most of the crawfish season, production will likely be negatively affected (McClain et al. 2007).

Alligator farmers depend on the collection of eggs from nests found in coastal or inland wetland habitats. Nesting efforts by female alligators are negatively affected by elevated salinity as well as high water levels during the spring prior to egg laying time. Stress levels increase as salinity increases causing female alligators to abort nesting when salinity reaches 8 to 10 ppt. Droughts along the coast and saltwater intrusion also may result in higher salinities. Nesting female alligators respond to high water events prior to nesting by building higher nests or moving to a higher site. High water events following egg laying result in drowning of the embryos should the eggs be submerged (Joanen and McNease 1989). Extreme precipitation events could lead to the submerging of nests (IPCC 2007).

If droughts increase in frequency as expected in parts of the SE, then decreased water levels, increased water temperature, and decreased dissolved oxygen may occur. An extreme drought like that in Texas and western Louisiana in the summer of 2011 resulted in large fish kills as reservoirs dried up and oxygen levels dropped. Nearly 124,000 fish were killed in just one lake, Lake Grapevine, a few miles northwest of Dallas (Texas Parks and Wildlife Department, personal communication). Other SE states could easily witness similar droughts. Additionally, reservoirs, farm ponds, aquaculture ponds and streams are all vulnerable to these climate change conditions.

9.3 Complicating Factors

SE fisheries and aquaculture are not closed systems operating without outside influence. Many factors, some discussed in this section, likely will influence the effects of climate change on these sectors.

The Gulf of Mexico Dead Zone

The Mississippi River captures runoff from 41% of the continental United States. As climate changes throughout the USA, changes in flows of the Mississippi River will affect the Gulf of Mexico. Since the 1970s a large hypoxic zone has been documented off the coast of Louisiana related to the Mississippi River's drainage. The oxygen levels in water there are so low that fish and shellfish often do not survive or must leave the area if possible. As flooding events increase and agricultural practices are adapted to climate change, the extent of the yearly dead zone is expected to increase. In 2010, the Dead Zone size was one of the largest ever recorded at 7,722 square miles (NOAA 2010). However, an increase in severe tropical storms could help offset this hypoxic zone with additional mixing of water (NOS 2011, Rabalais et al. 2009).

Harmful Algal Blooms

Harmful Algal Blooms (HABs) result from a rapid growth of *Karenia brevis* and other "red tide" organisms. An increase in nutrients from human-caused nutrient pollution often increases the prevalence of HABs resulting in fish kills, sea bird mortality, and human illness from contaminated shellfish. In Florida alone, HABs are estimated to cost $19 million to $32 million per year in economic damage (NOS 2011). Combinations of increased precipitation, runoff, and nutrient pollution will likely increase the frequency of HAB events, directly killing fish, affecting human and wildlife populations, and impacting the economics of the region.

Restoration Conflicts

In areas where fishers have already relocated to adapt to changes in catch location, such as in the upper reaches of the estuary in response to saltwater intrusion, restoration efforts to return natural tidal flows and salinity regimes can be in direct opposition to these fishers' adaptations. In coastal Louisiana, oyster fishers have moved their leases up the estuaries as saltwater intrusion has changed the oyster zones. Shrimp and crab fishers have started fishing further inland. Restoration such as freshwater diversions are designed to increase freshwater flow and return sediment to the wetlands. However, this freshwater lowers salinity detrimental to oyster leases and results in possible relocation of adult blue crabs and shrimp, forcing fishers and producers to adapt again to changes. Oyster lease relocation programs have, therefore, also been considered as part of the restoration (Caffey and Schexnayder 2002). Florida's clam industry faces these same challenges if there are shifts in salinity regimes due to climate change.

Water Use

Water is an essential resource for communities and for aquaculture. In Louisiana alone, $326 million is contributed to Louisiana's economy from aquaculture. However, this economic contribution requires a water investment, usually freshwater. If droughts increase in frequency as expected in parts of the SE, conflicts may arise over water use between communities and aquaculture producers throughout the SE. Best management practices will need to be encouraged for the most efficient use of water resources by all groups involved (Romaire et al. 2011).

9.4 Adaptation and Mitigation

Designing adequate mitigation and adaptation strategies for fisheries management will require continued monitoring, research, and predictive modeling. Existing adaption and mitigation practices exist which may help fisheries and aquaculture adjust to or even offset climate change factors. This section highlights specific concerns for adaptation and mitigation related to aquaculture and fisheries in the SE USA.

Species and systems will be impacted by other concurrent pressures—such as overfishing including age truncation and loss of genetic diversity, increased coastal storm activity, precipitation and runoff, habitat destruction, pollution, invasive species, and pathogens—making populations less resilient to unfavorable conditions related to climate (Knutson et al. 1998, Wolock and McGabe 1999, Brander 2005, 2007, and 2010, Planque et al. 2010). Some projections show that climate change may lead to local extinctions of exploited species, particularly in subpolar and tropical regions (Cheung et al. 2009). Designing adequate mitigation and adaptation strategies for fisheries management will require continued monitoring, research, and predictive modeling. Continued development of aquaculture production may contribute to future food security, although these systems are also likely to experience additional stresses due to climate change (See Chapter 9, Section 9.2.3)

Monitoring

Fishers and farmers adapting to some climate changes could be aided by increased use of weather and water condition monitoring systems in order to fish and harvest at optimal times. Offshore fishers could increase use of satellite weather and water conditions to help them decide if it is cost-effective to stay out on the water or head to port. In Florida, clam farmers currently have a water quality website (http://shellfish.ifas.ufl.edu/water_quality.html) to check wind speed, air and water temperature, and salinity prior to planting or harvest. This results in decreased fuel use and costs and, therefore, lowers emissions (University of Florida 2011).

Gear Efficiency

As fisheries face impacts from climate change, advances in gear technology may support adaptation through improving efficiency and economic resilience. Reducing drag on gear, and thereby fuel consumption, is one option to make the shrimp-trawl fishery more adaptable to a changing future. Reducing fuel expense and extending the intervals for various preventive maintenance activities may enable remaining operators to begin improving economic performance in the shrimp fishery. Efforts to reduce fuel use have also led to the ability to document a reduced carbon footprint. Experimental gear technology such as vented, cambered trawl doors; small-diameter, braided high-density, polyethylene (HDPE) webbing called Sapphire®; and Kaplan-style propellers could allow the industry to adapt to and mitigate effects of climate change. Results generated by co-operators across the Gulf and South Atlantic suggest that other fishers can expect somewhere between a 20% and 28% reduction in fuel use with the experimental fishing gear (Graham and Haby 2010). Fuel conservation and the reduction in fuel expense is, unequivocally, the largest savings attributable to the new gear, and it is immediate (Graham and Haby 2010).

Shifting Effort

The development of the hard clam aquaculture industry in Florida and other parts of the Gulf Coast is an excellent example of the efforts to shift from fishing to aquaculture. Former gillnet fishers who were no longer allowed to gillnet were trained in shellfish aquaculture, and the industry has become successful (Colson and Sturmer 2000). A shift to a new species or to a new sector (i.e., fishing to aquaculture) may be beneficial, but also involves costs for new resources. In selecting aquaculture species, however, an important consideration must be the degree of dependence on products from fisheries, such as fish meal and fish oil, for food supply. These fish products could also face threats from climate change (Naylor et al. 2000).

Carbon Sequestration

Use of bivalves for carbon sequestration may be plausible (Hall et al. 2011 and 2009, Lee et al. 2011). Mollusk shells sequester carbon, not directly from the atmosphere, but through algae consumption and uptake from the water column. Dehon (2010) studied the issue and concluded that oyster reefs could sequester geologically significant amounts of carbon. Use of artificial reefs for multiple functions has been explored by Hall et al. (2011) and many others. Natural or artificial reefs can become dominated by native oysters and can produce food and habitat, provide protection from erosion, aid in sedimentation, and be useful sustainable tools for estuarine management as well as carbon sequestration (Hall et al. 2011).

Some oyster cultivation in Florida combines commercial harvest and carbon sequestration (Baker 2011). The commercial culture of northern hard clams, *Mercenaria mercenaria*, in Florida is conducted in high-density lease areas, designated by the state in waters that were previously determined to be unproductive for shellfish. Clams grow rapidly in this environment and typically reach commercial size after about one year of growth in the leased areas. Clams are cultured in semi-rigid mesh bags, which provide hard substrata for fouling organisms on an otherwise soft-bottom environment. Market clams, however, accounted for only 70% of the bags. Nonharvested clams, oysters (*Crassostrea virginica* and *Ostrea equestris*), mussels (*Brachidontes* sp.) and barnacles (*Balanus* spp.), among other shell-bearing fauna, were recovered from both on and within the clam bags. With this material added, carbon sequestration estimates rose to 2.2-6.8 Mg ha^{-1} y^{-1} (Baker 2011).

Local Markets

Greater use of local markets may increase adaptive capacity for fishers and producers in several ways. By utilizing local markets, fishers and producers can reduce their fuel costs and emissions. Additionally, they can yield a high price per unit and be better able financially to adapt to lower catch, increased fuel costs, and variable weather from climate change. Some systems to support greater connection to local markets are emerging. For example, Delcambre Direct Seafood, Delcambre, Louisiana, uses the Internet to connect fishers with buyers who want to purchase directly off the boat. By the end of 2010, more than 20 vessels were enrolled and profiled in the Delcambre Direct network and buyer participation had risen to 675 subscribed individuals. Suppliers were reporting a steady and increasing number of requests for product and in many cases fishers reported having most or all of their catch sold prior to leaving port. On average, prices received via Delcambre Direct were 2.5 times greater than average dockside prices for commodity shrimp. Direct sales netted these fishers a $6,000 premium over dock prices annually (Hymel and Caffey 2011). In South Carolina, the interactive web-based tool MarketMaker, featuring a searchable database that connects consumers of South Carolina products with suppliers, was redesigned to include seafood and seafood products. The seafood component of MarketMaker serves all elements of the seafood industry (fishers, retail, distributor, and wholesaler) allowing each to create an online business profile highlighting the uniqueness of their products and businesses, and to choose from a nationally compiled list of seafood species and attributes to characterize their products on the sellers' side and specify their needs on the buyers' side (South Carolina Sea Grant Consortium 2012).

9.5 Research Needs

Aquaculture and fisheries are important economic drivers in the SE USA. For these industries to continue to grow and contribute to national food security, strategies must be adopted to mitigate the harmful impacts of climate change, such as sea level rise, coastal storm activity, freshwater inflow events, ocean temperature increase, and ocean circulation alteration (Scavia et al. 2002). However, interactions between climate change processes and anthropogenic factors, such as fishing pressure, are complex and may be unpredictable at our current level of understanding (Harley et al. 2006). Therefore, an active collaboration of ecologists, physiologists, geneticists, engineers, climatologists, oceanographers, economists, resource managers, and members of the fishery and aquaculture industries can be developed. Working together these groups can help prioritize and direct research efforts and policies of relevance to the aquaculture and fishery industries in the SE USA. All climate change predictions need to include ocean currents, sea surface and air temperatures, ocean acidification, land loss, sea level rise, oxygen concentrations, precipitation changes in frequency and intensity, and storm frequency and intensity. Some of the identified research needs are discussed in the following sections.

Impacts of Freshwater Inflow

There is great uncertainty regarding future rainfall and runoff patterns, especially in the Southeast. Additionally, as human populations grow or migrate, water use conflicts are likely to escalate.

Estuaries are particularly important for fisheries and aquaculture production, for example, serving as nursery grounds for larval fish and as the appropriate habitat for suspension-feeding shellfish. Physical impacts of inflow changes likely will include modified salinity regimes and estuarine stratification; increases in nutrient, sediment, and pollutant load to estuaries; and reduced freshwater availability for inland aquaculture (Kennedy 1990, Najjar et al. 2000). Potential biological impacts include changes in phytoplankton communities and increased eutrophication, resulting in expanded hypoxic or dead zones (Cloern 2001, Rabalais et al. 2002). Both physical and biological impacts of changes in freshwater inflow will interact with fisheries and aquaculture in the SE in complex ways and will require adaptation in the industries. Research examining possible coping strategies is currently lacking. In addition, developing reliable precipitation and inflow models for the SE, including the Gulf of Mexico, will aid future analyses.

Aquaculture Development

As capture fishery production moves northward or species go extinct at the southern edges of their ranges (Ware and Tanasichuk 1989, Friedland et al. 2003, Sims et al. 2004, Perry et al. 2005, Pörtner and Knust 2007), continued development of aquaculture may contribute to future food security. Local extinctions may be a particular problem in the Gulf of Mexico, where northward shifting species have nowhere to go. As a result, place-bound fishers may displace their activities to remaining species, resulting in the decline of these alternative species as well (Parsons and Lear 2001). Under that scenario, aquaculture development may become more important in the SE USA. Research examining methods of culturing new food fish and shellfish species, development of more efficient culture methods, and development of alternative feeds would aid development.

9.6 References

Allison, E.H., M.C. Badjeck, K. Meinhold. 2011. The implications of global climate change for molluscan aquaculture. In *Shellfish aquaculture and the environment*, ed. S.E. Shumway, 461-490. West Sussex, UK: John Wiley & Sons, Inc.

Aubrey, D.G. and K.O. Emery. 1993. Recent global sea levels and land levels. In *Climate and sea level change: Observations, projections and implications*, ed. R.A. Warrick, E.M. Barrow, and T.M.L. Wigley, 45-56. New York, USA: Cambridge University Press.

Baker, P. 2011. Long-term carbon fixation by molluscan aquaculture. Paper presented at the Coastal and Estuarine Research Federation 21st Biennial Conference, Daytona Beach, FL, November 6-11, 2011.

Beaugrand, C., P.C. Reid, F. Ibañez, J.A. Lindley, M. Edwards. 2002. Reorganization of North Atlantic marine copepod biodiversity and climate. *Science* 296 (5573): 1692-1694.

Beaugrand, C., K.M. Brander, J.A. Lindley, S. Souissi, P.C. Reid. 2003. Plankton effect on cod recruitment in the North Sea. *Nature* 426 (6967): 661-664.

Blum, M.D., H.H. Roberts. 2009. Drowning of the Mississippi Delta due to insufficient sediment supply and global sea-level rise. *Nature Geoscience* 2 (7): 488-491.

Brander, K. 2005. Cod recruitment is strongly affected by climate when stock biomass is low. *ICES Journal of Marine Science* 62 (3): 339-343.

Brander, K. 2007. Global fish production and climate change. *Proceedings of the National Academy of Science of the United States of America* 104 (50): 19709-19714.

Brander, K. 2010. Impacts of climate change on fisheries. *Journal of Marine Systems* 79 (3-4): 389-402.

Breitburg, D.L., D.W. Hondorp, L.A. Davias, R.J. Diaz. 2009. Hypoxia, nitrogen and fisheries: Integrating effects across local and global landscapes. *Annual Reviews in Marine Science* 1 (2009): 329-349.

Browder, J.A., H.A. Bartley, K.S. Davis. 1985. A probabilistic model of the relationship between marshland-water interface and marsh disintegration. *Ecological Modeling* 29 (1-4): 245-260.

Caffey, R.H. and M. Schexnayder. 2002. *Fisheries implications of freshwater reintroductions.* Baton Rouge, LA: LSU AgCenter. http://lacoast.gov/new/Data/Reports/ITS/Fish.pdf

Cheung, W.W.L., V.W.Y. Lam, J.L. Sarmiento, K. Kearney, R. Watson, D. Pauly. 2009. Projecting global marine biodiversity impacts under climate change scenarios. *Fish and Fisheries* 10 (3): 235-251.

Cloern, J.E. 2001. Our evolving conceptual model of the coastal eutrophication problem. *Marine Ecology Progress Series* 210 (2001): 223-253.

Colson, S. and L.N. Sturmer. 2000. One shining moment known as Clamelot: The Cedar Key story. *Journal of Shellfish Research* 19 (1): 477-480.

Dehon, D.D. 2010. *Investigating the use of bioengineered oyster reefs as a method of shoreline protection and carbon storage. Master's Thesis*. Baton Rouge, LA: Louisiana State University. http://etd.lsu.edu/docs/available/etd-04272010-175047/unrestricted/Dehon_thesis.pdf

Edwards, M., A.J. Richardson. 2004. Impact of climate change on marine pelagic phenology and trophic mismatch. *Nature* 430 (7002): 881-884.

FAO (Food and Agriculture Organization of the United Nations). 2012. Global Capture Production dataset http://www.fao.org/fishery/statistics.

Fields, P.A., J.B. Graham, R.H. Rosenblatt, G.N. Somero. 1993. Effects of expected global climate change on marine faunas. *Trends in Ecology and Evolution* 8 (10): 361-367.

Florida Fish and Wildlife Conservation Commission. 2011. The economic impact of freshwater fishing in Florida. http://myfwc.com/conservation/value/freshwater-fishing/.

Fogelson, S.B., F.S. Rikard, Y. Brady, R.K. Wallace. 2011. Histopathology of the digestive tissues and whole-body anaerobic bacteria counts of the Eastern oyster, *Crassostrea virginica*, after experimental exposure to anoxia. *Journal of Shellfish Research* 30 (3): 627-634.

Friedland, K.D., D.G. Reddin, J.R. McMenemy, K.F. Drinkwater. 2003. Multidecadal trends in North American Atlantic salmon (*Salmo salar*) stocks and climate trends relative to juvenile survival. *Canadian Journal of Fisheries and Aquatic Sciences* 60 (5): 563-583.

Furuhashi, T., C. Schwarzinger, I. Miksik, M. Smrz, A. Beran. 2009. Molluscan shell evolution with review of shell calcification hypothesis. *Comparative biochemistry and physiology part B: Biochemistry and molecular biology* 154 (3): 351-371.

Gosling, E. 2003. *Bivalve molluscs: Biology, ecology and culture*. Malden, MA: Blackwell Publishing.

Graham, G.L. and M.G. Haby. 2010. Measures to Enhance Fuel Efficiency in the Subtropical Shrimp-Trawl Fishery. Paper presented at the Energy Use in Fisheries Symposium: Improving Efficiency and Technological Innovations from a Global Perspective, Seattle, Washington, November 14 -17, 2010.

Hall, S.G., J.D. Risinger, A. Lutz, J. Farlow. 2011. Ecological engineering of artificial oyster reeds to enhance carbon sequestration via the algae-oyster complex. Paper presented at the 2011 ASABE International Meeting. Louisville, Kentucky, August 7-10, 2011. http://elibrary.asabe.org/azdez.asp?JID=5&AID=37340&CID=loui2011&T=2

Hall, S.G., R.R. Beine, T. Ortego, M. Campbell, M. Turley. 2009. Bioengineered reefs to enhance natural fisheries and culture eastern oyster (*Crassostrea virginica*) in the Gulf of Mexico. In *Fisheries, Aquaculture and Biotechnology*, ed. N. Thangadurai, S.G. Hall, A. Manimekalan, and G. Mocz, 27-34. Bikaner, India: Agrobios (India).

Harley, C.D.G., A.R. Hughes, K.M. Hultgren, B.G. Miner, C.J.B. Sorte, C.S. Thornber, L.F. Rodriguez, L. Tomanek, S.L. Williams. 2006. The impacts of climate change in coastal marine systems. *Ecology Letters* 9 (2): 228-241.

Hill, J.E. and R.P.E. Yanong. 2010. *Freshwater ornamental fish commonly cultured in Florida.* Ruskin, FL: Institute of Food and Agricultural Sciences.

Hollowed, A.B., M. Barange, S. Ito, S. Kim, H. Loeng, M.A. Peck. 2011. Effects of climate change on fish and fisheries: Forecasting impacts, assessing ecosystem responses, and evaluating management strategies. *ICES Journal of Marine Science* 68 (6): 984-985.

Houde, E.D. and E.S. Rutherford. 1993. Recent trends in estuarine fisheries: Predictions of fish production and yield. *Estuaries* 16 (2): 161-176.

Hymel, T. and R.H. Caffey. 2011. Louisiana direct development of coastal marketing networks. Grant submitted to oil disaster recovery program direct marketing outreach fund, 1-12.

ICES Advisory Committee on Fishery Management. 2004. *Report of the Working Group on Northern Pelagic and Blue Whiting Fisheries*. Copenhagen, Denmark: ICES. http://www.ices.dk/reports/ACOM/2007/WGNPBW/ACFM2907.pdf

IPCC (Intergovernmental Panel on Climate Control). 2001. *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. New York and United Kingdom: Cambridge University Press.

IPCC (Intergovernmental Panel on Climate Control). 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* New York and United Kingdom: Cambridge University Press.

Joanen, T. and L.L. McNease. 1989. Ecology and physiology of nesting and early development of the American alligator. *American Zoologist* 29 (3): 987-998.

Jones, G. 1994. Global warming, sea level change and the impact on estuaries. *Marine Pollution Bulletin* 28 (1): 7-14.

Kennedy, V.S. 1990. Anticipated effects of climate change on estuarine and coastal fisheries. *Fisheries* 15 (6): 16-24.

Kim, Y., E.N. Powell, T.L. Wade, B.J. Presley, J.M. Brooks. 1999. Influence of climate change on interannual variation in contaminant body burden in Gulf of Mexico oysters. *Marine Environmental Research* 48 (4-5): 459-488.

Knutson, T.R., R.E. Tuleya, Y. Kurihara. 1998. Simulated increase of hurricane intensities in a CO2 warmed climate. *Science* 279 (5353): 1018-1021.

Kraines, S. and Y. Suzuki. 1996. Separating biological and physical changes in dissolved oxygen concentration in a coral reef. *Limnology and Oceanography* 41 (8): 1790-1799.

Lee, S.W., S.H. Lee, Y.N. Jang, K.S. Lim, S.K. Jeong. 2011. CO_2 sequestration using principles of shell formation. *The Canadian Journal of Chemical Engineering* 89 (3): 555-561.

Lowther, A. 2011. *Fisheries of the United States 2010*. Silver Spring, MD: National Marine Fisheries Service http://www.st.nmfs.noaa.gov/st1/fus/fus10/FUS_2010.pdf.

Lubchenco, J., S.A. Navarrette, B.N. Tissot, J.C. Castilla. 1993. Possible ecological response to global climate change: Nearshore benthic biota of northeastern Pacific coastal ecosystems. In *Earth system responses to global climate change: Contrasts between North and South America*, ed. H.A. Mooney, E.R. Fuentes and B.I. Kronberg, 147-166. San Diego, CA: Academic Press.

Mann, K.H. and K.F. Drinkwater. 1994. Environmental influences on fish and shellfish production in the Northwest Atlantic. *Environmental Reviews* 2 (1): 16-32.

McClain, W.R., R.P. Romaire, C.G. Lutz, M.G. Shirley. 2007. *Louisiana crawfish production manual*. Rayne, LA: Louisiana State University Agricultural Center. http://www.lsuagcenter.com/NR/rdonlyres/3AD14F0D-567D-4334-B572-D55D1C55A1F1/34429/pub2637CrawfishProductionManualLOWRES.pdf

Miller, A.W., A.C. Reynolds, C. Sobrino, G.F. Reidel. 2009. Shellfish face uncertain future in high CO_2 world: Influence of acidification on oyster larvae calcification and growth in estuaries. *PLOS One* 4 (5): e5661. doi:10.1371/journal.pone.0005661.

Munro, A.D., A.P. Scott, T.J. Lam. 1990. *Reproductive seasonality in teleosts: Environmental influences*. Boca Raton, FL: CRC Press, Inc.

Murawski, S.A. 1993. Climate change and marine fish distributions: Forecasting from historical analogy. *Transactions of the American Fisheries Society* 122 (5): 647-658.

Najjar, R.G., H.A. Walker, P.J. Anderson, E.J. Barro, R.J. Bord, J.R. Gibso, V.S. Kennedy, C.G. Knight, J.P. Megonigal, R.E. O'Connor, C.D. Polsky, N.P. Psuty, B.A. Richards, L.G. Sorenson, E.M. Steele, R.S. Swanson. 2000. The potential impacts of climate change on the mid-Atlantic coastal region. *Climate Research* 14 (3): 219-233.

National Assessment Synthesis Team. 2001. Climate change impacts on the United States: The potential consequences of climate variability and change. Cambridge, UK: Cambridge University Press.

National Marine Fisheries Service. 2010. *Fisheries economics of the United States 2009: Economics and sociocultural status and trends series*. Silver Spring, MD: NOAA Fisheries. https://www.st.nmfs.noaa.gov/st5/publication/econ/2009/FEUS%202009%20ALL.pdf

Naylor, R.L., R.J. Goldburg, J.H. Primavera, N. Kautshy, M.C.M. Beveridge, J. Clay, C. Folke, J. Lubchenco, H. Mooney, M. Troell. 2000. Effect of aquaculture on world fish supplies. *Nature* 405 (6790): 1017-1024.

NOAA (National Oceanic and Atmospheric Administration). 2010. http://www.noaanews.noaa.gov/stories2010/20100809_deadzone.html

NOAA (National Oceanic and Atmospheric Administration). 2011. Tides and Currents webpage. Sea levels online. http://tidesandcurrents.noaa.gov/sltrends/index.shtml. Accessed on October 28, 2011.

Noori, T., M. Taylor. 2011. Waves of change: a resource for environmental issues in the US Virgin Islands. University of the Virgin Islands.

NOS (National Ocean Service). 2011. *The Gulf of Mexico at a glance: A second glance*. Washington, DC: US Department of Commerce.

Parker, L.M., P.M. Ross, W.A. O'Connor. 2009. The effect of ocean acidification and temperature on the fertilization and embryonic development of the Sydney rock oyster *Saccostrea glomerata* (Gould 1850). *Global Change Biology* 15 (9): 2123-2136.

Parsons, L.S. and E.B. Colbourne. 2000. Forecasting fishery performance for northern shrimp (*Pandalus borealis*) on the Labrador Shelf (NAFO Divisions 2HJ). *Journal of Northwest Atlantic Fisheries Science* 27 (December): 11-20.

Parsons, L.S. and W.H. Lear. 2001. Climate variability and marine ecosystem impacts: A North Atlantic perspective. *Progress in Oceanography* 49 (1-4): 167-188.

Perry, A.L., P.J. Low, J.R. Ellis, J.D. Reynolds. 2005. Climate change and distribution shifts in marine fishes. *Science,* 308 (5730): 1912-1915.

Planque, B., J.M. Fromentin, P. Cury, K. Drinkwater, S. Jennings, R.I. Perry, S. Kifani. 2010. How does fishing alter marine populations and ecosystems sensitivity to climate? *Journal of Marine Systems* 79 (3-4): 403-417.

Porter, S.M. 2007. Seawater chemistry and early carbonate biomineralization. *Science* 316 (5829): 1302.

Pörtner, H.O. and R. Knust. 2007. Climate change affects marine fishes through the oxygen limitation of thermal tolerance. *Science* 315 (5808): 95-97.

Quero, J.-C., M.-H. Du Buit, J.-J. Vayne. 1998. Les observations de poissons tropicaux et le rechauffement des eaux dans l'Atlantique europeen. *Oceanological Acta* 21 (2): 345-351.

Rabalais, N.N., R.E. Turner, R.J. Díaz, D. Justić. 2009. Global change and eutrophication of coastal waters. *ICES Journal of Marine Science* 66 (7): 1528–1537.

Rabalais, N.N., R.R. Turner, D. Scavia. 2002. Beyond science into policy: Gulf of Mexico hypoxia and the Mississippi River. *BioScience* 52 (2): 129-142.

Raven, J., K. Caldeira, H. Elderfield, O. Hoegh-Guldberg, P. Liss, U. Riebesell, J. Shepherd, C. Turley, A. Watson. 2005. *Ocean acidification due to increasing atmospheric carbon dioxide.* London, UK: The Royal Society.

Richardson, A.J. and D.S. Schoeman. 2004. Climate impact on plankton ecosystems in the Northeast Atlantic. *Science* 305 (5690): 1609-1612.

Romaire, R.P., W.R. McClain, C.G. Lutz. 2011. Water resource use in Louisiana Aquaculture. *Louisiana Agriculture Magazine* Fall 2011: 32-33.

Rose, J.B., P.R. Epstein, E.K. Lipp, B.H. Sherman, S.M. Bernard, J.M. Patz. 2001. Climate variability and change in the United States: Potential impacts on water- and foodborne diseases caused by microbiologic agents. *Environmental Health Perspectives* 109 (2): 211-220.

Rosenzweig, C., G. Casassa, D.J. Karoly, A. Imeson, C. Liu, A. Menzel, S. Rawlins, T.L. Root, B. Seguin, P. Tryjanowski. 2007. Assessment of observed changes and responses in natural and managed systems. In *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson, 79-131. New York and United Kingdom: Cambridge University Press.

Sarmiento, J.L., R. Slater, R. Barber, L. Bopp, S.C. Doney, A.C. Hirst, J. Kleypas, R. Matear, U. Mikolajewicz, P. Monfray, J. Orr, V. Soldatov, S.A. Spall, R. Stouffer. 2005. Response of ocean ecosystems to climate warming. *Global Biogeochemical Cycles* 18, GB3003; doi: 10.1029/2003GB002134.

Scavia, D., J.C. Field, D.F. Boesch, R.W. Buddemeier, V. Burkett, D.R. Cayon, M. Fogarty, M.A. Harwell, R.W. Howarth, C. Mason, D.J. Reed, T.C. Royer, A.H. Sallenger, J.G. Titus. 2002. Climate change impacts on U.S. coastal and marine ecosystems. *Estuaries* 25 (2): 149-164.

Sims, D.W., V.J. Wearmouth, M.J. Genner, A.J. Southward, S.J. Hawkins. 2004. Low-temperature-driven early spawning migration of a temperate marine fish. *Journal of Animal Ecology* 73 (2): 333-341.

Soniat, T.M., J.M. Klinck, E.N. Powell, E.E. Hofmann. 2006. Understanding the success and failure of oyster populations: Climatic cycles and *Perkinsus marinus*. *Journal of Shellfish Research* 25 (1): 83-93.

South Carolina Sea Grant Consortium. 2012. Coastal Science@Work, E-newsletter, No. 1. Accessed at is http://www.scseagrant.org/Content/?cid=535#award.

Spero, H., J. Bijma, D.W. Lea, E.B. Bemis. 1997. Effect of seawater carbonate concentration on foraminiferal carbon and oxygen isotopes. *Nature* 390 (6659): 497-500.

Stebbing, A.R.D., S.M.T. Turk, A. Wheeler, K.R. Clarke. 2002. Immigration of southern fish species to the south-west of England linked to warming of the North Atlantic (1960-2001). *Journal of the Marine Biological Association of the UK* 82 (2): 177-180.

Swann, L. 1992. A basic overview of aquaculture: History, water quality, types of aquaculture and production methods. Illinois-Indiana Sea Grant Program Extension Bulletin AS-457 and IL-IN-SG-E-90-2. Purdue University. West Lafayette, IN. http://www.extension.iastate.edu/fisheries/publications/TB102.pdf

Talmage, S.C. and C.J. Gobler. 2010. Effects of past, present, and future ocean carbon dioxide concentrations on the growth and survival of larval shellfish. *Proceedings of the National Academy of Sciences of the United States of America* 107 (40): 17246-17251.

Thomas, C.D., A. Cameron, R.E. Green, M. Bakkenes, L.J. Beaumont, Y.C. Collingham, B.F.N. Erasmus, M.F. de Siqueira, A. Grainger, L. Hannah, L. Hughes, B. Huntley, A.S. van Jaarsveld, G.F. Midgley, L. Miles, M.A. Ortega-Huerta, A. Townsend Peterson, O.L. Phillips, S.E. Williams. 2004. Extinction risk from climate change. *Science* 427 (6970): 145-148.

USDA (U.S. Department of Agriculture). 2005. 2002 Census of Agriculture. http://www.agcensus.usda.gov/Publications/2002/Aquaculture/AQUACEN.pdf

US Fish and Wildlife Service. 2006. *2006 National Survey of Fishing, Hunting, and Wildlife-Associated Recreation.* Washington, DC: U.S. Department of the Interior. http://myfwc.com/media/131114/fhw06-nat.pdf.

UF (University of Florida). 2011. *Online resource guide for Florida shellfish aquaculture*. Cedar Key, FL: UF Shellfish Extension Office. http://shellfish.ifas.ufl.edu/water_quality.html

Vaquer-Sunyer, R., C.M. Duarte. 2008. Thresholds of hypoxia for marine biodiversity. *Proceedings of the National Academy of Sciences of the United States of America* 105 (40): 15452-15457.

Waldbusser, G.G., E.P. Voigt, H. Bergschneider, M.A. Green, R.I.E. Newell. 2011. Biocalcification in the Eastern oyster (*Crassostrea virginica*) in relation to long-term trends in Chesapeake Bay pH. *Estuaries and Coasts* 34 (2): 221-231.

Ware, D.M. and R.W. Tanasichuk. 1989. Biological basis of maturation and spawning waves in Pacific herring (*Clupea harengus pallasi*). *Canadian Journal of Fisheries and Aquatic Sciences* 46 (10): 1776-1784.

Willmer, P., G. Stone, I. Johnston. 2000. Environmental Physiology of Animals. Maldon, MA: Blackwell Science Ltd.

Wolock, D.M. and G.J. McCabe. 1999. Simulated effects of climate change on mean annual runoff in the conterminous United States. *Journal of the American Water Resources Association* 35 (6): 1341-1350.

Chapter 10

Impacts of Climate Change and Variability on Water Resources in the Southeast USA

COORDINATING LEAD AUTHOR

Ge Sun (gesun@fs.fed.us; Eastern Forest Environmental Threat Assessment Center, Southern Research Station, USDA Forest Service, Raleigh, North Carolina)

CONTRIBUTING AUTHORS

Sankar Arumugam (Department of Civil, Construction and Environmental Engineering, North Carolina State University, Raleigh, North Carolina)

Peter V. Caldwell (Eastern Forest Environmental Threat Assessment Center, Southern Research Station, USDA Forest Service, Raleigh, North Carolina)

Paul A. Conrads (US Geological Survey, South Carolina Water Science Center, Raleigh North Carolina)

Alan P. Covich (Odum School of Ecology, University of Georgia, Athens, Georgia)

James Cruise (Department of Civil and Environmental Engineering, University of Alabama- Huntsville, Huntsville, Alabama)

John Feldt (NOAA/NWS/SERFC, Peachtree City, Georgia)

Aris P. Georgakakos (School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, Georgia)

Richard T. McNider (Department of Atmospheric Science, University of Alabama in Huntsville, Huntsville, Alabama)

Steven G. McNulty (Eastern Forest Environmental Threat Assessment Center, Southern Research Station, USDA Forest Service, Raleigh, North Carolina)

Daniel A. Marion (Center for Bottomland Hardwoods Research, USDA Forest Service, Hot Springs, Arkansas)

Vasu Misra (Meteorology Department, Florida State University, Tallahassee, Florida)

Todd C. Rasmussen (Warnell School of Forestry and Natural Resources, The University of Georgia, Athens, Georgia)

Luigi Romolo (Department of Geography and Anthropology, Louisiana State University, Baton Rouge, Louisiana)

Adam Terando (Climate Change Science Center, North Carolina State University, Raleigh, North Carolina)

The Southeast (SE) and Caribbean encompasses of a large geographic region including 11 states, and Puerto Rico and US Virgin Island. The region is known for warm climate, abundant water resources, and rich ecosystems and biodiversity. Many areas of the SE have seen population increases between 45% and 75% during the past three decades. The population is projected to increase 50% in the next 50 years, representing one of the most dynamic economies in the nation (Wear and Greis 2011). The region relies on water resources to maintain this growing economy that is largely based on forestry, recreation, manufacturing, tourism, agriculture, power generation, fisheries, and navigation.

However, in recent decades the 'water rich' SE region has experienced periodic water shortages due to recurring severe droughts and the increasing levels of consumptive water use from multiple sources (Sun et al. 2008). Water stress is especially critical in the large metropolitan areas such as Atlanta and Charlotte. Thus, any additional stresses implied by climate changes are beginning to concern all economic sectors (Caldwell et al. 2012).

Climate change is hydrologic change. Water is essential to life. Hydrologic alterations due to climate change have profound impacts to ecosystems and society. The objectives of this chapter are (1) to document the consequences of climate change and variability in altering the quantity, quality, and timing of water supplies at multiple scales during the past and the next 50 years; (2) to present case studies showing how climate change has affected regional water resources; and (3) to discuss water resource management strategies to mitigate and adapt to climate change across the southeastern region.

Key Findings

- Future climate warming likely will increase water loss through evapotranspiration (ET) due to increased evaporative potential and plant species shift. Greater ET can decrease total streamflow, groundwater recharge, flow rate, and regional water supplies.
- Water supply stress is projected to increase significantly by 2050 due to hydrologic alteration caused by climate change and increased water use by key economic sectors, such as domestic water supply, irrigation agriculture, and power plants. Water supply stress will become most severe in the summer season when normal rainfall is typically not sufficient to meet evaporative demand of the atmosphere.
- Declining runoff and increasing demands for water resources are likely to increase the pressure on the existing reservoirs, leading to deeper and longer lasting drawdowns.
- Runoff and soil erosion potential are projected to increase in some areas due to changes in rainfall that either increase rainfall erosivity or decrease vegetative cover protection.
- Inland water temperature is projected to increase with increases in air temperature, resulting in possible adverse impacts on coldwater fish habitat in the Appalachians.

- Salinity intrusion in coastal fresh water systems likely will increase in response to sea level rise and potential decreases of fresh water inputs from uplands due to climate change.
- Ecosystem restoration, including afforestation, has the potential to mitigate or reduce adverse impacts of hydrologic extremes (droughts or floods) and water quality caused by climate change.
- Large knowledge gaps exist about how future climate change and other stressors—such as human population growth, land use change, energy security, and policy shifts—will interactively affect both surface and ground water availability.
- Consequences of proposed adaptation management options, such as increase in irrigated agriculture and bioenergy development, must be carefully evaluated to maximize their effectiveness and cost-benefit.

10.1 Water Resources in the Southeast

The 2009 National Climate Assessment suggests that droughts, floods, and water quality problems are likely to be amplified by climate change in the SE (Karl et al. 2009). More descriptions of climate change in the SE region can be found in Chapter 2 of this volume. Projected demographic and socioeconomic changes associated with rapid population growth further threaten water resources (Lockaby et al. 2011, Marion et al. 2012). Recent drought experience in many areas of the USA indicate that even small changes in drought severity and frequency may have major impact on agricultural production and ecosystem services, including drinking water supplies (Easterling et al. 2000). Unique to the SE are the 8000 km long, mostly populated, low-lying coastal areas that are vulnerable to salt water intrusion, flooding, erosion, water quality degradation, and wetland losses in addition to projected sea level rise and intensified tropical storms (Lockaby et al. 2011). Recent modeling studies suggest that the frequency of major hurricanes (Categories 3 to 5) likely will increase in the future, while the overall number of tropical cyclones will likely decrease (see Chapter 2). The devastating consequences of Hurricane Katrina in 2005 indicate the severity of what extreme climate impacts might be on coastal zones. The large range of hydrometeorological and socioeconomic characteristics across the region implies that responses to climate change in the SE require a multifaceted adaptation and mitigation management strategy (Marion et al. 2012).

10.2 Key Constraints to Water Resources in the Southeast

Changing Climate

Climate change alters stream water quantity and quality by altering hydrometeorological patterns, elevating ET potential, and disrupting biological processes. Climate variability, growing water demands, and limited storage capacity exacerbate the risk of water shortages during droughts. In addition, buildup of dissolved phosphorus and cyanobacteria in drinking water reservoirs and rivers is a major threat to public health (Meybeck 2004, Osidele and Beck 2004). Damage from tropical and winter storms has also increased dramatically. As a result, the region is faced with the need to develop new infrastructure, such as reservoirs and water treatment facilities; management strategies; and planning policies to respond to these challenges. Climate-related hazards, particularly tropical storms and drought, are the most frequently occurring natural hazards in the Caribbean. Projected increase of drought frequency is of vital concern for the Caribbean islands, which already have limited freshwater sources (Farrell et al. 2011).

Sea Level Rise

If global temperatures continue to increase, sea levels are expected to rise as much as 2 ft by 2050 in the coastal areas in the SE (Titus et al. 2009, Obeysekera et al. 2011). Water resources in coastal areas in Louisiana, Mississippi, Alabama, Florida, and the Caribbean Islands are vulnerable to saltwater intrusion and flooding. Some of the major economic and environmental consequences of saltwater intrusion into freshwater aquifers and drainage basins include the degradation of natural ecosystems and the contamination of municipal, industrial, and agricultural water supplies (Bear et al. 1999). Changes to patterns of coastal flooding as a result of sea level rise may increase damage to forests and wetlands, and property and infrastructure (Heimlich et al. 2009). In addition, sea level rise will have significant effects on river form and processes and may alter channel behavior far upstream of the estuaries and coastline.

Rising Water Use for Energy Generation

The relationship between water and energy, called the “water-energy nexus,” represents a critical business, security, and environmental issue (Glassman et al. 2011). The growing population and irrigated agriculture in the SE has increased the demand for energy by orders of magnitude over the past decades. Power production by nuclear, coal, gas, and hydropower is the largest overall user of water resources in the region (Kenny et al. 2009). Water availability is a large concern in the SE, especially during drought conditions when cumulative effects of thermal discharges reduce the assimilative capacity of streams and the sensitivity of aquatic organisms during periods of high temperatures and low dissolved oxygen (Webb et al. 2008). Loss of dissolved oxygen for aquatic species is further accelerated by eutrophication and the accumulation of nutrients from outdated wastewater treatment plants and agricultural fertilizer runoff from feed lots and eroding farmlands. Competition between water use for energy and other water uses, such as drinking water and irrigation, are most severe during droughts. During the 2007-2008 drought, water providers from Atlanta, GA, to Raleigh, NC, urged residents to conserve water while power plants struggled to avoid blackouts. In North Carolina, water woes forced Duke Energy to reduce output at its G.G. Allen and Riverbend coal plants on the Catawba River (Averyt et al. 2011). In Alabama, the Browns Ferry nuclear plant had to drastically reduce its output to avoid exceeding the river temperature limit and killing fish in the Tennessee River (Averyt et al. 2011).

Increasing Water Use for Irrigation

The 2008 US Farm Bill established the Agricultural Water Enhancement Program (AWEP) to encourage more efficient and effective irrigation and water conservation measures. In order to maintain a robust agricultural economy and food prices, there is a large potential to expand irrigated agriculture in the SE, especially in South Carolina and Alabama. Florida, Georgia, and Mississippi have substantially expanded irrigation in the last 40 years, but irrigation withdrawals impair summer stream flows and threaten riverine ecosystems. Increasing existing water storage is being considered as a potential strategy to restore environmental flows. For example, Alabama farmers have recently begun to build off- stream reservoirs to store water during the winter, when streamflows are greatest, for use during the spring and summer crop season (Curtis and Rochester, 2012).

Changing Land Use and Land Cover

The conversion of forest lands and wetlands to residential, commercial, industrial, and agricultural uses likely will exacerbate the impacts of climate change (Lockaby et al. 2011, Sun and Lockaby et al. 2012). For example, large areas of the North Carolina Pocosin system in the Atlantic Coastal Plain region have been modified into an extensive network of drainage canals to make agricultural production feasible in the normally hydric soils. These canals have altered the hydrology, lowered the water table, and increased the vulnerability of the system to long-lived fires. As the climate warms, droughts likely will be more severe, more frequent, or both, thus increasing the exposure to fires that can burn for many weeks (Liu et al. 2012). Climate change influences streamflows differently from land use change (Wang and Hejazi 2011). In the Appalachian region, the influence of recent climatic trends is larger than the influence of direct human impacts from urbanization or agriculture. However, in the Piedmont and Coastal Plain regions, direct human impacts on streamflow have generally been larger than the impacts of recent climatic trends (Wang and Hejazi 2011).

Insufficient Water Storage

Unlike the western USA, most of the reservoir-reliant water supply systems in the SE are within-year systems that store water during the high-flow fall and winter season and release it during the low-flow spring and summer season. The smaller size of these systems makes them more vulnerable to any substantial increase or decrease in annual runoff due to climate change. Detailed uncertainty analyses of climate change impact on the vulnerability of water supply systems are important tools for adaptation and mitigation. Currently, the high level of uncertainty in precipitation and runoff projections does not warrant application of projections for major long-term investment decisions, such as building a new reservoir to respond to drought or flood over the next 50 years. However, it is important to develop strategies to reduce the vulnerability of systems if projected climate changes occur or projections become more certain.

Unique Biodiversity

Native ecosystems in the SE are among the most diverse and unique in the world. Few areas on the planet have such biodiversity and few face as great a threat of destruction. Trying to reconcile regional development against the backdrop of fragile and fragmented ecosystems is a key sustainability issue (Richter et al. 2003). Allocating proper environmental streamflows is essential to protect the aquatic resources.

Unique Cultures

The racial legacy in the SE has left an imprint on educational institutions both from segregation and desegregation, and environmental perceptions. Trying to bridge the old versus the new South will require the development of communication and collaboration mechanisms that are relevant to important subcultures, not only the existing African-American and rural communities, but also the emerging Latin-American communities. In addition, there is increasing evidence that the poor and elderly in the SE have unequal access to natural resources, including water (John et al. 2012).

10.3 Historical Climate Trends

Observed and projected climate change in the SE is spatially complex due to the interacting influences of global climate change and natural large scale climate oscillations including El Niño-Southern Oscillation (ENSO), Atlantic Multi-decadal Oscillation (AMO) and the Pacific Decadal Oscillation (PDO) (Li L. et al. 2011, see Chapter 2). Across the region, mean air temperature increased 0.9°C between 1970 and 2008 (Karl et al. 2009). During the 20th century, annual rainfall amounts increased 20% to 30% or more for some portions of the SE, although other portions experienced declines in rainfall amounts. The amount of very heavy rainfall (more than 2 in per event) increased 15% to 20% from 1958 to 2007. The SE summer rainfalls have exhibited higher interannual variability with more frequent and intense summer droughts and anomalous wetness in the recent 30 years (1978 to 2007) than earlier in the 20th century (1948 to 1977) (Karl et al. 2009, Wang et al. 2010). The number of abnormally wet and dry summers in the SE region doubled over the last few decades (Li W. et al. 2011). As anthropogenic forcing continues to increase and the North Atlantic Subtropical High (NASH) climate system continues to intensify, the SE will experience more frequent wet and dry summers during positive Pacific Decadal Oscillation phases (Li W. et al. 2011). Average annual temperatures in the region are expected to increase by an additional 2.5°C to 3.5°C over the next 50 years (McNulty et al. 2012). More discussion about climate change in the SE can be found in Chapter 2.

10.4 Uncertainty in Predicting Future Climate and Hydrologic Impacts

Most global climate models (GCMs) predict that as the climate warms, the frequency of extreme precipitation will increase across the globe (O'Gorman and Schneider 2009). However, less than two-thirds of GCMs agree on the predicted change in direction of future precipitation events for the eastern USA (IPCC 2007). The uncertainty of predicting local, regional, global precipitation patterns at different temporal scale is well recognized (Chapter 2, Chan and Misra 2009, Misra et al. 2009).

Climate change impacts hydrologic processes and water resources directly through precipitation, evapotranspiration, groundwater recharge, peak flow, and water yield; and indirectly through water quality and water use by irrigation. Many of the responses are not unidirectional and can be additive or cancel each other. For example, increase in atmospheric CO_2 concentration may increase plant water use efficiency and reduce ET demand. But increase in air temperature is likely to increase potential water loss through ET and stimulate plant growth when soil moisture and nutrients are not limited. (See Chapters 7 and 11 for more details.) So the net hydrologic effects can be uncertain. Similarly, agricultural abandonment followed by reforestation tends to increase ET and reduce streamflows (Wu et al. 2007, Cruise et al. 2010), thus mitigating the impacts of extreme climate and hydrology (e.g., flooding) (Ford et al. 2011). Consequently, projections of timing and spatial distribution of climatic variables, such as radiation and cloudiness, and climate impacts on ET and precipitation remain difficult.

10.5 Water Resources Impacts of Climate Change

This section reviews historical trends and future projections for water quantity for average and extreme events, including low flow conditions and drought. The review then focuses on issues of water quality including temperature, erosion and sedimentation, impacts on aquatic biota and salinity intrusion.

Water Supply

Streamflow rates from 1940 to 1999 show statistically significant increasing trends in the Appalachians and Mississippi Alluvial Valley regions, and to a lesser extent in the Coastal Plain and Piedmont regions (Lins and Slack 1999, 2005). The increasing trends in streamflows occurred as a result of a steep increase in precipitation beginning around 1970 (Groisman et al. 2003, McCabe and Wolock, 2002).

The uncertainty of future climate and the interactive relationship between hydrological cycle and land use change and human water demand means the future of water supplies in the SE cannot be precisely predicted at this time (Sun et al. 2008, Caldwell et al. 2012). The Apalachicola-Chattahoochee-Flint (ACF) river basin in the three-state area of Alabama, Florida, and Georgia is one example of how climate change will interact with other factors such as land use changes. For example, for the Flint River Basin in Georgia, modeling results suggest a declining streamflow trend relative to current conditions (Viger et al. 2011, Walker et al. 2011, Georgakakos et al. 2010). However, under a "business-as-usual" scenario of continued urbanization, some of these streamflow declines may be offset due to increasing surface runoff from impervious surfaces.

Recently, Moreau (2007) provided an excellent review on the projected climate changes by various coupled global circulation models (CGCMs) over the SE. Moreau compared the change in precipitation suggested by various models from 1980 to 1999 and concluded that there is no agreement between the CGCMs on either the magnitude and the direction of change in precipitation over the SE. Most importantly, the review shows that the differences among CGCMs are largest during the summer season, which is the most critical for the SE water supply. Despite disagreements among models on precipitation, Krakauer and Fung (2008) argued that climate change will ultimately decrease future streamflows across the USA due to increased evapotranspiration.

Sankarasubramanian et al. (2001) predicted that streamflow in the SE would increase 2% for every 1% increase in precipitation, which was estimated based purely on the observed records of precipitation and temperature over the last 50 years. Bates et al. (2008) reported that the changes in runoff over many watersheds are not consistent with changes in precipitation. Milly et al. (2005) combined runoff downscaled from different climate models and also found that the streamflow over the SE is expected to increase 2% for a 1% increase in precipitation.

Multiple CGCMs and multiple scenarios are required to quantify the uncertainty in projections. For instance, it has been shown that combining multiple models optimally reduces model uncertainty and improves seasonal climate and streamflow forecasts (Devineni et al. 2008). Multimodel combination algorithms for reducing model uncertainty in atmospheric general circulation models (AGCMs) also has improved seasonal climate forecasts (Barnston et al. 2003, Devineni and Sankarasubramanian 2010). Greene et al. (2006) show that developing multimodel combinations of atmospheric-ocean global circulation models (AOGCMs) using Bayesian hierarchical modeling provide better correspondence with regional air temperature under climate change projections.

To understand water resource issues, both water supply and water demand must be examined simultaneously at a basin scale (Sun et al. 2008, Caldwell et al. 2012). The same study defined Water Supply Stress Index (WaSSI) as the ratio of human related water use by all economic sectors (for example, thermoelectric, irrigation, domestic water withdrawal) to the total water supply, such as surface and groundwater. Climate change affects both water supply and demand dynamics, thus greatly influencing WaSSI values. The importance of integrated climate assessments for water planning and management is exemplified in the Apalachicola-Chattahoochee-Flint case study presented later in this chapter (Georgakakos et al. 2010).

Groundwater is a major source for water supply and use, especially for costal areas in the SE (Kenny et al. 2009). As 'one water', surface water and groundwater are connected in many cases. Climate change and human influences on surface water also affect groundwater. This is especially true in regions, such as Florida, where karst topography creates a unique hydrogeology. There are many issues to consider for a comprehensive review of climate change and watershed management including groundwater withdrawal for domestic use and irrigation, inland wetland and coastal habitats, storm water management, and salt water intrusion (Heimlich et al. 2009).

Future projections for water yield. Using the mean water yield response output from four climate models, the CSIRO-A1B, CSIRO-B2, HAD-B2, and MIROC-A1B climate projections, the WaSSI model results project that annual water yield across the SE as a whole will decline in the first half of the 21st century (Caldwell et al. 2012, Marion et al. 2012). The annual decrease is predicted to be approximately 10 mm per decade (3.7% of 2001 to 2010 mean annual water yield) or 50 mm (18% of 2001 to 2010 levels) by 2060 (Figure 10.1). There is considerable interannual variability in the projected water yield, but the general trend is a statistically significant decrease ($p < 0.05$). Likewise, there is considerable variability in the magnitude of water yield changes among the four climate projections; however, all four projections considered in this study exhibited decreasing trends. The projected trend in the mean water yield varies considerably across the SE as well (Caldwell et al. 2012, Marion et al. 2012), with most watershed projections exhibiting statistically significant declining trends in mean water yield of more than 2.5% per decade (Figures 10.1 and 10.2). Across the region, the mean water yield trend is projected to decline between 2010 and 2025, level off between 2025 and 2045, and decline again after 2045 (Figure 10.1)

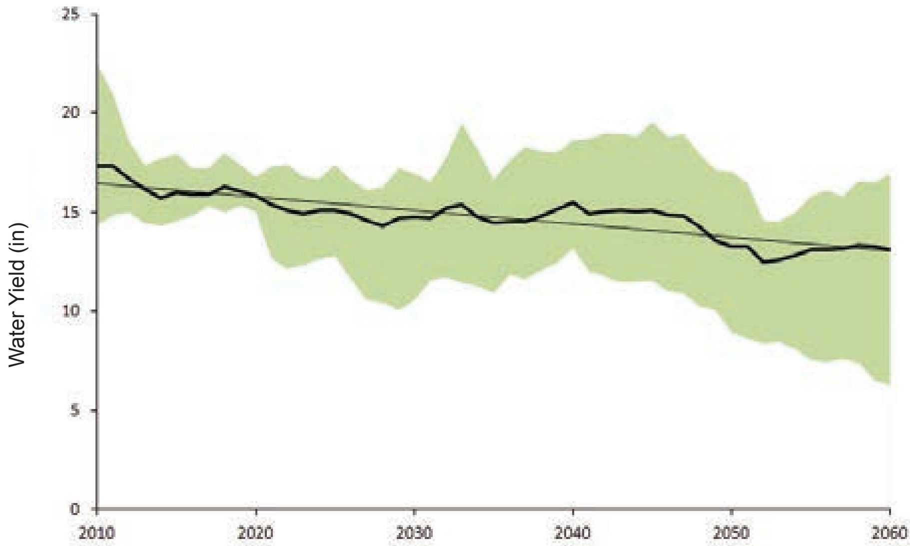


Figure 10.1 Predicted Southeast-wide 10-year moving-mean annual water yield. The wide green band represents the range in predicted water yield over the four climate projections (Marion et al. 2012).

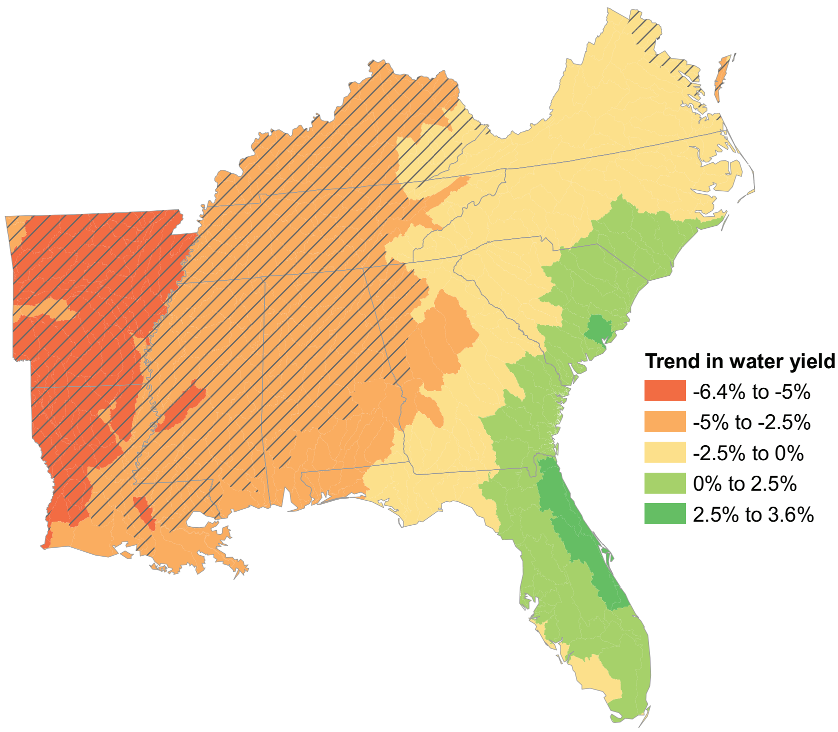


Figure 10.2 Mean trends predicted for 2010 to 2060 in mean annual water yield, normalized by the 2001 to 2010 mean annual water yield. Hatched area represents locations where the predicted trend in water yield is statistically significant ($p < 0.05$) (Marion et al. 2012).

Impacts on water stress. Population growth impacts water demand due to domestic water use, while land use and climate change affect water supply through alteration of the watershed water balances (Sun et al., 2008). The impact of declining water yield and increasing population is projected to increase water supply stress by 2060 in much of the SE, particularly in developing watersheds (Figure 10.3) (Caldwell et al. 2012, Marion et al. 2012). For example, the Upper Neuse River watershed, which provides water supply for the Raleigh-Durham, NC metropolitan area, is projected to experience a 14% decline in water yield due to climate change; at the same time, population growth likely will increase water demand by 21%. This simulation suggests an increase in WaSSI from 0.30 from 2001 to 2010 to 0.44 from 2051 to 2060. A WaSSI value of 0.40 has been used as a general threshold at which a watershed begins to experience water supply stress (Alcamo et al. 2000, Vörösmarty et al. 2000), although stress may occur at lower or higher values depending on local water infrastructure and management protocols.

Low Flows

Low flows levels are an integral component of a flow regime of any river and can occur seasonally or during drought (Smakhtin 2001). Low flows affected by climate change likely will have serious consequences for water supply to reservoirs, transportation, and power generation. In addition, water quality may also be affected in terms of, for example, dissolved oxygen concentration, water temperature, salinity, and nutrient levels, as well as the quality of aquatic habitat.

Previous studies suggested that the low flow characteristics have been changing variably across the SE. For example, Lins and Slack (1999; 2005) reported significant increasing trends in annual minimum and 10th percentile flows between 1940 and 1999 at most sites in the Appalachian-Cumberland, Mississippi Alluvial Valley, and Mid-South (MS) subregions while many sites in the Coastal Plain and Piedmont subregions exhibited significant decreasing trends in low flows. A case study on three forest-dominated headwater watersheds in the Lower Mississippi River Basin suggested that low flows were occurring more frequently over time as the watersheds have become drier in the past 60 to 90 years (Marion et al. 2012).

A continental watershed hydrologic simulation study with the WaSSI model (Sun et al. 2008) showed that monthly mean low flows were projected to decrease 6.1% per decade across the southern USA into the first half of the 21st century under various climate change scenarios (CSIRO-A1B, CSIRO-B2, HAD-B2, and MIROC-A1B); the largest decreases in flow magnitude in the study were in the Appalachian-Cumberland and Mississippi Alluvial Valley (MAV) subregions. The large projected decrease in the MAV was partially due to decreasing flows from streams outside of the study region (Marion et al. 2012).

Water Quality

Climate change affects both water quantity and quality through altering the hydrologic, energy, biogeochemical, and biological cycling of ecosystems. Water quality is highly coupled to water quantity discussed in the previous sections. This section focuses on key water quality parameters that are directly affected by climate change.

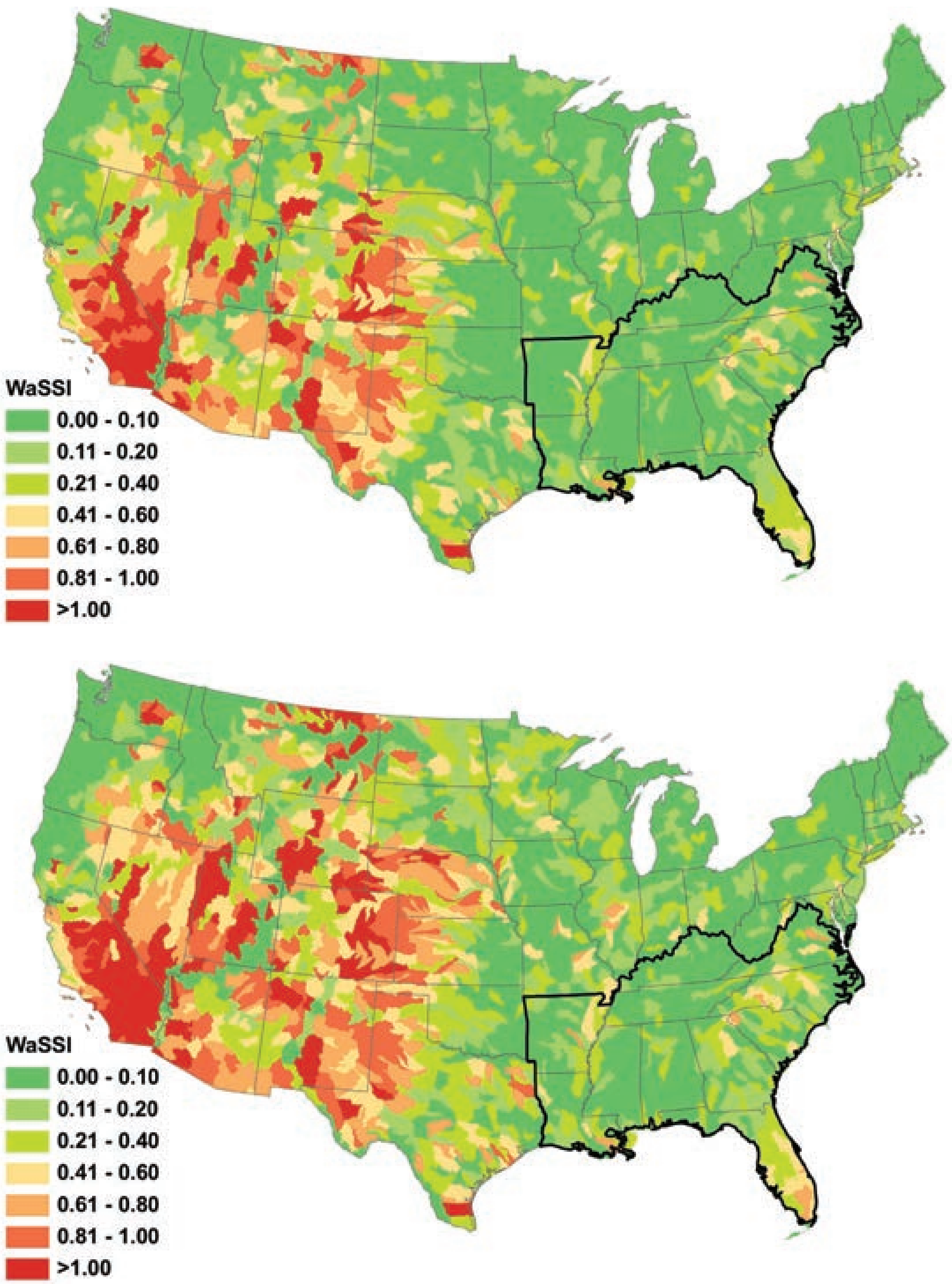


Figure 10.3 Mean annual Water Supply Stress Index (a ratio of water demand/water supply) based on four climate projections for (a) Baseline (2001 to 2010), and (b) Future (2051 to 2060) (Marion et al. 2012).

Water Temperature. Climate change affects water quality as well as water quantity (Cruise et al. 1999, Murdoch et al. 2000, Whitehead et al. 2009). A warming climate may elevate water temperature and decrease instream dissolved oxygen concentrations, which would adversely affect aquatic life (Mohseni and Stefan 1999, Webb et al. 2008, Kaushal et al. 2010). Warmer water is of particular concern for coldwater fish habitats for species such as Eastern Brook Trout (*Salvelinus fontinalis*) in the southern Appalachians. The lethal limit for such species is approximately 25°C (Meisner 1990, Matthews and Berg 1997). Several natural factors influence the extent to which changes in air temperature impact stream temperature, including total stream flow, the relative groundwater contribution to flow (Sullivan et al. 1990, Matthews and Berg 1997, Webb et al. 2008), and canopy cover over the stream. In addition, human-related factors that influence the air-water temperature relationship include runoff from impervious surfaces (Nelson and Palmer 2007), thermal discharges (Webb and Nobilis 2007), and reservoir releases (Webb and Walling 1993). A recent analysis using a monthly air-water temperature model for 91 low-impact sites in the SE was reported in Marion et al. (2012). This modeling study found that 62 of the 91 sites showed significant trends, of increasing mean annual stream water temperature (T_s) between 1960 and 2007. The mean increase in annual stream water temperature across the 62 sites with significant trends was 0.14°C per decade, ranging from 0.08°C to 0.29°C per decade. The largest increasing trends were found in the Appalachian region. More relevant to aquatic ecosystems than mean annual T_s are the extreme temperature conditions, such as the annual maximum monthly T_s. Of the 91 sites, 71 show significant increasing trends in annual maximum monthly T_s between 1960 and 2007. The mean trend in annual maximum monthly T_s for the 71 sites was 0.20°C per decade, ranging from 0.04°C to 0.37°C per decade. Under four future climate change scenarios, all 91 sites were projected to have significant warming trends in mean annual T_s (0.21°C to 0.35°C per decade) from 2011 to 2060. The mean significant warming trend in annual maximum T_s over all sites and climate projections was 0.25°C per decade.

Soil Erosion and Sedimentation. Sediment is one of the primary pollutants affecting water quality in the SE (West 2002). Changes in precipitation amount or storm intensity can affect surface soil erosion potential by changing the runoff magnitude, the kinetic energy of rainfall or the amount and type of vegetation cover resisting erosion. Increased erosion results in increased sediment delivery to streams and lakes. Increases in water temperature and sediment concentrations may occur in combination with decreased flow rates and velocities, magnifying the individual impacts of these factors on fish and other aquatic animals (Henley et al. 2000).

The rainfall-runoff erosivity factor (R-factor) provides an index of the intensity and amount of rainfall occurring at a given location over a long period of time, and as such is directly affected by climate. The R-factor provides a useful surrogate for assessing potential changes in future surface erosion related to climate change. In general, the R-factor value changes modeled showed little consistency for the South (Phillips et al. 1993, Nearing, 2001). Overall, past work evaluating potential R-factor changes provides inconclusive results for the SE (Nearing 2001). A study by Marion et al. (2012) provides a new examination using a somewhat more conservative emission scenario (Hadley GCM and the B2 emission scenario) and a finer-scale climate projection than past studies. This study suggests that large future changes in soil erosion potential concentrate in three major geographic clusters including the Central Gulf Coast, Blue Ridge Mountains, and South Florida (Marion et al. 2012). The modeled effect of R-factor increases on surface erosion within the Blue Ridge Mountains may be amplified by the steeper terrain where landslides are of particular concern.

Aquatic Biota

Changes in water quantity and quality due to climate change in turn affect aquatic systems (see Chapter 11). Species richness and biodiversity rates are sensitive to hydrologic changes, and transformation into altered or qualitatively different states can occur (Kwak and Freeman 2010, Spooner et al. 2011). Degraded ecosystem functions and services that are the product of past human actions that have altered the landscape can also be exacerbated by climate change.

Climate change has cascading effects on watershed and ecosystems in the SE and the Caribbean. For example, in Puerto Rico, large runoff rates result in both periodic and intense sediment discharges and chronic elevated nutrient levels (Larsen and Webb 2009). As in conterminous SE, elevated runoff rates and nutrient levels are related to human land use activities. Sediment discharge in these watersheds is highly episodic and spatially variable. In Puerto Rico, small watersheds with large channel gradients combine with intense rainfall events to transport large amounts of sediment directly to the coast, which threatens coral reef systems (Larsen and Webb 2009). The largest sediment transport events occur when tropical systems pass over the islands and deposit multiple centimeters of rain in one event. Although much uncertainty remains about future trends in precipitation, hurricane frequency, and hurricane intensity, these results suggest that increases in future extreme precipitation events will result in large sediment and nutrient discharges into reef systems. Other reef stressors such as increasing salinity, acidity, and ocean temperatures will compound sediment and nutrient stress (see Chapter 11).

Salinity Intrusion

Saltwater intrusion into freshwater aquifers and drainage basins can degrade natural ecosystems and contaminate municipal, industrial, and agricultural water supplies (Bear et al. 1999). The balance between hydrologic flow conditions within a coastal drainage basin and sea level governs the magnitude, duration, and frequency of salinity intrusion into coastal rivers. Future changes in precipitation patterns have the potential of decreasing streamflow to the coast, which favors salinity intrusion, especially combined with sea level rise (Conrads et al. 2006, 2010a, 2010b).

A study by Conrads et al. (2010a) indicates that future sea level rise can potentially affect salinity intrusion threatening the municipal water supply from two municipal intakes, on the Atlantic Intracoastal Waterway (AIW) and the Waccamaw River near Myrtle Beach along the Grand Strand of the South Carolina Coast. Results suggest that an increase in number of days that specific conductance values, which measure salinity level, exceeded the threshold level of 2,000 $\mu S\ cm^{-1}$ with historic sea level rises and decreases of streamflow. For example, a 1 ft sea level rise combined with a 10% decrease in historical streamflow would increase the days that the intake is unavailable by 25%, or an additional 100 days. A 25% reduction of low streamflows increases the number of days of unavailability to more than 700 days. Conrades et al. (2010b) also examined effects of climate change on salinity intrusion on the lower Savannah River estuary.

Climate Change Implications for River Basin Management: A Case Study of the Apalachicola-Chattahoochee-Flint River Basin

Impacts of global climate change on water resources are site-specific. Prescribing adaptive watershed management strategies and measures requires a comprehensive assessment of the likely influences of climate change on all aspects of the watershed functions. Involvement of local stakeholders and decision makers is essential to the success of sound integrated watershed management in responding to climate change. We use the Apalachicola-Chattahoochee-Flint (ACF) River Basin study, a well-studied basin with high significance in the SE, to demonstrate the processes of climate change assessment and water resource adaptation planning at a large basin scale.

Significance. The Apalachicola-Chattahoochee-Flint (ACF) River Basin drains 19,600 sq mi and receives an average annual rainfall of 1,140 mm of which 25% and 45% becomes runoff for the south and north, respectively. The principle water uses are irrigation at 2.9/0.2 (summer/winter) billion gallons per day (bgd), thermoelectric: 2.5/2.2 bgd, and municipal and industrial: 1.8/1.4 bgd. The ACF includes one nuclear and six fossil fuel power plants. The ACF River system is navigable from the mouth of the Apalachicola in Florida up to Columbus, GA, and is used to transport construction materials. The ACF includes four federal (369 MW) and five private (276 MW) hydroelectric plants, including the South East Power Administration (SEPA) and Southern Company Services. The basin sustains rich ecosystems, including the Apalachicola Bay, which supports 131 freshwater and estuarine fish species and serves as a nursery for many significant Gulf of Mexico species (e.g., the Gulf sturgeon). According to the US Army Corps of Engineers, Lake Lanier and West Point Lake registered more than 15,000,000 visitor days in 2003 with an economic benefit exceeding $300 million. The Apalachicola Bay is a major ecotourism attraction valued at $73 billion per year. The basin is underlain by productive groundwater resources, including the Upper Floridan Aquifer, primarily pumped for irrigation but also for domestic and industrial water supply. Groundwater provides approximately 62% of the region’s irrigation.

Integrated Water Resources Assessment and Planning Framework. The ACF climate change assessment is carried out following the integrated water resources assessment and planning framework (Figure 10.4, Georgakakos et al. 2010 and 2011). The assessment process begins with the development and selection of consistent climate, demographic, socioeconomic, and land use and land cover scenarios, which are depicted across the top of Figure 10.4.

Historical (1960-2009) scenarios and responses are analyzed first to establish baseline conditions. The analysis clearly suggests that climatic change is already occurring in the ACF River Basin. Future (2000-2099) climate scenarios are based on GCMs available through the Intergovernmental Panel on Climate Change (IPCC) (A1B and A2 emission scenarios generated by 13 GCMs). Downscaling of GCM outputs through statistical, dynamic, or both methods is applied to generate high resolution (12x12

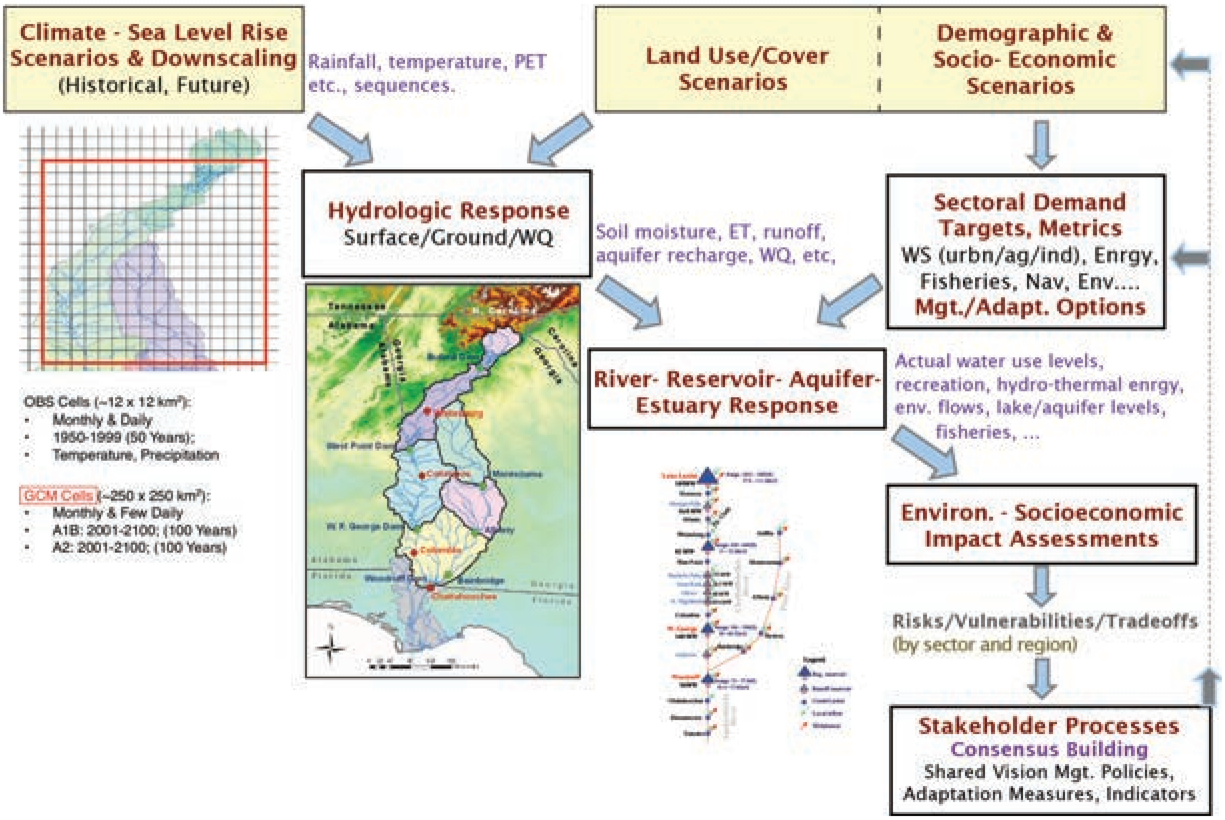


Figure 10.4 Integrated Water Resources Assessment and Planning Framework (Georgakakos et al. 2010 and 2011a).

km) atmospheric forcing, such as rainfall and temperature, over the ACF River Basin watersheds (Zhang and Georgakakos, 2012). Physically based watershed, aquifer, and estuary models are used to quantify the hydrologic and water quality response to alternative climate and land use and land cover scenarios at a basin scale. Water demand assessments are carried out for all water users including environmental and ecological flow and lake level requirements. The goal is to establish desired water use targets, performance metrics, and management and adaptation options. Adaptive optimization methods are used to generate system-wide management policies conditional on inflow forecasts. Subsequently, environmental and socioeconomic impact assessments are carried out to quantify the relative merits, risks, vulnerabilities, and tradeoffs of alternative adaptation and management strategies across the various water sectors and users. The generated information is used to inform stakeholder planning and decision processes aimed at developing consensus on adaptation measures, management strategies, and performance monitoring indicators. The assessment and planning process is driven by stakeholder input and is iterative and sequential.

Water Resources Assessments. Historical and future basin inflow sequences corresponding to A1B and A2 climate change scenarios were used to drive the ACF river basin model that incorporates the river network, all storage projects and hydroelectric facilities, water withdrawals and returns, in-stream flow requirements, and management procedures (Georgakakos et al. 2010). The impact assessment criteria include reliability of water supply for municipal, industrial, and agricultural users; lake levels; environmental and ecological flow requirements; navigation; and hydropower generation. Following is a summary of the assessment conclusions:

- Under the climate change scenarios and with current management procedures that follow rule curve based releases, the ACF River Basin is likely to experience more severe than historical stresses including deeper reservoir drawdowns, greater water supply deficits, less firm energy generation, and more frequent and severe violations of environmental flow requirements. The A2 climate scenario impacts are considerably more severe than those of the A1B.
- Adaptive management procedures and modified operation rules as proposed and tested by Georgakakos et al. (2010) and Georgakakos et al. (2012) prove to be useful to mitigate the impacts of climate change. However, adaptive management procedures and tools have yet to be adopted and made operational by federal and state agencies.

Case Study: The Apalachicola-Chattahoochee-Flint (ACF) River Basin

The Apalachicola-Chattahoochee-Flint (ACF) River Basin extends from the Blue Ridge Mountains across the Piedmont and Southeastern Plains to the Gulf of Mexico and drains an area of approximately 50,000 square kilometers (Figure 10.1.ACF). The headwaters in the upper ACF basin contain the Chattahoochee National Recreation Area and the Chattahoochee National Forest. The basin provides essential water supply for several million people where access to groundwater aquifers is constrained geologically. The main stem rivers support hydroelectric, thermoelectric and nuclear power production, waste assimilation, recreation, and navigation (in lower half of basin). These flows are managed by three federal and twelve state, or privately operated, main stem dams. Many small impoundments (i.e. lakes, ponds, wetlands) occur throughout the drainage area and provide some degree of flood protection, sediment storage, and local water supplies during prolonged droughts. The lower ACF basin intersects the extensive Floridan aquifer, which provides groundwater for irrigated agriculture over large areas of southwest Georgia.

The Upper Flint and Chattahoochee Rivers are highly valued for recreational hiking, camping, fishing, and boating. Lake Lanier, on the upper Chattahoochee, north of Atlanta, provides multimillion dollar recreational opportunities for bass fishing and boating. The cold-water outflows from the lower depths of Lake Lanier and creates valuable habitat for valuable trout fishing by people throughout the region, especially from metro Atlanta. Additional recreational opportunities and hydropower are available at West Point Lake and Lake Walter F. George on the Chattahoochee River.

The Flint River is one of the longest remaining free-flowing rivers in the contiguous 48 states. The Flint River flows from headwaters south of metro Atlanta, across the Piedmont and onto

Continued on next page

Continued from previous page

Case Study: The Apalachicola-Chattahoochee-Flint (ACF) River Basin

Coastal Plain before reaching the confluence with the Chattahoochee River and forming Lake Seminole, a main stem impoundment noted for its bass fishing and duck hunting. The Apalachicola River is formed by the outflow from Lake Seminole together with groundwater inputs at the Georgia-Florida border. The river contains a diverse floodplain known for exceptional habitat and species diversity before flowing to the Apalachicola Bay on the Gulf of Mexico, a barrier island estuary designated as a National Estuarine Research Reserve.

The Apalachicola River provides approximately 90% of the freshwater discharge to the Bay. The estuary supports a multimillion dollar production of shellfish (oysters, crabs, shrimp) and finfish. These fisheries depend on a specific salinity range maintained by freshwater inflow from the ACF rivers and groundwater from the Floridan aquifer. Oyster mortality in particular is dependent on an optimal range of salinity (16 to 26 ppt) for growth. Lower salinity values are associated with high river discharges and are thought to reduce mortality from salt-water fish predators. High river flows also bring nutrients into the Bay that contribute to planktonic food production used by oysters.

There have been decades of discussions, sometimes contentious, among water users in Georgia, Florida, and Alabama, the three states that compose the ACF basin. The focus of these ongoing deliberations is competing water interests: municipal supply (especially in upper basin), power plants, irrigated agriculture (lower basin), reservoir recreation and land values, fish and wildlife conservation (river and stream species that includes federally protected species in middle and lower basin), and estuarine fisheries. Specifically the issues rest on municipal water supplies for upstream users, especially metro Atlanta, versus sufficient environmental flows to sustain endangered species. Insuring good nutrient flow and optimal salinity ranges for oyster production within the Apalachicola Bay is also an issue. Consequently, long-term combinations of prolonged droughts, high storm flows from the river, and wind-driven wave action generated by hurricanes are

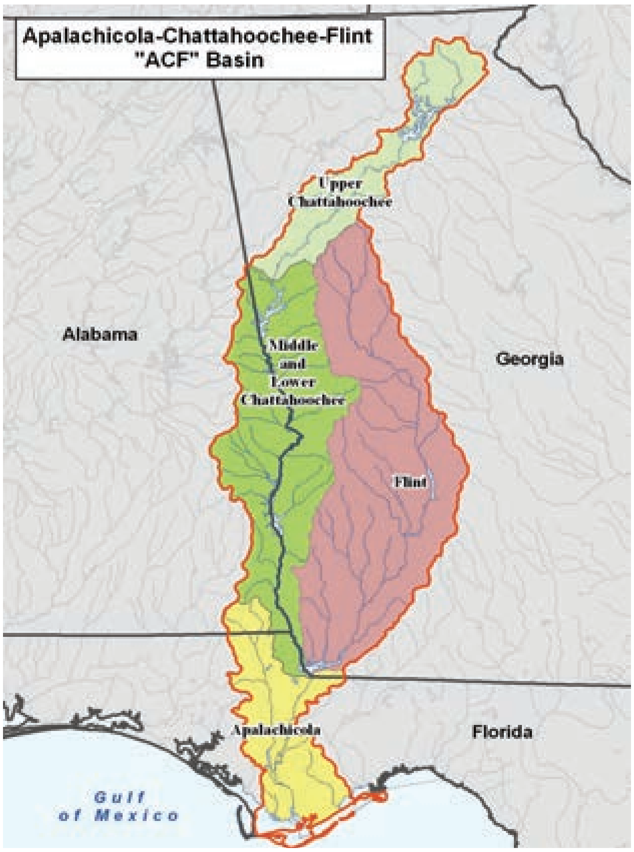


Figure 10.1.ACF Map of the Apalachicola-Chattachoochee-Flint River Basin. The basin includes drainage areas in three states with most of the catchment in Georgia.

Continued on next page

Continued from previous page

Case Study: The Apalachicola-Chattahoochee-Flint (ACF) River Basin

variables that may prove detrimental coastal fisheries.

Climate change impacts in the ACF likely will exacerbate conflicts among water users and anthropogenic stresses on these interconnected natural systems. Floods throughout the ACF basin are associated with intense, hurricane-derived rainfall. Higher evaporation and evapotranspiration by plants in the freshwater ecosystems likely will decrease water availability and river discharge. In addition, projected increases in extreme variability of rainfall and increased demands for water for irrigation and municipal supplies by rapidly growing regional populations will also likely continue to transform the ACF drainage network. Extremely low flows during prolong droughts and high temperatures combine to concentrate the effects of excessive nutrients from waste-water treatment plants and agricultural runoff that threaten local extinctions. These reduced flows will further threaten the high biodiversity of the freshwater biota. There are recent examples of perennial streams drying up in last decade for first time ever recorded; for example Spring Creek, an inflowing stream to Lake Seminole in southwest Georgia (Figure 10.2.ACF).

The aquatic species diversity in the ACF includes approximately 125 freshwater fishes, 33 unionid mussels, 30 crayfishes, and hundreds of less-well inventoried invertebrates. At least 30 fishes, mussels, and crayfishes (together) are endemic to the system, and new species continue to be discovered, such as a previously undescribed species of bass, Micropterus sp., that occurs in the headwaters of the Chattahoochee River system. In general, freshwater invertebrates are the most endangered group of organisms. Of the nearly 300 native unionid species of freshwater mussels in North America, 278 of them live only in the SE USA, and 33 are in the ACF. Four mussel species in the Lower Flint River and the Apalachicola River are federally listed as endangered (Medionidus pencillata, Pleurobema pyriforme, Amblema neislerii, Hamotia subangulata) (Figure 10.3.ACF).

Figure 10.2.ACF Spring Creek historically flowed into Georgia's Lake Seminole. During recent prolonged droughts, the channel has dried out and formed isolated pools. Photo by: Andrea Fritts, Warnell School of Forestry and Natural Resources, University of Georgia-Athens.

Most freshwater mussels require sufficient flows of high-quality water as well as the presence of particular species of fish that serve as hosts to complete larval development and dispersal within river drainages (Figure 10.4.ACF). These species provide important ecosystem services throughout the SE. For example, mussels filter as much as six gallons of water a day and feed on suspended micro-algae, bacteria and other organic particles. This biofiltration helps to improve water clarity and quality. In addition, since mussels are among the most sensitive, long-lived species that complete their life cycles completely in freshwaters with limited mobility,

Continued on next page

Continued from previous page

Case Study: The Apalachicola-Chattahoochee-Flint (ACF) River Basin

they are good bioindicators of increases in contaminants such as ammonia in relatively specific locations.

The ACF is an example of how tradeoffs among competing needs for sustainable freshwater resources require well-defined environmental flows that protect biodiversity and ecosystem services. The ACF stakeholders are being increasingly challenged to implement long-term plans because of the recent extreme variability in precipitation. The complex hydrological and economical connectivity of the water sources from upland forested areas with downstream groundwater will continue to require inter-state discussion and collaboration to bring about resolution.

Figure 10.3.ACF Striped mussel (*Hamotia subangulata*), (commonly called shiny rayed pocketbook), is a federally endangered species found in the ACF River Basin. Source: www.discoverlife.org, University of Georgia.

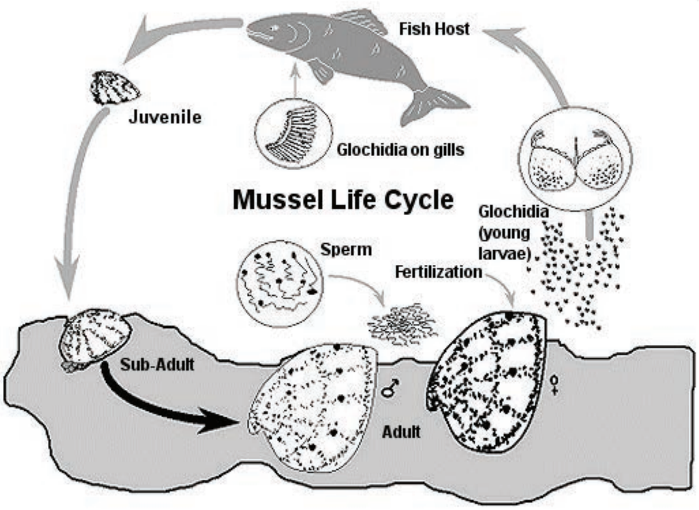


Figure 10.4.ACF Life cycle of freshwater mussels. Adult mussels produce small ectoparasitic larvae that attach to the gills of fish. The larvae grow and are dispersed by the fish to complete their growth in sediments. Some mussel species have evolved specialized mantel tissue resembling small fish that undulate. This movement attracts predatory fish closer to the adult mussel and increases chances of the larvae becoming attached to the fish gills. Source: Diagram from Cummings and Graf, 2009. The MUSSEL Project. http://www.mussel-project.net/. Funded by The National Science Foundation and USGS.

10.6 Mitigation and Adaptation Options

Although global climate model projections for the next several decades do not agree in terms of magnitude or direction of the expected changes for precipitation and some others affecting water resources, the model output all points towards a new climatic regime that the region has not experienced previously (Milly et al. 2008). Climate change already has affected water quantity and quality in several regions in the SE and likely will impact natural ecosystems (Carlisle et al. 2011) and society (Table 10.1) (Marion et al. 2012).

Table 10.1 Potential Adaptation Options for Managing Hydrologic Impact and Risks from Climate Change.

Hydrologic Impacts	Risks to Ecosystems	Adaptation Options
Water supply stress increase	Water shortage; drying up of drinking wells; Consequences to aquatic ecosystems, socioeconomics, and business	Reduce groundwater and surface water use for agriculture and lawns; enhance water conservation; increase water use efficiency and storage; recycle water; institute adaptive management.
Evapotranspiration increase	Hydrologic droughts; wildfires; insect, disease outbreaks	Use native tree species; reduce tree stocking; reduce water use by crops
Increase of peak flow, Storm flow volume, floods	Flooding; increased soil erosion and sedimentation	Reduce impervious areas; increase stormwater retention ponds; increase evapotranspiration by increasing forest coverage; increase water storage capacity
Low flow decrease; drought	Water quality degradation; fish habitat loss; reduced transportation capacity	Increase water storage; reduce off-stream water withdrawal
Wetland hydroperiod change	Wildlife habitat loss; greenhouse gas (CO_2, CH_4, NO_x) emission	Plug ditches; adjust outflows from reservoirs
Stream water temperature increase	Water quality degradation; loss of cold fish habitat	Maintain riparian buffers and shading
Soil erosion, sedimentation increase	Water quality degradation; siltation of reservoirs; increase cost of water treatment	Enhance best management practices (BMPs); redesign riparian buffers; minimize direct discharge of runoff from roads to streams
Chemical loading increase	Water quality degradation; higher cost of water treatment	Maintain streamflow quantity; applications of BMPs

A limited number of studies have considered adaptation options that might reduce or adapt to the severe consequences of climate changes, such as water supply shortages, habitat loss, and increased forest wildfires. For example, watershed manipulation experiments show that converting a deciduous forest cover to a conifer evergreen forest in the Appalachians can reduce flood risk in extreme wet years (Ford et al. 2011). Adaptation to intensified extreme storms involves consideration of alternative forest covers in future land planning. Current best management practices for reducing nonpoint source pollution may be adapted to better reflect future hydrologic and management conditions. The large area of forests in the SE are expected to have an increasing role to modulate regional climate, maintain water quality, and sequester carbon (Liu 2011, Chen et al. 2012, Lockaby et al. 2011). There is large potential to increase water use efficiency from all major water users, such as the agriculture and energy sectors, including power plants that produce bioenergy.

Facing the uncertainty of climate change, water planning and management organizations and stakeholders must create adaptive frameworks for solutions, re-evaluate past decisions in light of the changing climate, and identify the most effective policies based on the current scientific research and understanding (Rosenhead and Mingers 2001). Some researchers have proposed/tested new decision-making frameworks designed to be responsive to changing climate conditions and scientific understanding. Rosenhead and Mingers (2001) views planning under deep uncertainty as sequential and adaptive decisions made over time. Such an approach helps identify robust solutions, which may not be the best but provide more options for the decision makers in making decisions. Robustness could be thought of as making decisions between optimality and minimizing solutions (Groves 2006). For example, using a stochastic dynamic programming model, Chao and Hobbs (1997) revisit the decision of protecting the Great Lakes shoreline every year in such a way that the expected cost of sand nourishment is minimized under the anticipated probability of lake level change due to global warming. Projections of climate are not regularly represented probabilistically, so it is important that the water management framework explicitly quantify the reservoir yield and releases by assigning reliabilities (Sankarasubramanian et al. 2009a). Sankarasubramanian et al. (2009b) and Georgakakos et al. (2012) also show that updating climate forecasts on a monthly basis, and utilizing the updated forecasts within the seasonal reservoir operation, benefited the system more than an operational policy derived purely based on the climate forecasts at the beginning of the season. Further development of climate forecasts at seasonal and interannual scales could be useful in reducing the vulnerability of water supply systems under future climate change and population growth.

10.7 References

Alcamo, J., T. Henrichs, T. Rosch. 2000. World water in 2025: Global modeling and scenario analysis for the world commission on water for the 21st century. Kassel, Germany: University of Kassel: Center for Environmental Systems Research.

Averyt, K., J. Fisher, A. Huber-Lee, A. Lewis, J. Macknick, N. Madden, J. Rogers, S. Tellinghuisen. 2011. Freshwater use by U.S. power plants: Electricity's thirst for a precious resource. A report of the energy and water in a warming world initiative. Cambridge, MA: Union of Concerned Scientists. November.

Barnston, A.G., S.J. Mason, L. Goddard, D.G. Dewitt, S.E. Zebiak. 2003. Multimodel ensembling in seasonal climate forecasting at IRI. Bulletin of the *American Meteorological Society* 84 (12): 1783–1796.

Bates, B.C., Z.W. Kundzewicz, S. Wu, J.P. Palutikof. 2008. Climate change and water. (2008), Climate Change and Water Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, Switzerland: IPCC Secretariat. 210.

Bear, J., A.H.D. Cheng, S. Sorek, D. Ouazar, I. Herrera. eds. 1999. Seawater intrusion in coastal aquifers–concepts, methods and practices. Dordrecht, the Netherlands: Kluwer Academic Publishers. Dordrecht, The Netherlands.

Cahoon, D.R., S. Williams, B.T. Gutierrez, K.E. Anderson, E.R. Thieler, D.B. Gesch. 2009. The Physical Environment. Coastal Sensitivity to Sea-Level Rise: A Focus on the Mid-Atlantic Region. US Climate Change Science Program. Synthesis and Assessment Product 4.1.

Caldwell, P.V., G. Sun, S.G. McNulty, E.C. Cohen, J.A. Moore Myers. 2012. Impacts of impervious cover, water withdrawals, and climate change on river flows in the Conterminous US, *Hydrology and Earth System Sciences.* Discuss. 9: 4263-4304, doi:10.5194/hessd-9-4263-2012.

Carlisle, D.M., D.M. Wolock, M.R. Meador. 2011. Alteration of streamflow magnitudes, and potential ecological consequences: A multiregional assessment. *Frontiers in Ecology and the Environment* 9 (5): 264-270. doi:10.1890/100053.

Chan, S. and V. Misra. 2009. A diagnosis of the 1979-2005 extreme rainfall events in the southeastern United States with Isentropic moisture tracing. *Monthly Weather Review* 138 (4): 1172-1185.

Chao, P.T. and B.F. Hobbs. 1997. Decision analysis of shoreline protection under climate change uncertainty. *Water Resources Research* 33 (4): 817-829.

Chen, G., M. Notaro, Z. Liu, Y.Q. Liu. 2012. Simulated local and remote biophysical effects of afforestation over SE United States in boreal summer. Journal of Climate (In review). 25 (13): 4511-4522.

Conrads, P.A., E.A. Roehl, R.C. Daamen, W.M. Kitchens. 2006. Simulation of water levels and salinity in the rivers and tidal marshes in the vicinity of the Savannah National Wildlife Refuge, Coastal South Carolina and Georgia: US Geological Survey, Scientific Investigations Report 2006-5187, 134.

Conrads, P.A., E.A. Roehl Jr., C.T. Sexton, D.L. Tufford, G.J. Carbone, K. Dow, and J.B. Cook. 2010. Estimating Salinity Intrusion Effects Due To Climate Change Along the Grand Strand of the South Carolina Coast, Conference Proceedings Paper for the 4th Federal Interagency Hydrologic Modeling Conference Las Vegas, NV June 2010.

Conrads, P.A., E.A. Roehl Jr., R.C. Daamen, J.B. Cook, C.T. Sexton, D.L. Tufford, G.J. Carbone, and K. Dow. 2010. Estimating Salinity Intrusion Effects Due To Climate Change on the Lower Savannah River Estuary. Conference Proceeding Paper of South Carolina Environmental Conference, North Myrtle Beach, South Carolina, March 2010.

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

Cruise, J.F., C.A. Laymon, O.Z. Al-Hamdan. 2010. Impact of 20 years of land-cover change on the hydrology of streams in the southeastern United States. *Journal of the American Water Resources Association* 46 (6): 1159-1170. DOI: 10.1111/j.1752-1688.2010.00483.x

Curtis, L. and E. Rochester. Water Harvesting for Irrigation: Developing an Adequate Water Supply. ANR-827, New May 1994. http://www.aces.edu/pubs/docs/A/ANR-0827/ANR-0827.html. Data accessed on October 16, 2012.

Devineni, N., A. Sankarasubramanian, S. Ghosh. 2008. Multi-model ensembling of probabilistic streamflow forecasts: Role of predictor state space in skill evaluation. *Water Resources Research* 44 (9), W09404. doi:10.1029/2006WR005855.

Devineni, N. and A. Sankarasubramanian. 2010. Role of ENSO state in developing multimodel combination for improving U.S. Winter Precipitation Improving the prediction of winter precipitation and temperature over the continental United States: Role of ENSO state in developing multimodel combinations. *Monthly Weather Review* 138 (6): 2447-2468.

Easterling, D.R., G.A. Meehl, C. Parmesan, S.A. Changnon, T.R. Karl, L.O. Mearns. 2000. Climate extremes: Observations, modeling, and impacts. Science 289 (5487): 2068-2074. doi:10.1126/science.289.5487.2068

Farrell, D., A. Trotman, C. Cox. 2011. Drought early warning and risk reduction: A case study of the Caribbean drought of 2009-2010. Global Assessment Report on Disaster Risk Reduction. GAR 2011. 22.

Ford, C.R., S.H. Laseter, W.T. Swank, J.M. Vose. 2011. Can forest management be used to sustain water-based ecosystem services in the face of climate change? *Ecological Applications* 21 (6): 2049-2067.

Georgakakos, A., F. Zhang, H. Yao. 2010. Climate variability and change assessment for the ACF river Basin, Southeast US. Georgia Water Resources Institute (GWRI) Technical Report sponsored by NOAA, USGS, and Georgia EPD, Georgia Institute of Technology, Atlanta, Georgia, 321.

Georgakakos, A. and F. Zhang. 2011. Climate Change Scenario Sequences and Assessment for ACF, OOA, SO, ACT, TN, and OSSS Basins in Georgia. Georgia Water Resources Institute (GWRI) Technical Report sponsored by NOAA, USGS, and the Georgia EPD; Georgia Institute of Technology, Atlanta, Georgia, USA, 229.

Georgakakos, A.P., H. Yao, M. Kistenmacher, K.P. Georgakakos, N.E. Graham, F.Y. Cheng, C. Spencer, E. Shamir. 2012. Value of adaptive water resources management in northern California under climatic variability and change: Reservoir management. *Journal of Hydrology* on line publication, 412-413 (January): 34-46. doi.org/10.1016/j.jhydrol.2011.04.038.

Glassman, D., M. Wucker, T. Isaacman, C. Champilou. 2011. The water-energy nexus: Adding water to the energy agenda. New York, NY: World Policy Institute. 33.

Greene, A.M., L. Goddard, U. Lall. 2006. Probabilistic multimodel regional temperature change projections. *Journal of Climate* 19 (17): 4326-4343.

Groisman, P.Y., R.W. Knight, T.R. Karl, D.R. Easterling, B. Sun, J.H. Lawrimore. 2003. Contemporary changes of the hydrological cycle over the contiguous United States: Trends derived from in situ observations. *Journal of Hydrometeorology* 5 (1): 64-85.

Groves, D.G. 2006. New methods for identifying robust long-term water resources management strategies for California. Pardee RAND Graduate School, Santa Monica, CA. Graduate Thesis.

Heimlich, B.N., F. Bloetscher, D.E. Meeroff, J. Murley. 2009. Southeast Florida's resilient water resources: Adaptation to sea level rise and other impacts of climate change. Boca Raton, FL: Florida Atlantic University. Florida Atlantic University Center for Urban and Environmental Solutions and Department of Civil Engineering, Environmental, and Geomatics Engineering.

Henley, W.F., M.A. Patterson, R.J. Neves, A. Dennis Lemly. 2000. Effects of sedimentation and turbidity on lotic food webs: a concise review for natural resources managers. *Review in Fisheries Science* 8 (2):125-139.

IPCC (Intergovernmental Panel on Climate Change). 2007. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. In Core Writing Team, eds. R.K. Pachauri, and A. Reisinger. Climate Change 2007: Synthesis Report. Geneva, Switzerland: IPCC.

Johnson, C.Y. et al. 2012. Climate Change, Human Populations, and Social Vulnerability in the South: An Ecosystem-level Examination of Freshwater Access, 2010-2040. In Climate Change Adaptation and Mitigation Management Options (CCAMMO), ed. J. Vose. CRC Press. (In Press).

Kaushal, S.S., G.E. Likens, N.A. Jaworski, M.L. Pace, A.M. Sides, D. Seekell, K.T. Belt, D.H. Secor, R.L. Wingate. 2010. Rising stream and river temperatures in the United States. *Frontiers in Ecology and the Environment* 8 (9): 461-466.

Keim, B.D. and G.E. Faiers. 1996. Heavy rainfall distributions by season in Louisiana: Synoptic interpretations and quantile estimates. *Journal of the American Water Resources Association* 32 (1): 117-124.

Kenny, J.F., N.L. Barber, S.S. Hutson, K.S. Linsey, J.K. Lovelace, M. A. Maupin. 2009. Estimated use of water in the United States in 2005, US Geological Survey Circular 1344, 52.

Karl, T.R., J.M. Melillo, T.C. Peterson, eds. 2009. Global Climate Change Impacts in the United States. New York, NY: Cambridge University Press, New York.

Krakauer, N.Y. and I. Fung. 2008. Mapping and attribution of change in streamflow in the coterminous United States. *Hydrology and Earth System Science* 12 (4): 1111-1120.

Kwak, T.J. and M.C. Freeman. 2010. Assessment and management of ecological integrity. *In:* Inland fisheries management in North America, ed. W.A. Hubert and M.C. Quist., editors. *Inland fisheries management in North America*, third edition. Bethesda, Maryland: American Fisheries Society.

Larsen, M.C. and R.M.T. Webb. 2009. Potential effects of runoff, fluvial sediment, and nutrient discharges on the coral reefs of Puerto Rico. *Journal of Coastal Research* 25 (1): 189-208.

Li, L., W. Li, Y. Kushnir. 2011. *Variation of North Atlantic subtropical high western ridge and its implication to the southeastern US summer precipitation. Climate Dynamics* doi:10.1007/s00382-011-1214-y.

Li, W., L. Li, R. Fu, Y. Deng, H. Wang. 2011. Changes to the North Atlantic subtropical high and its role in the intensification of summer rainfall variability in the southeastern United States. *Journal of* Climate 24 (5): 1499-1506.doi: http://dx.doi.org/10.1175/2010JCLI3829.1

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

Lins, H.F. and J.R. Slack. 2005. Seasonal and regional characteristics of US streamflow trends in the United States from 1940-1999. *Physical Geography* 26 (6): 489-501.

Liu, Y.Q. 2011. A numerical study on hydrological impacts of forest restoration in the southern United States. *Ecohydrology* 4 (2): 299-314. doi:10.1002/eco.178.

Liu, Y.Q., J. Prestemon, S. Goodrick, T. Holmes, J. Stanturf, J.M. Vose, G. Sun. 2012. Future Wildfire Trends, Impacts, and Mitigation Options in Southern U.S Climate Change Adaptation and Mitigation Management Options (CCAMMO), ed. J. Vose. CRC Press. (In Press).

Lockaby, G., C. Nagy, J.M. Vose, C.R. Ford, G. Sun, S. McNulty, P. Caldwell, E. Cohen, J.A.M. Moore Myers. 2011. Water and forests. In: The Southern Forest Futures Project. Technical Report, ed. D. N. Wear and J. G. Greis. Asheville, NC: The Southern Forest Futures Project: Technical Report. USDA Forest Service, Southern Research Station, Asheville, NC. General Technical Report.

McCabe, G.J., and D.M. Wolock. 2002. A step increase in streamflow in the conterminous United States. *Geophysical Research Letters* 29 (24): 2185.

Manuel, J. 2008. Drought in the southeast: Lessons for water management. *Environmental Health Perspectives* 116 (4): A168-A171.

Marion, D., G. Sun, et al. 2012. Managing Forest Water Quantity and Quality Under Climate Change in the Southern U.S. In Climate Change Adaptation and Mitigation Management Options (CCAMMO), ed. J. Vose. CRC Press. (In Press).

Matthews, K.R. and N.H. Berg. 1997. Rainbow trout responses to water temperature and dissolved oxygen stress in two southern California stream pools. *Journal of Fish Biology* 50 (1): 50-67. doi: 10.1111/j.1095-8649.1997.tb01339.x.

McNulty, S.G., J.M. Myers, P. Caldwell, G. Sun. 2012. Climate Change. In Southern forest future project, ed. D.N. Wear, D.N. and J. G. Gries. Asheville, NC: USDA Forest Service Southern Research Station. Southern Forest Future Project. (In Review).

Meisner, J.D. 1990. Effect of climatic warming on the southern margins of the native range of brook trout, *Salvelinus fontinalis*. *Canadian Journal of Fisheries and Aquatic Science* 47 (6): 1065-1070.

Meybeck, M. 2004. The global change of continental aquatic systems: Dominant impacts of human activities. *Water Science & Technology* 49 (7): 73-83.

Milly, P.C.D., K.A. Dunne, A.V. Vecchia. 2005. Global pattern of trends in streamflow and water availability in a changing climate. *Nature* 438 (7066): 347-350.

Milly, P.C.D., J. Betancourt, M. Falkenmark, R.M. Hirsch, Z.W. Kundzewicz, D.P. Lettenmaier, R.J. Stouffer. 2008. Stationarity is dead: Whither water management. *Science* 319 (5863): 573-574.

Misra, V., S. Chan, R. Wu, E. Chassignet. 2009. Air-sea interaction over the Atlantic warm pool in the NCEP CFS. *Geophysical Research Letters*. 36, L15702; doi:10.1029/2009GL038525.

Mohseni, O. and H.G. Stefan. 1999. Stream temperature air temperature relationship: A physical interpretation. *Journal of Hydrology* 218 (3-4): 128-141.

Moreau, D. 2007. What are the experts saying about effects of climate change on rainfall and streamflow in the Southeast? Raleigh, NC: Water Resources Research Institute Publications.

Murdoch, P.S., J.S. Baron, T.L. Miller. 2000. Potential effects of climate change on surface-water quality in North America. *Journal of the American Water Resources Association* 36 (2): 347-366.

Nearing, M.A. 2001. Potential changes in rainfall erosivity in the U.S. with climate change during the 21st century. *Journal of Soil and Water Conservation*, 56 (3): 229-232.

Nelson, K.C. and M.A. Palmer. 2007. Stream temperature surges under urbanization and climate change: Data, models, and responses. *Journal of the American Water Resources Association* 43 (2): 440-452.

Obeysekera, J., J. Park, M. Irizarry-Ortiz, P. Trimble, J. Barnes, J. VanArman, W. Said, E. Gadzinski. 2011. Past and projected trends in climate and sea level for South Florida. West Palm Beach, FL: South Florida Water Management District. 3301 Gun Club Road, West Palm Beach, Florida.

O'Gorman, P.A. and T. Schneider. 2009. The physical basis for increases in precipitation extremes in simulations of 21st-century climate change. Proceedings of the National Academy of Sciences of the United States of America 106 (35): 14773-14777. doi:10.1073/pnas.0907610106.

Osidele, O.O. and M.B. Beck. 2004. Food web modelling for investigating ecosystem behaviour in large reservoirs of the south-eastern United States: Lessons from Lake Lanier, Georgia. *Ecological Modelling* 173 (2-3): 129-158.

Phillips, D.L., D. White, C.B. Johnson. 1993. Implications of climate change scenarios for soil erosion potential in the United States. *Land Degradation and Rehabilitation* 4 (2): 61-72.

Rosenhead, J. and J. Mingers. 2001. Rational analysis for a problematic world revisited: Problem structuring methods for complexity, uncertainty, and conflict. Chichester, United Kingdom: Wiley and Sons. Chichester, UK.

Richter, B.D., R. Mathews, D.L. Harrison, R. Wigington. 2003. Ecologically sustainable water management: managing river flows for ecological integrity. *Ecological Applications* 13: 206-224.

Sankarasubramanian, A., U. Lall, F.D. Souza Filho, A. Sharma. 2009a. Improved water allocation utilizing probabilistic climate forecasts: Short term water contracts in a risk management framework. *Water Resources Research* 45, W11409; doi:10.1029/2009WR007821.

Sankarasubramanian, A., U. Lall, N. Devineni, S. Espinueva. 2009b. The role of monthly updated climate forecasts in improving intraseasonal water allocation. *Journal of Applied Meteorology and Climatology* 48 (7): 1464-1482.

South Florida Water Management District. 2009. Climate change & water management in South Florida. West Palm Beach, FL: Interdepartmental Climate Change Group. http://my.sfwmd.gov/portal/page/portal/xrepository/sfwmd_repository_pdf/climate_change_and_water_management_in_sflorida_12nov2009.pdf.

Spooner, D.E., M.A. Xenopoulos, C. Schneider, D.A. Woolnough. 2011. Coextirpation of host-affiliate relationships in rivers: The role of climate change, water withdrawal, and host-specificity. *Global Change Biology* 17 (4): 1720-1732. doi:10.1111/j.1365-2486.2010.02372.x.

Sun, F., M.L. Roderick, G.D. Farquhar. 2012. Changes in the variability of global land precipitation. *Geophysical Research Letters* (39) L19402, 6. doi:10.1029/2012GL053369.

Sun, G., S.G. McNulty, J.A. Moore Myers, E.C. Cohen. 2008. Impacts of multiple stresses on water demand and supply across the southeastern United States. *Journal of the American Water Resource Association* 44 (6): 1441-1457.

Sun, G. and G. Lockaby. 2012. Water quantity and quality at the urban-rural interface. In: Urban-Rural Interfaces: Linking People and Nature, eds. D.N. Laband and B.G. Lockaby (In Review). Madison, WI: American Society of Agronomy.

Sullivan, K., J. Tooley, K. Doughty, J.E. Caldwell, P. Knudsen. 1990. Evaluation of prediction models and characterization of stream temperature regimes in Washington. Timber/Fish/Wildlife Rep. No. TFW-WQ3-90-006. Olympia, WA: Washington Department of Natural Resources. Olympia, Washington. 224.

Titus, J.G., K.E. Anderson, D.R. Cahoon, D.B. Gesch, S.K. Gill, B.T. Gutierrez, E.R. Thieler, S.J. Williams. 2009. The physical environment. In: Coastal sensitivity to sea-level rise: A focus on the Mid-Atlantic region, ed. D.R. Cahoon, S.J. Williams, B.T. Gutierrez, K.E. Anderson, E.R. Thieler, and D.B. Gesch, 9-84. Washington, DC: US Climate Change Science Program.

Viger, R.J., L.E. Hay, S.L. Markstrom, J.W. Jones, G.R. Buell. 2011. Hydrologic effects of urbanization and climate change on the Flint River Basin, Georgia. *Earth Interactions* 15 (20): 1-25.

Vörösmarty, C.J., P. Green, J. Salisbury, R. Lammers. 2000. Global water resources: Vulnerability from climate change and population growth. *Science* 289 (5477): 284-288.

Wang, H., R. Fu, A. Kumar, W. Li. 2010. Intensification of Summer Rainfall Variability in the Southeastern United States during Recent Decades, *Journal of Hydrometeorology.*

Walker, J.F., L.E. Hay, S.L. Markstrom, M. Dettinger. 2011. Characterizing climate-change impacts on the 1.5-yr flood flow in selected basins across the United States: A probabilistic approach. *Earth Interactions* 15 (18): 1-16.

Wang, H., R. Fu, A. Kumar, W. Li. 2010. Intensification of summer rainfall variability in the southeastern United States during recent decades. *Journal of Hydrometeorology* 11 (4): 1007-1018.

Wang, D. and M. Hejazi. 2011. Quantifying the relative contribution of the climate and direct human impacts on mean annual streamflow in the contiguous United States. *Water Resources Research* 47, W00J12; doi:10.1029/2010WR010283.

Webb, B.W., D.M. Hannah, R.D. Moore, L.E. Brown, F. Nobilis. 2008. Recent advances in stream and river temperature research. *Hydrological Processes* 22 (7): 902-918. doi: 10.1002/hyp.6994.

Webb, B.W. and F. Nobilis. 2007. Long-term changes in river temperature and the influence of climatic and hydrological factors. *Hydrological Sciences Journal* 52 (1): 74-85.

Webb, B.W. and D.E. Walling. 1993. Longer-term water temperature behavior in an upland stream. *Hydrological* Processes 7 (1): 19-32. 1993.

Wehner, M., D.R. Easterling, J.H. Lawrimore, R.R. Heim, R.S. Vose, B.D. Santer. 2011. Projections of future drought in the continental United States and Mexico. *Journal of Hydrometeorology* 12 (6): 1359-1377.

Wear, D.N. and J.G. Greis. 2011. The southern forest futures project: Summary report. Asheville, NC: USDA Forest Service Southern Research Station. Draft. http://www.srs.fs.usda.gov/futures/reports/draft/summary_report.pdf. Date accessed 7 September 2011.

West, B. 2002. Water quality in the South. In *Southern Forest Resource Assessment*, eds. D.N. Wear, J.G. Greis. US Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC. General Technical Report SRS-54: 455-476

Whitehead, P.G., R.L. Wilby, R.W. Battarbee, et al. 2009. A review of the potential impacts of climate change on surface water quality. *Hydrological Sciences* 54: 101–123.

Wu, W., C.A.S. Hall, F.N. Scatena. 2007. Modelling the impact of recent land-cover changes on the stream flows in northeastern Puerto Rico. *Hydrological Processes* 21 (21): 2944-2956.

Zhang, F. and A.P. Georgakakos. 2012. Joint variable spatial downscaling. *Journal of Climatic Change* 111 (3-4): 945-972. Online publication, doi:10.1007/s10584-011-0167-9.

Chapter 11

The Effects of Climate Change on Natural Ecosystems of the Southeast USA

CONTRIBUTING AUTHORS

Charles S. Hopkinson (chopkins@uga.edu; Department of Marine Sciences, University of Georgia, Athens, Georgia)

Alan P. Covich (Odum School of Ecology, University of Georgia, Athens, Georgia)

Christopher B. Craft (School of Public and Environmental Affairs, Indiana University, Indiana)

Kristine DeLong (Department of Geography and Anthropology, Louisiana State University, Louisiana)

Thomas W. Doyle (United States Geological Survey National Wetlands Research Center)

Neal Flanagan (Duke University, Wetland Center, Nicholas School of the Environment Durham, North Carolina)

Mary C. Freeman (Odum School of Ecology, University of Georgia, Athens, Georgia)

Ellen R. Herbert (School of Public and Environmental Affairs, Indiana University, Indiana)

Andrew Mehring (Odum School of Ecology, University of Georgia, Athens, Georgia)

Jacqueline E. Mohan (Odum School of Ecology, University of Georgia, Athens, Georgia)

Catherine M. Pringle (Odum School of Ecology, University of Georgia, Athens, Georgia)

Curtis J. Richardson (Duke University, Wetland Center, Nicholas School of the Environment, Durham, North Carolina)

This chapter examines those ecosystems not covered by other chapters in this report, focusing primarily on ecosystems of the southeast that are either aquatic or experience soil water saturation and flooding on a regular, annual basis. Agricultural and forest systems are discussed in separate chapters of this report. We were unable to be exhaustive in our ecosystem coverage, which means that several very important natural ecosystems of the Southeast (SE) are not discussed anywhere in this report.

Our approach was to broadly cover the impacts of key elements of climate change in the Southeast, including temperature, precipitation, storms, and ocean acidification. Hydrology and the water budget play a critical role in how the ecosystems covered in this report will be impacted by climate change, because of the close connection between temperature and precipitation with ecosystem evapotranspiration (ET). The interaction between the physical aspects of climate change and the feedbacks from biotic communities will affect the vulnerability and sustainability of natural ecosystems of the Southeast. Because of the possibility of rivers, reservoirs, and wetlands totally drying out because of climate change and human engineering of terrestrial and river systems, we find the aquatic systems of the Southeast to be perhaps the most susceptible to climate change. If our grandchildren are to be able to appreciate these natural ecosystems in their lifetimes, it is essential that we fully understand the complex linkages and feedbacks between the combined effects of climate change, land use change, and human engineering of the landscape.

Key Findings

Three very different aspects of climate change are very likely to affect natural ecosystems of the Southeast. Those aspects are (1) warming and hydrology (rainfall and evapotranspiration) (2) sea level rise (SLR), especially for tidal fresh to saline marshes and swamps, and (3) ocean acidification, especially for hard bottom reefs and coral reefs.

For all the natural ecosystems considered in this chapter, it is difficult to isolate the effects of climate change from the many other threats to these systems, including, for example, invasive species and disease, land use change, water withdrawals, and atmospheric deposition. A unique characteristic of many natural wetland ecosystems of the SE is that the combined effects of sea level rise, associated increase in salinity, increased interannual variability, and altered dry-wet cycles (see Chapter 2) likely will enhance the fluxes of potent greenhouse gases (GHGs), especially methane (CH_4) and nitrous oxide (N_2O), into the atmosphere. This increase in GHG emissions has implications for the USA carbon balance and its net contribution to the global increase in effective CO_2 concentrations in the atmosphere.

- For aquatic ecosystems in the SE an important aspects of climate change will be warmer water temperatures that are expected to put organisms closer to the threshold temperature for their thermal tolerance and exacerbate low dissolved oxygen conditions, which already characterize many of the blackwater streams draining the SE coastal plain.

- In parts of the Southeast, more frequent droughts coupled with increasing water demands from greater evapotranspiration (ET) and growing human consumption may result in more frequent stream drying, even in systems historically considered perennial, which may in turn increase the frequency of local species extirpations.
- Non-native, invasive species will increase due to less frequent and shorter durations of cold temperatures caused by climate change.
- Climate change is expected to have major harmful impacts in the increasingly rare longleaf pine savannas of the SE.
- Some parts of the SE are projected to experience more frequent droughts and higher rates of ET, which is expected to worsen the fire risk that is already the greatest threat to millions of acres of freshwater peat wetlands. CO_2 emissions during fire can reverse centuries of CO_2 sequestration and ultimately convert these systems from being net C sinks to significant C sources.
- In the SE tidal wetlands, the higher predicted rates of SLR are likely to outpace the ability of wetlands to accrete sediment and increase their elevation. As a result, wetlands are expected to become vulnerable to coastal erosion and increased inundation, eventually converting to open water. Such changes have been apparent in coastal Louisiana for several decades, where loss is exacerbated by high rates of land subsidence as well. With the loss of tidal wetlands, upland human settlements will lose important protection from storm surges, which could result in significant economic loss to coastal communities.
- Coral reefs and other hard-bottom reefs of the SE are also susceptible to climate change, especially due to warming waters, acidification, and sea level rise. Effects of ocean acidification and warming can be exacerbated when present with other stressors in reef systems, such as disease, coastal runoff, overexploitation, vessel damage, marine debris, and exotic species.

Climate effect on hydrology in the SE will be perhaps the single most important impact on natural ecosystems during the coming century. This aspect may also have the greatest policy relevance because society has the ability to control or regulate precipitation runoff, river flow, water storage, and water use. To some extent, warming of aquatic systems can be moderated by water management that insures adequate flow during summer months. Likewise, salinity intrusion and the upstream shifting of brackish habitats can be controlled, though not prevented, by water management that buffers the effects of droughts. Loss of river and noncoastal wetlands might also be moderated or controlled by water management policy that limits drainage, maintains connection to the river network, and meets minimal flow requirements of the various types of wetlands of the SE.

How natural ecosystems of the SE will respond to climate change is the subject of ongoing research. How climate changes will interact with other anthropogenic activities, such as land use change and human water use, are also important avenues of study. Available research suggests that future policy and management activities may need to be adaptive by design and changed as knowledge expands.

11.1 Background

In this chapter, the major ecosystems of the SE and Caribbean region are discussed, excluding those discussed in other chapters, namely natural and managed forests, agriculture, and the systems supporting major commercial fisheries and mariculture operations. This review begins with the aquatic systems of the SE, the lakes, reservoirs, streams, and rivers. The chapter then transitions down elevation to review the effects of climate change on savannas, then freshwater wetlands and swamps, tidal wetlands and swamps, and finally offshore coral reefs and hard-bottom reefs.

Not all natural ecosystems of the SE are discussed, only those that are considered to be most vulnerable to changes in the hydrologic cycle as a result of changes in temperature, precipitation, and evapotranspiration. Two types of systems that are uniquely vulnerable to other aspects of climate change, sea level rise and ocean acidification, are also discussed. Important systems not examined include maritime forests on barrier islands (Figure 11.1), other barrier island ecosystems, such as dunes (Greaver and Steinberg 2010), and southern Appalachian bogs. These should be included in future assessments of climate change in the SE.

Climate projections considered in this chapter were developed for the 2012 Southeast Climate Assessment report (Konrad et al. 2012), and are based on regional downscaling of the National Climate Assessment using the IPCC A2 and B1 scenarios for climate projections. The A2 scenario is somewhat pessimistic in that it assumes many nations will change behaviors only modestly. For the SE, it assumes population will triple by 2100. The B1 scenario in contrast is optimistic that nations will mitigate human activities that can further warm the planet. For the SE, it assumes population will increase about one-third by 2100. With respect to climate, all scenarios suggest there will be marked warming across the SE, especially during summer. Temperature is likely to increase 1.2˚C to 2.2˚C in the Caribbean to as much as 4.4˚C in interior regions of the SE. Warming will be pronounced in urban areas, because of the urban heat island effect (see Chapter 5). There likely will be increases in annual net precipitation across much of the SE, but with decreased rainfall during summers. There is increased likelihood for the number of extreme precipitation events to increase throughout the region especially across the lower Mississippi River Valley and along the northern Gulf coast. Interannual variability is projected to increase with greater likelihood of drought across the lower Mississippi River and Gulf Coast but fewer droughts across the northern tier of the SE region and in the mid-Atlantic. Thus we can expect to see increased frequency and severity of drought with consequent effects on hydrology and river flow. Sea level rise is expected to increase between 0.2 m and 2 m by the end of the century.

11.2 Southeastern Freshwater Aquatic Ecosystems

The aquatic systems of the SE are diverse and include the largest river system of the USA, the Mississippi and Atchafalaya Rivers; first-order mountain streams of the Smokey Mountains in Tennessee and North Carolina; manmade ponds and reservoirs so common on farms and throughout the Tennessee River Valley; the blackwater rivers of coastal Georgia, Florida and South Carolina; and the freshwater Everglades of Florida.

Figure 11.1 Maritime forests on some of the few remaining, relatively intact barrier islands of the Southeast, for example on Ossawbaw Island, GA, are vulnerable to climate change through the devastating impact of winds, surge, salt spray, and shoreline erosion from hurricanes and sea level rise. This artistic rendering by Philip Juras (*Passing Storm*, 2009, oil on canvas) shows remnants of the maritime forest now in the intertidal beach zone.

Streams, Rivers, Lakes and Reservoirs

Many freshwater ecosystems in the SE increasingly are subject to changing climatic conditions (Cook et al. 2007, Karl et al. 2009, Kaushal et al. 2010). Warmer waters, the potential for more frequent and severe droughts in some regions, and floods from more extreme storm events such as major hurricanes, will continue to alter freshwater ecosystems and will stress a wide range of freshwater species (Emanuel 2005, Gibson et al. 2005, Elsner and Jagger 2006, Shepherd et al. 2007, Parisi and Lund 2008, Kaushal et al. 2010, Dai 2011). Long-term (more than 100 years) decreases in rainfall have been observed for warmer months of the year for Georgia, North Carolina, and South Carolina (Alexandrov and Hoogenboom 2001). In some SE coastal plain regions, decreases in summer rainfall combined with increased groundwater withdrawals for irrigation are resulting in significant decreases in stream discharge (Rugel et al. 2012). These declines have been linked to decreased exports of carbon as suspended organic matter to coastal areas and with potential increases in local mineralization rates and corresponding release of CO_2 from streams (Mehring 2012).

Where long-term trends of increasing temperatures and extremes in rainfall (droughts and floods) occur, these are likely to alter distributions and abundance of freshwater algae, zooplankton, benthic invertebrates, and fish as well as ecosystem processes. In general, the effects of increased temperatures will decrease dissolved oxygen concentrations and increase rates of respiration for freshwater species. For example, many cold-water fish such as trout in southern Appalachian headwater streams are currently near their upper thermal limits during extreme summer heat waves (see Chapter 10). Even warm water species can be limited by extremely high water temperatures in shallow ponds and pools where cool, deep waters or spring-fed inflows are not available as thermal refugia. Of particular concern are largemouth bass, a large component of the multimillion-dollar recreational fishing industry in southeastern waters (Boyle et al. 1998, Hay 1988).

There are many direct and indirect ways in which warming can impact aquatic systems of the SE. Higher temperatures in shallow lakes and reservoirs can increase growth rates for warm-water species but only to thresholds of thermal tolerance (Rypel 2009). Higher water temperatures are also expected to exacerbate low dissolved oxygen conditions, which already characterize many blackwater streams that drain the southeastern coastal plain (Mulholland et al. 1997,Utley et al. 2008). Moreover, the prolonged droughts often associated with these warmer waters can also lower water levels and eliminate essential habitats for completion of life cycles and effective foraging. Fishes that disperse within large drainage basins can adjust to warmer temperatures by moving northward to find cooler waters if their routes for dispersal are unimpeded by dams, diversions, or dry-river channels (Matthews and Marsh-Matthews 2003, Ficke et al. 2007). However, the potential combination of record warm temperatures with possible increased frequencies and intensities of droughts (see Chapter 2) may place many species at risk over wide regions. Warmer waters also increase the exposure of freshwater fish and other species to diseases and parasites that diminish survivorship (Ficke et al. 2007). The increase in risk from toxic cyanobacteria that are extending their geographic ranges and causing massive fish kills is also associated with warmer waters where high nutrient loading can provide a competitive advantage to these harmful algae (Paerl et al. 2011). Warmer waters associated with droughts and floods are also linked to increases in various species of mosquitoes. Expanding ranges and pulsed population increases in these vectors that reproduce in temporary waters and wetlands can result in disease outbreaks among wildlife and humans (Shaman et al. 2002).

Impacts on rare species of fish and mussels are of particular concern in a changing climate. For example, freshwater mussel life-history connections can be disrupted by habitat loss for specific fish hosts (Box and Williams 2000). In addition, high densities of invasive bivalves such as zebra mussels (*Dreissena polymorpha*) and corbicula (*Corbicula fluminea*) may cause declines of native species of freshwater mussels during periods of low water (McMahon and Bogan 2001, Cherry et al. 2005). The Atlantic and Gulf sturgeon (*Acipenser oxyrinchus oxyrinchus, A. oxyrinchus desotol*) grow large by using both marine and estuarine habitats as adults and reproduce in coastal rivers along the Atlantic and Gulf of Mexico (Freeman et al. 2003, Grunwald et al. 2008). Their populations have declined previously due to overfishing, reduction in spawning sites by dam construction, and river pollution. These large, slow growing species require specific water depths, temperatures, and substrata for spawning in the remaining coastal waters available for sustaining their complex life histories. However, reduced flows from groundwater, lower river-water levels, and generally warmer waters during drought are additional stresses. These fish historically supported fisheries but are now considered imperiled. Shortnose sturgeon (*A. brevirostrum*), which remain in rivers their entire life, are also of particular concern as their southern range, limited by temperature, is likely to shift northward out of Georgia as warming proceeds in this century. This species is also vulnerable to impacts associated with salt water intrusion, as oligohaline tidal waters are a critical habitat during their multidecadal adult years.

The SE has the highest aquatic diversity of any temperate system; however, the ecological relationships and life histories of many SE species are not yet well understood within the constraints of current climatic variability (Golladay and Battle 2002, Golladay et al. 2004). In addition, sustaining this exceptionally high regional biodiversity is difficult because emerging cumulative effects are creating novel habitats and dynamics that have not previously been observed. Currently, many species declines are associated with widespread alteration of stream habitats and flow regimes, and these effects are expected to be exacerbated by climate change (Box and Williams 2000). Specifically, some areas may experience more frequent droughts coupled with increasing water demands. In these areas, the heightened water demand is expected to result in more frequent stream drying, even in systems historically considered perennial, and thus increasing the frequency of local species extirpations (McCargo and Peterson 2010, Peterson et al. 2011).To the extent that greater short-term flow variability occurs, particularly during warmer seasons, there will be expected lower reproductive success of many fish that require periods of stable flow during nesting, spawning, and juvenile development. Decreased base flows will reduce habitat availability and lower survival for species requiring flowing-water habitats. Freshwater mussel reproduction may fail if temperatures exceed tolerance levels or if low flows limit the effectiveness of mechanisms for attracting host fish. Decreased base flows in combination with nutrient loading from agricultural and urban areas may result in algal blooms that alter food webs and benthic habitats, shifting biotic communities as well as threatening water supplies. Where more frequent drought and unpredictable flow alter steam systems, these conditions are expected to result in faunal homogenization, in which communities become dominated by species most capable of re-colonizing or surviving in such conditions. Faunal homogenization is currently seen in the spread of the invasive red shiner (Walters et al. 2008), loss of highland endemic fishes from southern Appalachian streams (Scott and Helfman 2001, Scott 2006, Walters et al. 2003), and reduced diversity in fragmented and flow-altered systems.

Climate change is also expected to facilitate establishment of non-native and invasive species by lessening constraints imposed by frequency and duration of cold temperatures. Non-native subtropical and tropical species, including many species already established in Florida, and potentially spread by unintended release from aquaculture (e.g., Tilapia, *Oreochromis* spp.), aquaria, or live fish markets (e.g., swamp eel, *Monopterus* spp.) may increase with warmer and milder winters (Collins et al. 2002, Nico et al. 2011). Higher stream temperatures and greater streamflow variability may also favor invasive species, which often have wider environmental tolerances than native species (Rahel and Olden 2008). The spread of invasive zooplankton such as *Daphnia lumholtzi* is expected to increase in response to warmer waters (Fey and Cottingham 2011).

In every region, it is difficult to isolate the effects of climate change from the other aspects that threaten freshwater species. For example, accelerated erosion from climate change, or from flooding induced from land-use changes, diminishes habitat quality for many species. Although rivers and reservoirs fill with sediment during floods and water levels decline during droughts, the subsequent dredging of rivers to maintain shipping channels can have a longer-lasting effect on many freshwater species than the shorter term climate-related impacts. Additionally, warmer summers and growing populations increase societal demand for freshwater. Heat waves require more cooling waters for energy production to meet the increased use of air-conditioning and for pumping water to irrigate crops. The rapid increase in construction of water storage reservoirs and ponds in the SE has created relatively permanent changes in the region's hydrology. Reservoirs are also associated with increased introductions of invasive species (Rahel and Olden 2008). Freshwater habitats have lost critical characteristics of their natural flow regimes (Gibson et al. 2005, Poff et al. 2007). In many cases, the past connectivity among headwater streams, groundwater, rivers, and their floodplains has been modified or lost completely (Freeman et al. 2007). These changes and losses of habitats may continue or even increase as solutions are devised for increasing water storage to meet growing demands, mitigate droughts, and regulate floods.

11.3 Southeastern Savannas

Fire-dependent longleaf pine (*Pinus palustris*) savannas historically covered much of the southeastern Coastal Plain, but are now less than 5% of the landscape (Christensen 2000, Keddy 2009). Remnant examples of these savannas (Figure 11.2) classified hydrologically as wet, mesic (moist), or dry--are some of the most species-rich terrestrial communities ever measured at small spatial scales, ranging to more than 50 species per square meter (Walker and Peet 1984). Diversity is particularly high on frequently burned mesic and wet savannas, and is exemplified by abundant orchids and carnivorous plants such as pitcher plants (*Sarracenia* spp.), sundews (*Drosera* spp.), and the native range of Venus fly trap (*Dionaea muscipula*). East of the Mississippi River, longleaf pine savannas contain abundant wiregrass (*Aristida* spp.) in the understory; west of the Mississippi wiregrass is replaced by little bluestem (*Schizacharium scoparium*), a grass also common in the tallgrass prairies of the Midwest. A recent study in the western Gulf Coastal Plain using fire scars on longleaf pine trees growing in mesic longleaf-bluestem savannas suggested an average fire frequency of 2.2 years during the period from 1650 to 1905 CE—one of the most frequent fire histories ever documented (Stambaugh et al. 2011). These fires typically occur in the growing season, with important consequences for plant reproduction. Wiregrass and other savanna species only flower after growing season fires and not after managed fires set in the dormant season (Platt et al. 1988). In wet savannas, abundant *Sphagnum* peat moss and dead peat have accumulated and currently store significant amounts of carbon.

With warmer temperatures, diminished summer precipitation, and an increase in frequency and severity of drought predicted for parts of the Southeast over the remainder of the century, the likelihood of fire will increase as well (Mearns et al. 2003, Liu et al. 2010). The combined effects of drought, warmer temperatures, and higher fire probability likely will increase the flow of carbon to the atmosphere by the decomposition

Figure 11.2 Longleaf pine savanna of the southeastern Coastal Plain. This forest is actively managed through controlled burns on the Fort Stewart Military base in Georgia. Species diversity is particularly high in these ecosystems. While warmer winter temperatures may benefit the longleaf pine ecosystem in the northern range margin, the majority of longleaf pine savannas likely will fare less well due to increasing summertime droughts. (*Photograph by Charles Hopkinson.*)

and burning of drier vegetation and peat, as in other peatland ecosystems throughout the world (Ise et al. 2008, Taylor 2010, Hergoualc'h and Verchot 2011).

In addition to fire, the composition and function of these ecosystems are strongly influenced by drought frequency. In most of the longleaf pine range, spring and summer precipitation are the most important climatic variables associated with growth. While warmer winter temperatures may benefit the longleaf pine ecosystem in the northern margin of its range, most longleaf pine savannas will likely fare less well if future conditions include increasing summertime droughts (See Chapter 2).

Wet longleaf pine savannas often grade into swamps dominated by cypress tree species (*Taxodium distichum* and *T. ascendens*) and swamp gums (*Nyssa biflora* and *N. aquatica*). A 10year study in coastal South Carolina analyzed tree growth and ecosystem productivity in forests across a range of soil moisture types and found that severe drought affected wet swamp forests more than mesic oak-pine forests or dry longleaf ecosystems (Conner et al. 2011). Another study found that spring and summer precipitation and temperatures were the most important environmental variables explaining tree growth in swamps of the Congaree National Park (Doyle 2009). In both cypress-gum swamps and longleaf pine savannas, predicted increases in the frequency of major hurricanes (see Chapter 2) likely will increase forest damage and create biophysical feedbacks to climate through temporary changes in surface albedo (reflectivity) and reductions in evapotranspirative cooling (Juárez et al. 2008).

11.4 Southeastern Freshwater Marshes and Swamps

Freshwater marshes and swamps of the SE are found throughout the region, but they are especially prevalent along low gradient river systems (e.g., Mississippi and Atchafalaya Rivers) and the extensive coastal plain physiographic province that lies between the Atlantic and Gulf coasts and the fall-line adjacent to the Piedmont province. While many of these wetlands are perennially connected to the river network, others are continually isolated or connected via ephemeral streams. Land use changes for urbanization or agriculture significantly affect the integrity of these systems and must be considered along with climate change for future assessments.

As with the stream, river, lake, and reservoir aquatic systems of the SE, freshwater marshes and swamps are also highly vulnerable to warming, changes in precipitation quantity and severity of storms, and the frequency and severity of drought. The combined effects of warming and changes in precipitation likely will alter overall hydrology including increased evapotranspiration and reduced stream base flows (IPCC 2001, Mulholland et al. 1997, Schindler 1997, Vörösmarty et al. 2000). In general, temperature regimes of freshwater ecosystems are projected to change in parallel with shifts in air temperature because of the tight relationships between air and water temperature (Mohseni and Stefan 1999, Mohseni et al. 2003, Allen et al. 2005). Alterations of regional and catchment hydrology predicted by global climate models include increasing frequency and intensity of extreme precipitation events driven by increased temperature (Easterling et al. 2000), although increased water inputs may be offset by increased evapotranspiration and runoff, and these effects may exhibit high regional variability (M.C. Todd et al. 2010 and 2011). Resulting impacts of climate change on riverine wetland ecosystems are predicted to include increased periods of water drawdown, greater frequency and intensity of high flow events, and increased water temperature (IPCC 2001, Alcamo et al. 2003, Carpenter et al. 2005, Webster et al. 2005, IPCC 2007, Erwin 2009, Mulholland and Sale 1998).

Wetland ecosystems will play a critical role in determining climate change feedbacks, as shifts in hydrology and increased soil temperature will enhance GHG emissions at catchment and regional scales (Erwin 2009) further contributing to climate change. The vast amount of carbon stored in the peat soils of the pocosins and Everglades makes them especially important due to the danger of an autocatalytic reaction between climate change and drought: as climate change leads to more drought, it also leads to more oxidation of peat soil, which releases GHGs and further speeds the rate of GHG induced atmospheric warming and more drought. Drainage of these wetlands has also caused large carbon losses from soil and slower rates of carbon storage, contributing to global climate change (Bridgham et al. 2006).

Ecosystem fluxes of greenhouse gasses, including CO_2, N_2O, and CH_4, depend not only on hydrologic position and flow paths within wetland complexes (Pennock et al. 2010), but also exhibit considerable temporal variation with changes in hydroperiod, including hydrologic pulsing from surface water inputs (Altor and Mitsch 2008, Mander et al. 2011). The responses of biogeochemical cycling of carbon and nitrogen to climate change impacts in southeastern wetlands ecosystems are particularly understudied, and represent a critical source of uncertainty in projecting future climates (Clough et al. 2007). The types of wetlands addressed in this assessment represent known and predicted climate change effects on freshwater wetlands in the southeastern USA. They include the Carolina Bays and Pocosins, mountain bogs, riverine floodplain swamps, coastal wetland forests, and the Florida Everglades.

Fire is the greatest threat to these wetland ecosystems under climate-induced drought. For example, a recent study estimated carbon emissions for a large peatland fire in North Carolina using remote sensing to reconstruct burn severity and topographic Light Detection and Ranging (LiDAR) to estimate peat burn depths (Poulter et al. 2006). This study estimated that total carbon emissions for a 40,000-ha (98,842-acre) 1985 fire was from 1 to 3.8 Tg (1.1 to 4.2 million tons), with spatially heterogeneous patterns of carbon fluxes from 0.2 to 11 kg C m^{-2} (4.7 to 258 lb C ft^{-2}) depending on vegetation type, peat burn depth, soil substrate (mineral or organic), and fire severity. A more recent fire in the Pocosins Lakes Wildlife Refuge during the severe drought of 2008 burned 16,785 ha (41,549 acres) of abandoned drained peatlands, releasing an estimated 10 million metric tons (11 trillion tons) of carbon from the peat soil to the atmosphere. These two events show the potential for massive releases of carbon from fires in Pocosin peatlands under lower water tables resulting from climate-induced droughts.

Carolina Bays

Southern wetlands are vulnerable to changes in precipitation frequency and warmer temperatures, especially as these changes are likely to result in more frequent droughts and higher rates of evapotranspiration (Mulholland and Sale 1998). Wet and dry cycles are thought to drive plant community dynamics in Carolina Bay wetlands, with wet periods characterized by larger areas of aquatic and emergent species and dry periods leading to the expansion of grasses and woody species. The potential increase in drought frequency would be likely to drive a shift to communities dominated by less flood tolerant woody species, especially in smaller bays that are more prone to drying (Stroh et al. 2008). Future cycling between wet and dry conditions likely will be driven by a balance between changes in precipitation, and increased evapotranspiration by increased temperature (Pyzoha et al. 2008). In southern mountain bogs, predicted increases in evapotranspiration in concert with anthropogenic increased nitrogen deposition might lower water tables and accelerate peat decomposition leading to a shift to alternative ecosystems (such as ephemeral wetlands or dry land ecosystems) and local extinction of several bog species (Schultheis et al. 2010).

Pocosins

Pocosins, also known as southeastern shrub bogs, are characterized by a very dense growth of mostly broadleaf evergreen shrubs with scattered pond pines. The typically thick layer of peat soils, 1 m to 3 m (histosols), underlying pocosin soils store nearly 300 Mt (330.7 million tons) of carbon in North Carolina alone (Richardson 2012). Under normal saturated hydrologic conditions, decomposition in organic soils is minimized due to a lack of oxygen, allowing for accumulation of organic carbon. Bridgham and Richardson (1992) incubated peat from pocosins in anaerobic conditions and found very low CH_4 production potentials relative to other peatlands. However, they also found that CO_2 increased greatly in aerobic soils under drought conditions--a climate scenario projected to happen in parts of the southeastern USA under climate change (IPCC 2007, also see Chapter 2). A recent field study by Morse et al. (2012) in restored and natural Pocosin soils also found very low levels of CH_4 release to the atmosphere in comparison with CO_2 and N_2O under dryer conditions. Morse found increases in CH_4 gas under higher water levels, more CO_2 release from dryer soils and seasonal fluxes of CO_2 to the atmosphere, further supporting the earlier findings of Bridgham and Richardson (1992) and suggesting that climate-induced drought could change the magnitude and form of GHG fluxes. Further research is needed to establish how these GHG fluxes will change.

Southern Bottomland Swamp Communities

In southern bottomland swamp communities, alteration of growing season length and water regime could influence the ability of dominant canopy species to regenerate. Middleton (2009) found a distinct shift in species that germinate under flood and nonflood conditions within bald cypress (*Taxodium distichum*) swamps, and concluded that with the already low regeneration potential of dominant tree species, the range of bald cypress swamps may be compressed from the South in future climate scenarios. Stallins et al. (2010) found the interplay of lower baseflow on Apalachicola River, floodplain geomorphology, and canopy gap dynamics was associated with shifts in species composition of the floodplain forest canopy. This trend was most pronounced in backwater swamps where obligate wetland tree species, such as water tupelo (*Nyssa aquatica*), ogechee tupelo (*N. ogeche*), and Carolina ash (*Fraxinus caroliniana*), have undergone marked reductions in stem densities and there has been a muddling of the compositional contrasts between plant communities along the wet to dry gradient that typifies riparian floodplains.

The hydrology of coastal forested wetlands is expected to be very responsive to changes in both precipitation and temperature with declines in floodplain water table elevations and stream base flows expected under many future model scenarios (Dai et al. 2010, Dai et al. 2011). Similar results are seen in pine flatwoods where these effects are expect to be most pronounced in depression wetlands during dry cycles (Lu et al. 2009). Conner et al. (2011) examined the effects of drought on ecosystem productivity along a moisture gradient within coastal plain wetland forests in South Carolina and found that, both in terms of trunk diameter and above ground net primary productivity, wet sites were more sensitive to drought conditions than drier sites.

Everglades

The successional dynamics of the Everglades are mainly controlled by the interaction of climatic patterns (droughts and rainfall) and human alterations of hydroperiod, which in turn influence fire frequency and the degree of fire intensity as well as the transfer and release of carbon and nutrients on the landscape (Richardson 2008). In the Everglades, the dominant sawgrass (*Cladium mariscus,* spp. *jamaicense*) communities (Figure 11.3) growing typically on one to three meters of peat are thought to be resilient to a wider range of inundation durations and depths than other species, although prolonged periods of flooding cause problems (Richardson 2008). However, other communities such as pine savanna, red mangrove scrub, bay-hardwood, and muhly grass have more pronounced physiological limitations to inundation depth, duration, or both, and are more restricted in their distribution (Richardson 2008, MJ. Todd et al. 2010). Within the context of more extreme cycling between wet and dry conditions, this suggests that these plant communities may undergo a contraction of spatial extent under future climate scenarios. Knowledge of long-term climatic patterns is important to understand changes within the Everglades. With impending sea level rise due to global climate change, saltwater becomes even more of a factor as it invades farther into the southern Everglades and alters freshwater communities (Bartlett et al. 1995). It is unclear whether freshwater flow can counteract or prevent saltwater intrusion associated with sea level rise. A sudden change from freshwater to saltwater conditions may accelerate oxidization of organic substrate leaving large areas of thin substrate or bare limestone bedrock with a greatly reduced potential for plant community shifts in response to climate change (Pearlstine et al. 2010, Willard and Bernhardt 2011).

Figure 11.3 *Nymphaea* open water slough surrounded by Sawgrass (*Cladium jamaicense*) in the central Everglades. The peat depths are 1.8 m at this site. Wetland prairies such as these are highly vulnerable to changes in the hydrologic cycle. While these systems are currently strong carbon sinks, under a warmer and drier climate they could become carbon sources emitting powerful greenhouse gases such as CH_4, in addition to CO_2. (*Photograph by Curtis J. Richardson.*)

11.5 Southeastern Tidal Marshes and Swamps

The greatest expanse of tidal wetlands in the continental USA is found in the Southeast. More than half of all tidal marshes are associated with the Mississippi River delta in coastal Louisiana. Because of their location at the land-sea interface, these areas are impacted by changes occurring in the sea as well as throughout the upland watersheds that drain to the coast. The magnitude of ecosystem services provided by these systems is among the highest of all ecosystems. They provide water quality amelioration benefits, high rates of carbon sequestration, and nursery grounds that support the vast majority of recreational and industrial fisheries in the SE region, and storm surge abatement that protects hundreds of billion dollars of coastal real estate (Barbier et al. 2011).

Coastal wetlands, sentinel ecosystems for environmental change and human-induced degradation of natural systems, are predicted to disappear at an accelerating rate (Nicholls et al. 1999, Nicholls et al. 2007). The distribution of coastal wetland habitats is determined predominantly by land elevation relative to sea level, freshwater, and climate. Climate change is predicted to cause widespread degradation of the coastal wetlands of the southeastern USA due to sea level rise (SLR), changes in freshwater flows, and increased frequency of extreme weather events (Meehl et al. 2007, Karl et al. 2009). Human activities, including hydrologic alterations (e.g., dams and levee construction), coastal development, and pollution will likely interact with climate change and further degrade coastal systems (Gedan et al. 2009). The most pressing issues for wetlands facing climate change and how they will alter the coastal landscape are discussed in the following paragraphs.

Sea level is the overriding factor determining the existence of tidal wetlands (Figure 11.4). Tidal wetlands have existed in a state of equilibrium with sea level rise (~0.2 mm/year) over the past 4,000 years by accumulating mineral sediment and organic matter produced by marsh vegetation (Morris et al. 2002, Mudd et al. 2009). Rates of SLR along the southeastern Atlantic and Florida coasts (2.5 mm/year) are comparable to the current global average of 2 to 3 mm/year (Meehl et al. 2007, NOAA 2011). Rates of SLR in the Louisiana Gulf Coast are much higher (9.5 mm/year) due to a combination of human activity and tectonic subsidence (NOAA 2011). Climate change is predicted to accelerate SLR in the coming century resulting in a sea level increase of up to 2 m or more by 2100 (see Chapter 2), Meehl et al. 2007, Rahmstorf 2007, Rahmstorf et al. 2007, Richardson et al. 2009, Vermeer and Rahmstorf 2009). As rates of SLR outpace the ability of wetlands to build elevation, they will become vulnerable to coastal erosion and increased inundation rates, eventually resulting in the conversion of coastal wetlands to open water (Day and Templet 1989, Donnelly and Bertness 2001, Craft et al. 2009, Kirwan et al. 2010).

Anthropogenic activities will reduce the ability of coastal wetlands to adapt to SLR. Increased freshwater and fossil fuel withdrawals increase local subsidence rates (Yuill et al. 2009). The construction of dams and other freshwater control devices reduce sediment delivery to the coast (Slattery et al. 2002, Graff et al. 2005). Large scale disappearance of wetlands in Louisiana has already been observed as sea level rises and sediment supply is restricted by large scale river alterations (Blum and Roberts 2009). At the same time, development has restricted the ability of coastal wetlands to migrate inland and upland with SLR via shoreline hardening and the placement of fill in the immediate coastal zone (Feagin et al. 2010).

The Atlantic Multidecadal Oscillation (AMO) and El Nino–Southern Oscillation (ENSO) cycles are closely linked to regional climate and ocean temperatures (see Chapter 2 Konrad et al. 2012). Increasing average sea temperatures over the past 40 years have been correlated with increased intensity of hurricanes, which in turn have been correlated with an increase in average summer wave heights in the Atlantic (Komar and Allan 2008, Kunkel et al. 2008). Increased storm and wave intensity cause erosion and shoreline retreat of coastal wetlands. Coastal wetlands are important for dissipating storm energy and their loss leads to the increased vulnerability of human structures on coastlines to wave erosion (Gedan et al. 2011). Storm surges can also introduce saltwater into sensitive freshwater ecosystems increasing wetland degradation.

Climate models predict greater interannual variability in temperature and precipitation with the potential for greater frequency of droughts and floods that, in combination with increased temperatures and accelerated rates of evapotranspiration across terrestrial landscapes, will alter the availability of freshwater to the coast. Increased human demands for freshwater and changes in seasonal precipitation patterns have and likely will continue to alter the timing and magnitude of freshwater delivery to the coast. Changes in precipitation regimes, storms and anthropogenic alterations of freshwater flows are predicted to compound the effects of SLR, resulting in saltwater intrusion into freshwater wetlands (Smith et al. 2005, Hilton et al. 2008, Craft et al. 2009).

Figure 11.4 Tidal salt water marshes and swamps, such as this *Spartina alterniflora* marsh near Sapelo Island, GA, are particularly vulnerable to sea level rise. If they are unable to build in elevation as rapidly as sea level rises, they will revert to open-water areas. Salt marshes are critical habitats for most of the commercial fisheries of the SE USA. (*Photograph by Christopher Craft.*)

Saltwater intrusion into coastal freshwater wetlands will accelerate the release of organic carbon by stimulating microbial decomposition, especially sulfate reduction, and negatively affect plant productivity and alter species composition (Craft 2007, Weston et al. 2006, Spalding and Hester 2007, Neubauer and Craft 2009, Neubauer 2011, Weston et al. 2011). Increased decomposition will lead to a reduced capacity to sequester carbon, increased greenhouse gas production (CO_2 and CH_4), and a reduced capacity to build elevation against SLR (Neubauer and Craft 2009, Neubauer 2011). Nitrogen cycling (e.g., denitrification, nitrification, and nitrogen accumulation) will be negatively affected by salinity, reducing nitrogen removal from coastal waters and increasing coastal eutrophication (Rysgaard et al. 1999, Giblin et al. 2010, Weston et al. 2010).

Plant metabolic processes will be stressed by the interaction of increased flooding and salinity as well as increased temperature. Saltwater intrusion and increased evapotranspiration caused by elevated temperatures will elevate soil salinities, thus coastal wetland plant communities will shift towards species with greater salinity tolerance (Craft et al. 2009, Neubauer and Craft 2009). Increased inundation can stimulate plant growth at limited water depths (40 to 60 cm below mean high tide), beyond which it will cause mortality (Morris et al. 2002, Kirwan et al. 2010). Increased temperatures and longer growing seasons might increase net primary productivity (Kirwan et al. 2009). Though increased productivity may help coastal wetlands build elevation against SLR via the addition of organic matter to soils (Pendall et al. 2004, Langley et al. 2009), increased rates of decomposition due to higher temperatures, saltwater intrusion, and coastal eutrophication may limit or negate this effect (Langley and Megonigal 2010, Kirwan and Blum 2011). Increased CO_2 concentrations also favor plants with a C3 metabolism over those with a C4 metabolism, indicating that large-scale shifts in plant community compositions may occur, which will have implications for habitat use and food resources for fish, birds, and other fauna (Rasse et al. 2005). The complex interactions between these factors are poorly understood, but will determine how plant communities respond to climate change.

Unpredictable nonlinear interactions may increase susceptibility of marsh ecosystems to drought and increased salinity. For example, Silliman et al. (2005) found that drought and salinity induced die-off of salt marsh vegetation was exacerbated by herbivore grazing. Large-scale diebacks of salt marsh vegetation, called "brown marsh," occurred along the southeastern and Gulf coasts between 2002 and 2004, affecting more than 250,000 acres (McKee et al. 2004, Silliman et al. 2005). These diebacks may accelerate salt marsh conversion to open water (McKee et al. 2004).

Tidal freshwater forests are extremely vulnerable to climate change (Figure 11.5). More than 80% of tidal wetland forests occur in the SE USA and dieback and retreat of these systems has been observed over the past several decades (Connor et al. 2007). Saltwater intrusion stunts the growth of the dominant species, such as bald cypress (Krauss et al. 2009), and extended periods of chronic saltwater exposure caused by SLR lead to forest dieback (Connor et al. 2007). These systems are also sensitive to increased flooding associated with SLR, not just salt water exposure as rising sea levels will cause river water to backup and increasingly flood oligohaline wetlands (Connor et al. 2007). While herbaceous marshes can adapt to climate change by building elevation and rapid community shifts, tidal freshwater forests are less able to adapt via vertical accretion or migration due to their slow growth and development, low sedimentation rates, and adjacency to upland areas. They are often replaced by herbaceous freshwater and brackish marshes that alter habitat and decrease overall potential for carbon sequestration as woody biomass (Connor et al. 2007). Desantis et al. (2007) report that exposure to salinity stress as little as a few times a year reduces species diversity in Florida Gulf Coast tidal freshwater forests, converting communities with more than 20 species to low-diversity stands of cabbage palm (*Sabal palmetto*) and southern red cedar (*Juniperus virginiana*). At low elevations, increased frequency of saltwater intrusion causes these systems to convert to herbaceous marsh (Desantis et al. 2007, Geselbracht et al. 2011).

Climate change will facilitate the expansion of invasive species by altering climatic constraints and transport of invasive species (Hellmann et al. 2008). Cold weather is one of the primary factors limiting the abundance of the invasive semi-aquatic rodent nutria (*Myocastor coypus*; Dedah et al. 2010 and references therein). Nutria burrowing and feeding activities destroy root systems and depress soil accretion leading to erosion and submergence of wetlands (Gedan et al. 2009). The invasive tree Chinese tallow (*Triadica sebifera*) is predicted to move 300 to 700 km north of its current range with a 2°C increase in temperature (Pattison and Mack 2008, Wang et al. 2011) and *Melaleuca quinqueneria* is predicted to similarly expand its range northward. Hurricanes and other storm events may aid in the spread of invasive propagules, and repeated hurricane disturbance has been shown to favor certain invasive species over their native counterparts, for instance *Iris pseudocorus* over *I. hexagona* (Pathikonda et al. 2009). Direct

Figure 11.5 Tidal freshwater forest along the Satilla River in coastal Georgia. These forests are particularly vulnerable to salt water intrusion that occurs with sea level rise. Vegetation likely will be replaced by salt tolerant marsh species, such as *Zizaniopsis* sp. During the transition these environments can emit high rates of greenhouse gases, including CO_2 and CH_4. (*Photograph by Christopher Craft.*)

human actions could also enhance invasive potential for two highly productive and aggressive invasive species, *Arundo donax* and *Phalaris arundinacea,* which are being explored for biofuel production (Hellmann et al. 2008).

Warming may also facilitate the expansion of certain native species at the expense of others. Mangrove wetlands are limited by periodic freezes to southern Florida and the Louisiana and Texas coasts (Sherrod and Mcmillan 1981 and 1985, Mcmillan and Sherrod 1986, Sherrod et al. 1986, Pickens and Hester 2011). Multiple observations confirm the northward advance of mangrove species over the last 20 years due to the lack of freezes in the Gulf and South Atlantic regions (Zomlefer et al. 2006, Michot et al. 2010). Sea level rise is facilitating mangrove encroachment on the salt marsh dominant species *Spartina alterniflora* and allowing mangroves to move inland with saltwater intrusion to replace freshwater marshes on the Florida coast (Doyle et al. 2010, Krauss et al. 2011). Though there is some evidence that mangroves may build elevation in response to SLR more readily than salt marsh and may be more resilient to storm surges (McKee et al. 2007, Kumara et al. 2010), increased mangrove dominance has implications for coastal food webs, economically important fisheries (e.g., fish, shrimp, and other shellfish) and recreational activities.

Changes in the extent and productivity of wetland plant communities will have cascading impacts on fisheries, migratory birds, and bird breeding habitat (Craft 2007, Craft et al. 2009). Wetlands provide refuge and food for many post-larval and juvenile fish, crustaceans, and mollusks that are important to the maintenance of viable commercial and recreational fisheries (UNEP 2006). These systems provide habitat for resident and migratory water birds that are important to hunters and bird watchers. Many of these species rely on the preservation of an entire estuarine landscape because they feed in salt marshes but breed and nest preferentially in freshwater wetlands or upland edge habitat (e.g., the wood stork, painted bunting) (Winn et al. 2008, Brittain et al. 2011). Other species (e.g., rails) select nesting locations in relation to tide levels, putting them in danger as sea level rises and storm surges intensify (Rush et al. 2010, van de Pol et al. 2010). Delivery of ecosystem services associated with water quality improvement and carbon sequestration likely will decline as tidal wetland habitat is lost or altered (Craft et al. 2009).

Recent model simulations suggest the combined impacts of accelerated SLR and saltwater intrusion will drastically alter the estuarine landscape over the next century through submergence and landward migration of estuarine systems (Craft et al. 2009, Neubauer and Craft 2009). The greatest losses likely will occur at both ends of the estuarine spectrum, namely salt marshes and tidal freshwater forests (Donnelly and Bertness 2001, Craft et al. 2009, Geselbracht et al. 2011). Climate change impacts on both terrestrial and marine systems also affect wetlands, the future survival of which will depend on management of an entire continuum of landscapes from the headwaters of rivers to the ocean.

11.6 Coral Reefs of the Southeast USA

Coral reefs and hard bottom reefs are some of the most biologically diverse ecosystems in the temperate, subtropical, and tropical oceans (Veron 2000). In the southeastern USA, stony corals exist in the shallow waters of the western Atlantic, the Gulf of Mexico, as well as US territories in the Caribbean including Puerto Rico, the US Virgin Islands, and Navassa Island (Figure 11.6). Most of these reefs are within managed areas including three national parks (Biscayne, Dry Tortugas, and Virgin Islands); national monuments and national historical parks (Buck Island and Salt River Bay); national marine sanctuaries (Flower Garden Banks, Florida Keys, and Gray's Reef); and a state park (John Pennekamp in Florida). Other coral reefs are found along the SE coast of Florida from Martin County to Dade County, Florida. Middle Grounds and Pulley Ridge in the Gulf of Mexico contain some of the deepest stony corals in the USA. Detailed assessment and status reports for coral reefs in the USA have been produced by NOAA, Global Coral Reef Monitoring Network, and Reef and Rainforest Research Center. In the following section, some aspects of these reports are summarized as they relate to the effects of global climate change (Waddell and Clarke 2008, Wilkinson 2008, Wilkinson and Souter 2008).

Figure 11.6 Location of coral reefs in the SE USA including Flower Garden Banks (FGB), Florida Middle Grounds (FMG), Pulley Ridge (PR), Dry Tortugas (DT), Florida Keys (FK), Biscayne (B), southeast Florida reefs (SEFL), Gray's Reef (GR), Navassa Island (NI), Puerto Rico (PRR), and US Virgin Islands (USVI). Orange areas are coral reefs from ReefBase (http://reefgis.reefbase.org/).

Coral reefs worldwide are in decline as a result of multiple stressors, including climate change (Wilkinson 2008). The Florida Keys and US Caribbean reefs, once structurally complex, have declined with few reefs exhibiting a mean live coral coverage greater than 10% (Waddell and Clarke 2008) and with 21% of the reefs destroyed are unlikely to recover (Wilkinson 2008). The largest changes documented since the 1970s indicate that the most prevalent branching corals, the acroporid corals, have experienced population declines of greater than 90% (Acropora Biological Review Team 2005). Two of these corals, *Acropora palmata* and *A. cervicornis*, were listed in 2006 as threatened under the Endangered Species Act (Hogarth 2006). In 2010, the National Marine Fisheries Service found sufficient evidence to list 82 additional coral species as threatened, including eight Caribbean species (NOAA 2010). The majority of coral reefs in the Caribbean-Atlantic-Gulf of Mexico region are reported to be in poor or fair condition with Flower Garden Banks having the fewest threats (Waddell and Clarke 2008). However, the 2010 Deepwater Horizon oil leak occurred to the east of Flower Garden Banks and monitoring continues to assess any impacts from the accident.

The major direct climate change threats to coral reefs are increases in water temperature, ocean acidification, and sea level rise (IPCC 2007). Effects of ocean acidification and warming can be exacerbated when coupled to other stressors in reef systems, including disease, coastal runoff, overexploitation, vessel damage, marine debris, and exotic species (Carilli et al. 2009). In 1983, 93% of a sea urchins species, *Diadema antillarum,* died in the Caribbean (Lessios 1988). Sea urchins are important because they graze on algae thereby providing suitable habitat for coral settlement. Diseases of coral reef organisms can be expected to increase in the future as climate change stressors increase (Richardson 1998, Waddell and Clarke 2008). Coral diseases include coral bleaching, black-band disease, dark-spots disease, red-band disease, white-band disease, white-plague disease, white pox, and yellow-blotch disease (Richardson 1998).

There is active investigation and research of climate change impact on corals and their capacity to adapt. While some studies report declining coral growth rates (De'ath et al. 2009, Cantin et al. 2010, Manzello 2010), others show some species having greater extention rates but with decreased skeletal density (Helmle et al. 2011). Additionally some studies suggest that changes in temperature may offset changes in pH for some corals (Cooper et al. 2012, McCulloch et al. 2012), while others suggest the opposite (Rodolfo-Metalpa et al. 2011). There has been concern that high CO_2 levels (Veron et al. 2009, Veron 2011) may lead to the demise of corals, but some studies suggest corals may adapt or survive in refugia (Hughes et al. 2003, Fabricius et al. 2011, Howells et al. 2012, Karnauskas and Cohen 2012).

Prolonged events of abnormal water temperatures lead to coral bleaching, when corals expel the symbiotic zooxanthellae that provide the coral with nutrients (Muscatine 1973, Jokiel and Coles 1977). Corals can recover from short duration bleaching events (i.e., days); however, prolonged or drastic temperature changes for weeks can result in bleaching that leads to coral death (Jokiel and Coles 1977). Such events were unheard of before the 1970's and are now occurring in some locations with increased frequency (3 to4 years) and currently bleaching events take place each summer somewhere in the USA coral reef system (Wilkinson and Souter 2008). A massive regional coral bleaching event affected virtually the entire Caribbean basin in the late summer and fall of 2005.

Following this bleaching event, a coral disease epidemic resulted in about a 50% decline in live coral cover and in places up to 90% mortality (García-Sais et al. 2006, Miller et al. 2006, Wilkinson and Souter 2008). Conversely, cold water events can also lead to bleaching and coral death, such as the anomalous cold event in 2010 that killed numerous near-shore corals in the Florida Keys and southeast Florida (NOAA 2011, Colella et al. 2012).

Tropical storms can have damaging effects on coral reefs by overturning colonies, altering the habitat, increasing turbidity, and increasing nutrient concentrations from land runoff (Wilkinson and Souter 2008). During the 2005 hurricane season, extensive damage to coral reefs occurred in the Flower Garden Banks, the Dry Tortugas, and the Florida Keys; however, these reefs were spared from bleaching because the passing hurricanes reduced water temperatures (Stone et al. 2005, Gierach and Subrahmanyam 2008, Wilkinson and Souter 2008). An increase in the frequency of intense tropical storms predicted by climate models (Trenberth and Shea 2006, Bender et al. 2010, Mousavi et al. 2011, see Chapter 2), would result in more wave damage to coral reefs while scouring some areas and accumulating sediments and rubble in others thus altering the coral reef habitat (Wilkinson and Souter 2008).

Much remains to be learned concerning the effects of ocean acidification in coral reef systems from the physiological scale to ecosystem level (Fabricius et al. 2011, Pandolfi et al. 2011). Decreases in pH reduce growth rates of organisms that have calcified skeletons, such as corals; mollusks; and some plankton, echinoderms, and crustaceans (Veron et al. 2009). Changes in ocean pH have been documented for the Caribbean and Gulf of Mexico (Gledhill et al. 2008, Gledhill et al. 2009) and ocean acidification models predict pH may drop another 0.3 pH units by 2100 with business-as–usual climate change scenarios (Caldeira and E.Wickett 2003, Feely et al. 2009, National Research Council of the National Academies 2010). Future projections that model continued warming and ocean acidification show increased coral bleaching and coral disease resulting in widespread morality (Hoegh-Guldberg et al. 2007, IPCC 2007, Veron et al. 2009, Pandolfi et al. 2011).

Sea level rise is a concern in reef systems primarily as it affects water depth and light penetration (IPCC 2007). Coral reefs can respond to slow rates of sea level rise as they have during past glacial-interglacial cycles (Lidz 2006); however, coral reefs may not be able to keep up with the rates of sea level rise that are possible by the end of the 21st century, especially when considering other stressors on coral health.

Finally, increased precipitation associated with climate change may impact coral reefs by increasing runoff of contaminants, sediments, and nutrients into oceans thus further reducing coral health and contributing to the decline of coral reefs (Weber et al. 2006, Deslarzes and Lugo-Fernández 2007, Waddell and Clarke 2008).

11.7 Summary

For all the natural ecosystems considered in this chapter, it is difficult to isolate the effects of climate change from the many other threats to these systems, including for example invasive species, disease, land use change, water withdrawals, and atmospheric deposition.

Sea level rise and ocean acidification are two additional aspects of global climate change that uniquely affect the natural ecosystems considered in this chapter, especially coastal tidal wetlands and coral reefs. It is likely that acidification effects also will be experienced in freshwater stream, lake, reservoir, and river systems. Another unique aspect of many natural ecosystems of the SE is that the combined effects of sea level rise, associated increase in salinity, and alternating wet and dry cycles likely will enhance the fluxes of potent GHGs, CH_4 and N_2O, into the atmosphere.

In the SE, higher water temperatures are expected to put organisms closer to their thermal temperature limits and exacerbate low dissolved oxygen conditions, which already characterize many blackwater streams draining the southeastern coastal plain. Fish that disperse within basins can adjust to warmer temperatures by moving northward to find cooler waters, but only if their routes for dispersal are unimpeded by dams, diversions, and dry-river channels. Freshwater mussel reproduction may fail if temperatures exceed tolerance levels or if low flows limit the effectiveness of mechanisms for attracting host fish.

More frequent droughts coupled with increasing water demands, from of greater evapotranspiration (ET) and growing human consumption, likely will result in more frequent stream drying, even in systems historically considered perennial, which will increase the frequency of local species extirpations. The net result is faunal homogenization, in which communities become dominated by a smaller number of species that are most capable of recolonizing or surviving in stream systems affected by more frequent drought and unpredictable flow conditions.

Climate change is expected to further the establishment of non-native, invasive species by lessening constraints imposed by frequency and duration of cold temperatures.

Climate change is expected to have major impacts in the increasingly rare longleaf pine savannas of the SE. The combined effects of drought, warmer temperatures, and fire probability will increase the flow of carbon to the atmosphere by the decomposition and burning of drier vegetation and peat. While warmer winter temperatures may benefit the longleaf pine ecosystem in the northern range margin, the majority of longleaf pine savannas will likely fare less well due to increasing summertime droughts.

Southeastern freshwater wetlands are vulnerable to climate driven changes in precipitation and temperature, where more frequent droughts and higher rates of ET are predicted. Most of the SE freshwater wetlands experience shifts in seasonal fluxes of greenhouse gases, with more CH_4 under wet conditions, and more CO_2 and N_2O under dry conditions.

Fire is the greatest threat to millions of acres of freshwater peat-based wetlands in the SE under climate-induced drought. CO_2 emissions during fire can reverse centuries of CO_2 sequestration and ultimately convert these systems from being net C sinks to important C sources. Wet and dry cycles drive plant community dynamics in freshwater wetlands and where increased drought frequency occurs, it is likely to drive a shift to communities dominated by less flood tolerant woody species.

For tidal wetlands of the SE, rates of sea level rise could outpace the ability of wetlands to build elevation. As a result wetlands likely will become vulnerable to coastal erosion and increased inundation rates, eventually converting to open water, as has been experienced in coastal Louisiana for several decades now. The construction of dams and other freshwater control devices reduce sediment delivery to the coast further exasperating wetland loss. Increased storm and wave intensity cause erosion and shoreline retreat of coastal wetlands. Tidal freshwater forests are less able to adapt either via vertical accretion or migration due to their slow growing time, low sedimentation rates and their adjacency to upland areas.

Warming will likely facilitate the expansion of certain native species at the expense of others. For example mangrove wetlands, which are limited in their northern limits by periodic freezes, are advancing northward in the Gulf and South Atlantic coastal regions of the SE.

Coral reefs and other hard bottom reefs of the SE are also susceptible to climate change, especially because of warming waters, acidification, and sea level rise. Effects of ocean acidification and warming can be exasperated when coupled to other stressors in reef systems, including disease, coastal runoff, overexploitation, vessel damage, marine debris, and exotic species. Warm water temperatures lead to coral bleaching and when prolonged can lead to death of corals. Changes in tropical storm frequency and intensity will impact coral reefs as many forms of coral are susceptible to wave damage.

Much remains to be learned about the effects of acidification on coral reef systems, from the physiology to the entire ecosystem. Sea level rise affects light transmission to the reef, especially so if the reef has limited ability to build vertical elevation. In addition most reef building is via calcification, which is highly sensitive to ocean pH.

Southeast aquatic and coastal systems are also sensitive to climate changes that may increase freshwater runoff from land as well as carry contaminants and nutrients that can degrade these environments.

11.8 References

Acropora Biological Review Team. 2005. *Atlantic acropora status review document*. Miami, FL: National Marine Fisheries Service.

Alcamo, J., P. DÖli, T. Henrichs, F. Kaspar, B. Lehner, T. Rösch, S. Siebert. 2003. Development and testing of the WaterGAP 2 global model of water use and availability. *Hydrological Sciences Journal* 48 (3): 317-337.

Alexandrov, V.A. andG. Hoogenboom. 2001. Climate variation and crop production in Georgia, USA, during the twentieth century. *Climate Research* 17 (1): 33-43.

Allen, A.P., J.F. Gillooly, J.H. Brown. 2005. Linking the global carbon cycle to individual metabolism. *Functional Ecology* 19 (2): 202-213.

Altor, A.E. and W.J. Mitsch. 2008. Pulsing hydrology, methane emissions and carbon dioxide fluxes in created marshes: A 2-year ecosystem study. *Wetlands* 28 (2): 423-438.

Barbier, E.B., S.D. Hacker, C. Kennedy, E.W. Koch, A.C. Stier, B.R. Silliman. 2011. The value of estuarine and coastal ecosystem services. *Ecological Monographs* 81 (2): 169-193.

Bartlett, K.B., R.S. Clymo, C.B. Craft, C.J. Richardson. 1995. Non-coastal wetlands. In *Intergovernmental Panel on Climate Change (IPCC) working Group II second Assessment Report*, eds. M.G. Oquist and B.H. Svennson, Chapter 6. Paris: International council of Scientific Unions.

Bender, M.A., T.R. Knutson, R.E. Tuleya, J.J. Sirutis, G.A. Vecchi, S.T. Garner, I.M. Held. 2010. Modeled impact of anthropogenic warming on the frequency of intense Atlantic hurricanes. *Science* 327 (5964): 454-458.

Blum, M.D. and H.H. Roberts. 2009. Drowning of the Mississippi Delta due to insufficient sediment supply and global sea-level rise. *Nature Geoscience* 2 (7): 488-491.

Box, J.B. and J.D. Williams. 2000. *Unionid mollusks of the Apalachicola Basin in Alabama, Florida, and Georgia*. Tuscaloosa, AL: University of Alabama.

Bridgham, S.D. and C.J. Richardson. 1992. Mechanisms controlling soil respiration (CO_2 and CH_4) in southern peatlands. *Soil Biology and Biochemistry* 24 (11): 1089-1099.

Bridgham, S.D., J.P. Megonigal, J.K. Keller, N.B. Bliss, C. Trettin. 2006. The carbon balance of North American wetlands. *Wetlands* 26 (4): 889-916.

Brittain, R.A., A. Schimmelmann, D.F. Parkhurst, C. Craft. 2011. Habitat use by coastal birds inferred from stable carbon and nitrogen isotopes. *Estuaries and Coasts* 35 (2): 633-645.

Caldeira, K. and M.E. Wickett. 2003. Anthropogenic carbon and ocean pH. *Nature* 425 (6956): 365.

Cantin, N.E., A.L. Cohen, K.B. Karnauskas, A.M. Tarrant, D.C. McCorkle. 2010. Ocean warming slows coral growth in the central Red Sea. *Science* 329 (5989): 322-325.

Carilli, J.E., R.D. Norris, B.A. Black, S.M. Walsh, M. McField. 2009. Local stressors reduce coral resilience to bleaching. *PLOS ONE* 4 (7): e6324.

Carpenter, S.R., P.L. Pingali, E.M. Bennett, M.B. Zurek. 2005. *Ecosystems and human well-being: Volume 2 scenarios*. Washington, DC: Island Press.

Christensen, N.L. 2000. Vegetation of the southeastern coastal plain. In *North American terrestrial vegetation*, ed. M.G. Barbour and W.D. Billings, 397-448. Cambridge, United Kingdom: Cambridge University Press.

Clough, T.J., K. Addy, D.Q. Kellogg, B.L. Nowicki, A.J. Gold, P.M. Groffman. 2007. Dynamics of nitrous oxide in groundwater at the aquatic-terrestrial interface. *Global Change Biology* 13 (7): 1528-1537.

Colella, M., R. Ruzicka, J. Kidney, J. Morrison, V. Brinkhuis. 2012. Cold-water event of January 2010 results in catastrophic benthic mortality on patch reefs in the Florida Keys. *Coral Reefs* 31 (2): 621-632.

Collins, T.M., J.C. Trexer, L.G. Nico, T.A. Rawlings. 2002. Genetic diversity in a morphologically conservative invasive taxon: multiple introductions of swamp eels to the southeastern United States. *Conservation Biology* 16: 1024-1035.

Conner, W.H., B. Song, T.M. Williams, J.T. Vernon. 2011. Long-term tree productivity of a South Carolina coastal plain forest across a hydrology gradient. *Journal of Plant Ecology* 4 (1-2): 67-76.

Connor, W.H., T.W. Doyle, K.W. Krauss. 2007. *Ecology of tidal freshwater forested wetlands of the southeastern United States*. Dordrecht, the Netherlands: Springer.

Cook, E.R., R. Seager, M.A. Cane, D.W. Stahle. 2007. North American drought: Reconstructions, causes, and consequences. *Earth Science Reviews* 81 (1-2): 93-134.

Cooper, T.F., R.A. O'Leary, J.M. Lough. 2012. Growth of western Australian corals in the anthropocene. *Science* 335 (6068): 593-596.

Craft, C. 2007. Freshwater input structures soil properties, vertical accretion, and nutrient accumulation of Georgia and U.S. tidal marshes. *Limnology and Oceanography* 52 (3): 1220-1230.

Craft, C., J. Clough, J. Ehman, S. Joye, R. Park, S. Pennings, H.Y. Guo, M. Machmuller. 2009. Forecasting the effects of accelerated sea-level rise on tidal marsh ecosystem services. *Frontiers in Ecology and the Environment* 7 (2): 73-78.

Dai, A. 2011. Drought under global warming: A review. Wiley Interdisciplinary Reviews: *Climate Change* 2 (1): 45-65.

Dai, Z., C.C. Trettin, C. Li, D.M. Amatya, G. Sun, H. Li. 2010. Sensitivity of stream flow and water table depth to potential climatic variability in a coastal forested watershed. *Journal of the American Water Resources Association* 46 (5): 1036-1048.

Dai, Z., C.C. Trettin, C. Li, H. Li, G. Sun, D.M. Amatya. 2011. Effect of assessment scale on spatial and temporal variations in CH_4, CO_2, and N_2O fluxes in a forested wetland. *Water, Air, & Soil Pollution* 223 (1): 253-265.

Day, J.W. and P.H. Templet. 1989. Consequences of sea-level rise: Implications from the Mississippi Delta. *Coastal Management* 17 (3): 241-257.

De'ath, G., J.M. Lough, K.E. Fabricius. 2009. Declining coral calcification on the Great Barrier Reef. *Science* 323 (5910): 116-119.

Dedah, C., R. Kazmierczak, W. Keithly. 2010. The role of bounties and human behavior on Louisiana nutria harvests. *Journal of Agricultural and Applied Economics* 42 (1): 133-142.

Desantis, L.R.G., S. Bhotika, K. Williams, F.E. Putz. 2007. Sea-level rise and drought interactions accelerate forest decline on the gulf coast of Florida, USA. *Global Change Biology* 13 (11): 2349-2360.

Deslarzes, K. and A. Lugo-Fernández. 2007. Influence of terrigenous runoff on offshore coral reefs: An example from the Flower Garden Banks, Gulf of Mexico. In *Geological approaches to coral reef ecology*, ed. R.B. Aronson, 126-160. New York, NY: Springer Science.

Donnelly, J.P. and M.D. Bertness. 2001. Rapid shoreward encroachment of salt marsh cordgrass in response to accelerated sea-level rise. *Proceedings of the National Academy of Sciences of the United States of America* 98 (25): 14218-14223.

Doyle, T. 2009. *Modeling flood plain hydrology and forest productivity of Congaree Swamp, South Carolina*. Reston, VA: US Geological Survey.

Doyle, T.W., K.W. Krauss, W.H. Conner, A.S. From. 2010. Predicting the retreat and migration of tidal forests along the northern Gulf of Mexico under sea-level rise. *Forest Ecology and Management* 259 (4): 770-777.

Easterling, D.R., G.A. Meehl, C. Parmesan, S.A. Changnon, T.R. Karl, L.O. Mearns. 2000. Climate extremes: Observations, modeling, and impacts. *Science* 289 (5487): 2068-2074.

Elsner, J.B. and T.H. Jagger. 2006. Predicting models for annual U.S. hurricane counts. *Journal of Climate* 19 (12): 2935-2952.

Emanuel, K. 2005. Increasing destructiveness of tropical cyclones over the past 30 years. *Nature* 436 (7051): 686-688.

Erwin, K.L. 2009. Wetlands and global climate change: the role of wetland restoration in a changing world. *Wetlands Ecology and Management* 17 (1): 71-84.

Fabricius, K.E., C. Langdon, S. Uthicke, C. Humphrey, S. Noonan, G. De'ath, R. Okazaki, N. Muehllehner, M.S. Glas, J.M. Lough. 2011. Losers and winners in coral reefs acclimatized to elevated carbon dioxide concentrations. *Nature Climate Change* 1 (3): 165-169.

Feagin, R.A., M.L. Martinez, G. Mendoza-Gonzalez, R. Costanza. 2010. Salt marsh zonal migration and ecosystem service change in response to global sea-level rise: A case study from an urban region. *Ecology and Society* 15 (4): 14.

Feely, R.A., S.C. Doney, S.R. Cooley. 2009. Ocean acidification: Present conditions and future changes in a high-CO_2 world. *Oceanography* 22 (4): 36-47.

Fey, S.B. and K.L. Cottingham. 2011. Linking biotic interactions and climate change to the success of exotic *Daphnia lumholtzi*. *Freshwater Biology* 56 (11): 2196-2209.

Ficke, A.D., C.A. Myrick, L.J. Hansen. 2007. Potential impacts of global climate change on freshwater fisheries. *Fish Biology and Fisheries* 17 (4): 581-613.

Freeman, M.C., C.M. Pringle, C.R. Jackson 2007. Hydrologic connectivity and the contribution of stream headwaters to ecological integrity at regional scales. *Journal of the American Water Resources Association* 43 (1): 5-14.

Freeman, M.C., C.M. Pringle, E.A. Greathouse, B.J. Freeman. 2003. Ecosystem-level consequences of migratory faunal depletion caused by dams. *American Fisheries Society Symposium* 35 (January): 255-266.

García-Sais, J.R., R. Castro, J. Sabater-Clavell, R. Esteves, M. Carlo. 2006. *Monitoring of coral reef communities from natural reserves in Puerto Rico, 2006: Isla Desecheo, Rincon, Mayaguez Bay, Guanica, Ponce and Isla Caja de Muerto*. Lajas, Puerto Rico: Reef Surveys.

Gedan, K.B., M.L. Kirwan, E. Wolanski, E.B. Barbier, B.R. Silliman. 2011. The present and future role of coastal wetland vegetation in protecting shorelines: answering recent challenges to the paradigm. *Climatic Change* 106 (1): 7-29.

Gedan, K.B., B.R. Silliman, M.D. Bertness. 2009. Centuries of human-driven change in salt marsh ecosystems. *Annual Review of Marine Science* 1 (January): 117-141.

Geselbracht, L., K. Freeman, E. Kelly, D.R. Gordon, F.E. Putz. 2011. Retrospective and prospective model simulations of sea-level rise impacts on Gulf of Mexico coastal marshes and forests in Waccasassa Bay, Florida. *Climatic Change* 107 (1): 35-57.

Giblin, A.E., N.B. Weston, G.T. Banta, J. Tucker, C.S. Hopkinson. 2010. The effects of salinity on nitrogen losses from an oligohaline estuarine sediment. *Estuaries and Coasts* 33 (5): 1054-1068.

Gibson, C.A., J.L. Meyer, N.L. Poff, L.E. Hay, A. Georgakakos. 2005. Flow regime alterations under changing climate in two river basins: Implications for freshwater ecosystems. *River Research and Applications* 21 (8): 849-864.

Gierach, M.M. and B. Subrahmanyam. 2008. Biophysical responses of the upper ocean to major Gulf of Mexico hurricanes in 2005. *Journal of Geophysical Research* 113, C04029; doi:10.1029/2007JC004419.

Gledhill, D.K., R. Wanninkhof, C.M. Eakin. 2009. Observing ocean acidification from space. *Oceanography* 22 (4): 48-59.

Gledhill, D.K., R. Wanninkhof, F.J. Millero, M. Eakin. 2008. Ocean acidification of the greater Caribbean region 1996–2006. *Journal of Geophysical Research* 113, C10031; doi:10.1029/2007JC004629.

Golladay, S.W. and J.M. Battle. 2002. Effects of flooding and drought on water quality in Gulf Coastal Plain streams in Georgia. *Journal of Environmental Quality* 31 (4): 1266-1272.

Golladay, S.W., P. Gagnon, M. Kearns, J.M. Battle, D.W. Hicks. 2004. Response of freshwater mussel assemblages (Bivalvia:Unionidae) to a record drought in the Gulf Coastal Plain of southwestern Georgia. *Journal of the North American Benthological Society* 23 (3): 494-506.

Graff, C.D., A.M. Sadeghi, R.R. Lowrance, R.G. Williams. 2005. Quantifying the sensitivity of the riparian ecosystem management model (REMM) to changes in climate and buffer characteristics common to conservation practices. *Transactions of the ASAE* 48 (4): 1377-1387.

Greaver, T.L. and L. Steinberg. 2010. Decreased precipitation exacerbates the effects of sea level on coastal dune ecosystems in open ocean islands. *Global Change Biology* 16:1860-1869. Doi:10.1111/j.1365-2486.2010.02168.x

Grunwald, C., L. Maceda, J. Waldman, J. Stabile, I. Wirgin. 2008. Conservation of Atlantic sturgeon *Acipenser oxyrinchus oxyrinchus*: Delineation of stock structure and distinct population segments. *Conservation Genetics* 9 (5): 1111-1124.

Hellmann, J.J., J.E. Byers, B.G. Bierwagen, J.S. Dukes. 2008. Five potential consequences of climate change for invasive species. *Conservation Biology* 22 (3): 534-543.

Helmle, K.P., R.E. Dodge, P.K. Swart, D.K. Gledhill, C.M. Eakin. 2011. Growth rates of Florida corals from 1937 to 1996 and their response to climate change. *Nature Communications* 2 (3): 215.

Hergoualc'h, K. and L.V. Verchot. 2011. Stocks and fluxes of carbon associated with land use change in Southeast Asian tropical peatlands: A review. *Global Biogeochemical Cycles* 25, GB2001; doi:10.1029/2009GB003718.

Hilton, T.W., T.G. Najjar, L. Zhong, M. Li. 2008. Is there a signal of sea-level rise in Chesapeake Bay salinity? *Journal of Geophysical Research* 113, C09002; doi:10.1029/2007JC004247.

Hoegh-Guldberg, O., P.J. Mumby, A.J. Hooten, R.S. Steneck, P. Greenfield, E. Gomez, C.D. Harvell, P.F. Sale, A.J. Edwards, K. Caldeira, N. Knowlton, C.M. Eakin, R. Iglesias-Prieto, N. Muthiga, R.H. Bradbury, A. Dubi, M.E. Hatziolos. 2007. Coral reefs under rapid climate change and ocean acidification. *Science* 318 (5857): 1737-1742.

Hogarth, W.T. 2006. Endangered and threatened species: final listing determinations for elkhorn coral and staghorn coral. *Federal Register* 71 (89): 26852-26861.

Howells, E.J., V.H. Beltran, N.W. Larsen, L.K. Bay, B.L. Willis, M.J.H. van Oppen. 2012. Coral thermal tolerance shaped by local adaptation of photosymbionts. *Nature Climate Change* 2 (2): 116-120.

Hughes, T.P., A.H. Baird, D.R. Bellwood, M. Card, S.R. Connolly, C. Folke, R. Grosberg, O. Hoegh-Guldberg, J.B.C. Jackson, J. Kleypas, J.M. Lough, P. Marshall, M. Nyström, S.R. Palumbi, J.M. Pandolfi, B. Rosen, J. Roughgarden. 2003. Climate change, human impacts, and the resilience of coral reefs. *Science* 301 (5635): 929-933.

IPCC (Intergovernmental Panel on Climate Change). 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller, 749-844. New York and United Kingdom: Cambridge University Press.

IPCC (Intergovernmental Panel on Climate Change). 2001. *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, ed. J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson. New York and United Kingdom: Cambridge University Press.

Ise, T., A.L. Dunn, S.C. Wofsy, P.R. Moorcroft. 2008. High sensitivity of peat decomposition to climate change through water-table feedback. *Nature Geoscience* 1 (11): 763-766.

Jokiel, P.L. and S.L. Coles. 1977. Effects of temperature on the mortality and growth of Hawaiian reef corals. *Marine Biology* 43 (3): 201-208.

Juárez, R.I.N., J.Q. Chambers, H. Zeng, D.B. Baker. 2008. Hurricane driven changes in land cover create biogeophysical climate feedbacks. *Geophysical Research Letters* 35, L23401; doi:10.1029/2008GL035683.

Karl, T.R., J.M. Melillo, T.C. Peterson. 2009. *Global climate change impacts in the United States*. New York, NY: Cambridge University Press.

Karnauskas, K.B. and A.L. Cohen. 2012. Equatorial refuge amid tropical warming. *Nature Climate Change* 2 (7): 530-534.

Kaushal, S.S., G.E. Likens, N.A. Jaworski, M.L. Pace, A.M. Sides, D. Seekell, K.T. Belt, D.H. Secor, R.L. Wingate. 2010. Rising stream and river temperatures in the United States. *Frontiers in Ecology and the Environment* 8 (9): 461-466.

Keddy, P. 2009. Thinking big: A conservation vision for the southeastern Coastal Plain of North America. *Southeastern Naturalist* 8 (2): 213-226.

Kirwan, M.L. and L.K. Blum. 2011. Enhanced decomposition offsets enhanced productivity and soil carbon accumulation in coastal wetlands responding to climate change. *Biogeosciences* 8 (4): 987-993.

Kirwan, M.L., G.R. Guntenspergen, J.T. Morris. 2009. Latitudinal trends in *Spartina alterniflora* productivity and the response of coastal marshes to global change. *Global Change Biology* 15 (8): 1982-1989.

Kirwan, M.L., G.R. Guntenspergen, A. D'Alpaos, J.T. Morris, S.M. Mudd, S. Temmerman. 2010. Limits on the adaptability of coastal marshes to rising sea level. *Geophysical Research Letters* 37, L23401; doi:10.1029/2010GL045489.

Komar, P.D. and J.C. Allan. 2008. Increasing hurricane-generated wave heights along the US East Coast and their climate controls. *Journal of Coastal Research* 24 (2): 479-488.

Konrad, C.E., C. Fuhrmann, K. Kunkel, B. Keim, L. Stevens, M. Kruk, H. Needham, A. Billot, M. Shafer. 2012. Climate of the Southeastern United States: past, present and future. This report–Chapter 2.

Krauss, K.W., J.A. Duberstein, T.W. Doyle, W.H. Conner, R.H. Day, L.W. Inabinette, J.L. Whitbeck. 2009. Site condition, structure, and growth of Baldcypress along tidal/non-tidal salinity gradients. *Wetlands* 29 (2): 505-519.

Krauss, K.W., A.S. From, T.W. Doyle, T.J. Doyle, M.J. Barry. 2011. Sea-level rise and landscape change influence mangrove encroachment onto marsh in the Ten Thousand Islands region of Florida, USA. *Journal of Coastal Conservation* 15 (4): 629-638.

Kumara, M.P., L.P. Jayatissa, K.W. Krauss, D.H. Phillips, M. Huxham. 2010. High mangrove density enhances surface accretion, surface elevation change, and tree survival in coastal areas susceptible to sea-level rise. *Oecologia* 164 (2): 545-553.

Kunkel, K.E., P.D. Bromirski, H.E. Brooks, T. Cavazos, A.V. Douglas, K.A. Easterling, P. Groisman, G.J. Holland, T.R. Knutson, J.P. Kossin, P.D. Komar, D.H. Levinson, R.L. Smith. 2008. Observed changes in weather and climate extremes. In *Weather and climate extremes in a changing climate. Synthesis and assessment product 3.3*, ed. T.R. Karl, G.A. Meehl, C.D. Miller, S.J. Hassol, A.M. Waple, W.L. Murray, 35-80. Washington, DC: U.S. Climate Change Science Program.

Langley, J.A., K.L. Mckee, D.R. Cahoon, J.A. Cherry, J.P. Megonigal. 2009. Elevated CO_2 stimulates marsh elevation gain, counterbalancing sea-level rise. *Proceedings of the National Academy of Sciences of the United States of America* 106 (15): 6182-6186.

Langley, J.A. and J.P. Megonigal. 2010. Ecosystem response to elevated CO_2 levels limited by nitrogen-induced plant species shift. *Nature* 466 (7302): 96-99.

Lessios, H.A. 1988. Mass mortality of *Diadema antillarum* in the Caribbean: what have we learned. *Annual Review of Ecology and Systematics* 19 (1): 371-393.

Lidz, B.H. 2006. Pleistocene corals of the Florida Keys: Architects of imposing reefs–why? *Journal of Coastal Research* 22 (4): 750-759.

Liu, Y., J. Stanturf, S. Goodrick. 2010. Trends in global wildfire potential in a changing climate. *Forest Ecology and Management* 259 (4): 685-697.

Lu, J., G. Sun, S. McNulty, N. Comerford. 2009. Sensitivity of pine flatwoods hydrology to climate change and forest management in Florida, USA. *Wetlands* 29 (3): 826-836.

Mander, Ü., M. Maddison, K. Soosaar, K. Karabelnik. 2011. The impact of pulsing hydrology and fluctuating water table on greenhouse gas emissions from constructed wetlands. *Wetlands* 31 (6): 1023-1032.

Manzello, D. 2010. Coral growth with thermal stress and ocean acidification: Lessons from the eastern tropical Pacific. *Coral Reefs* 29 (3): 749-758.

Matthews, W.J. and E. Marsh-Matthews. 2003. Effects of drought on fish across axes of space, time and ecological complexity. *Freshwater Biology* 48 (7): 1232-1253.

McCulloch, M., J. Falter, J. Trotter, P. Montagna. 2012. Coral resilience to ocean acidification and global warming through pH up-regulation. *Nature Climate Change* 2 (8): 623-627.

McKee, K.L., D.R. Cahoon, I.C. Feller. 2007. Caribbean mangroves adjust to rising sea level through biotic controls on change in soil elevation. *Global Ecology and Biogeography* 16 (5): 545-556.

McKee, K.L., I.A. Mendelssohn, M.D. Materne. 2004. Acute salt marsh dieback in the Mississippi River deltaic plain: A drought-induced phenomenon? *Global Ecology and Biogeography* 13 (1): 65-73.

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

Mearns, L.O., F. Giorgi, L. McDaniel, C. Shields. 2003. Climate scenarios for the southeastern U.S. based on GCM and regional model simulations. *Climatic Change* 60 (1): 7-35.

Meehl, G.A., T.F. Stocker, W. Collins, P. Friedlingstein, A. Gaye, J. Gregory, A. Kitoh, R. Knutti, J. Murphy, A. Noda, S. Raper, I. Watterson, A. Weaver, Z.C. Zhao. 2007. Global climate predictions. In *Climate change 2007: The physical science basis. Contribution of working group 1 to* *the fourth assessment report of the intergovernmental panel on climate change*, ed. S. Solomin, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller. Cambridge, United Kingdom: Cambridge University Press.

Mehring, A.S. 2012. Effects of organic matter processing on oxygen demand in a south Georgia blackwater river. Ph.D. dissertation, University of Georgia, Athens, GA.

Michot, T.C., R.H. Day, C.J. Wells. 2010. Increase in black mangrove abundance in coastal Louisiana. Louisiana Natural Resources News. Newsletter of the Louisiana Association of Professional Biologists.

Mickler, R.A. and D. Welch. 2010. GIS mapping for Atlantic White Cedar. Final report to USFWS, Pocosins Lakes National Wildlife Refuge, Columbia NC.

Middleton, B.A. 2009. Regeneration potential of *Taxodium distichum* swamps and climate change. *Plant Ecology* 202 (2): 257-274.

Miller, J., R. Waara, E. Muller, C. Rogers. 2006. Coral bleaching and disease combine to cause extensive mortality on reefs in US Virgin Islands. *Coral Reefs* 25 (3): 418.

Mohseni, O. and H.G. Stefan. 1999. Stream temperature/air temperature relationship: A physical interpretation. *Journal of Hydrology* 218 (3-4): 128-141.

Mohseni, O., H.G. Stefan, J.G. Eaton. 2003. Global warming and potential changes in fish habitat in U.S. streams. *Climatic Change* 59 (3): 389-409.

Morris, J.T., P.V. Sundareshwar, C.T. Nietch, B. Kjerfve, D.R. Cahoon. 2002. Responses of coastal wetlands to rising sea level. *Ecology* 83 (10): 2869-2877.

Morse, J.L. 2010. Farm fields to wetlands: Biogeochemical consequences of re-flooding in coastal plain agricultural land. Ph.D. diss. Duke University, Durham, NC.

Mousavi, M., J. Irish, A. Frey, F. Olivera, B. Edge. 2011. Global warming and hurricanes: The potential impact of hurricane intensification and sea level rise on coastal flooding. *Climatic Change* 104 (3-4): 575-597.

Mudd, S.M., S.M. Howell, J.T. Morris. 2009. Impact of dynamic feedbacks between sedimentation, sea-level rise, and biomass production on near-surface marsh stratigraphy and carbon accumulation. *Estuarine, Coastal and Shelf Science* 82 (3): 377-389.

Mulholland, P.J. and M.J. Sale. 1998. Impacts of climate change on water resources: Findings of the IPCC regional assessment of vulnerability for North America. *Journal of Contemporary Water Research and Education* 112 (1): 10-15.

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-Herrera, R.G. Wetzel. 1997. Effects of climate change on freshwater ecosystems of the south-eastern United States and the Gulf Coast of Mexico. *Hydrological Processes* 11 (8): 949-970.

Muscatine, L. 1973. Nutrition of corals. In *Biology and geology of coral reefs*, ed. O. Jones and R. Endean, 7-115. New York, NY: Academic Press.

National Research Council of the National Academies. 2010. Ocean acidification: A national strategy to meet the challenges of a changing ocean. Washington, DC: The National Academies Press.

Neubauer, S.C. 2011. Ecosystem responses of a tidal freshwater marsh experiencing saltwater intrusion and altered hydrology. *Estuaries and Coasts* 34 (1).

Neubauer, S.C., C. Craft. 2009. Global change and tidal freshwater wetlands: Scenarios and impacts. In *Tidal freshwater wetlands*, ed. A. Barendregt, D.F. Whigham, A.H. Baldwin, 153-266. Leiden, the Netherlands: Backhuys Publishers.

Nicholls, R.J., F.M.J. Hoozemans, M. Marchand. 1999. Increasing flood risk and wetland losses due to global sea-level rise: Regional and global analyses. *Global Environmental Change* 9 (1): S69-S87.

Nicholls, R.J., P.P. Wong, V.R. Burkett, J.O. Cotignotto, J.E. Hay, R.F. McLean, S. Ragoonaden, C.D. Woddrofe. 2007. Coastal systems and low-lying areas. In *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessement report* *of the Intergovernmental Panel on Climate Change*, ed. M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hansen, 315-356. Cambridge, United Kingdom: Cambridge University Press.

NOAA (National Oceanic and Atmospheric Administration). 2010. *Endangered and threatened wildlife. Notice of 90–Day finding on a petition to list 83 species of corals as threatened or endangered under the endangered species act (ESA)*. Washington, DC: Federal Register.

NOAA (National Oceanic and Atmospheric Administration). 2011. *First florida cold-water bleaching event in 30 years*. Washington, DC: U.S. Department of Commerce. http://oceanservice.noaa.gov/news/weeklynews/mar10/cwcoral.html

NOAA (National Oceanic and Atmospheric Administration). 2011. Sea Levels Online. http://tidesandcurrents.noaa.gov/sltrends/index.shtml. Accessed: 28 October 2011.

Paerl, H.W., N.S. Hall, E.S. Calandrino. 2011. Controlling harmful cyanobacterial blooms in a world experiencing anthropogenic and climatic-induced change. *The Science of the Total Environment* 409 (10): 1739-1745.

Pandolfi, J.M., S.R. Connolly, D.J. Marshall, A.L. Cohen. 2011. Projecting coral reef futures under global warming and ocean acidification. *Science* 333 (6041): 418-422.

Parisi, F. and R. Lund. 2008. Return periods of continental U.S. hurricanes. *Journal of Climate* 21 (2): 403-410.

Pathikonda, S., A.S. Ackleh, K.H. Hasenstein, S. Mopper. 2009. Invasion, disturbance, and competition: Modeling the fate of coastal plant populations. *Conservation Biology* 23 (1): 164-173.

Pattison, R.R. and R.N. Mack. 2008. Potential distribution of the invasive tree *Triadica sebifera* (Euphorbiaceae) in the United States: Evaluating CLIMEX predictions with field trials. *Global Change Biology* 14 (4): 813-826.

Pearlstine, L.G., E.V. Pearlstine, N.G. Aumen. 2010. A review of the ecological consequences and management implications of climate change for the Everglades. *Journal of the North American Benthological Society* 29 (4): 1510-1526.

Pendall, E., S. Bridgham, P.J. Hanson, B. Hungate, D.W. Kicklighter, D.W. Johnson, B.E. Law, Y.Q. Luo, J.P. Megonigal, M. Olsrud, M.G. Ryan, S.Q. Wan. 2004. Below-ground process responses to elevated CO_2 and temperature: A discussion of observations, measurement methods, and models. *New Phytologist* 162 (2): 311-322.

Pennock, D., T. Yates, A. Bedard-Haughn, K. Phipps, R. Farrell, R. McDougal. 2010. Landscape controls on N_2O and CH_4 emissions from freshwater mineral soil wetlands of the Canadian Prairie Pothole region. *Geoderma* 155 (3-4): 308-319.

Peterson, J.T., J.M. Wisniewski, C.P. Shea, C.R. Jackson. 2011. Estimation of mussel population response to hydrologic alteration in a southeastern U.S. stream. *Environmental Management* 48 (1): 109-122.

Pickens, C.N. and M.W. Hester. 2011. Temperature tolerance of early life history stages of black mangrove *Avicennia germinans*: Implications for range expansion. *Estuaries and Coasts* 34 (4): 824-830.

Platt, W.J., G.W. Evans, M.M. Davis. 1988. Effects of fire season on flowering of forbs and shrubs in longleaf pine forests. *Oecologia* 76 (3): 353-363.

Poff, N.L., J.D. Olden, D.M. Merritt, D.M. Pepin. 2007. Homogenization of regional river dynamics by dams and global biodiversity implications. *Proceedings of the National Academy of Sciences of the United States of America* 104 (14): 5732-5737.

Poulter, B., N.L. Christensen Jr., P.N. Halpin. 2006. Carbon emissions from a temperate peat fire and its relevance to interannual variability of trace atmospheric greenhouse gases. *Journal of Geophysical Research* 111, D06301; doi:10.1029/2005JD006455.

Pyzoha, J.E., T.J. Callahan, G. Sun, C.C. Trettin, M. Miwa. 2008. A conceptual hydrologic model for a forested Carolina bay depressional wetland on the Coastal Plain of South Carolina, USA. *Hydrological Processes* 22 (14): 2689-2698.

Rahel, F.J. and J.D. Olden. 2008. Assessing the effects of climate change on aquatic invasive species. *Conservation Biology* 22 (3): 521-533.

Rahmstorf, S. 2007. A semi-empirical approach to projecting future sea-level rise. *Science* 315 (5810): 368-370.

Rahmstorf, S., A. Cazenave, J.A. Church, J.E. Hansen, R.F. Keeling, D.E. Parker, R.C. Somerville. 2007. Recent climate observations compared to projections. *Science* 316 (5825): 709.

Rasse, D.P., G. Peresta, B.G. Drake. 2005. Seventeen years of elevated CO_2 exposure in a Chesapeake Bay wetland: Sustained but contrasting responses of plant growth and CO_2 uptake. *Global Change Biology* 11 (3): 369-377.

Richardson, C.J. 2008. *The Everglades experiments: Lessons for ecosystem restoration*. New York, NY: Springer.

Richardson, C.J. 2012. Pocosins. In *Wetland habitats of North America: Ecology and conservation concerns*, ed., D.P. Batzer and A.H. Baldwin, 189-202. Berkeley, CA: University of California Press.

Richardson, K., W. Steffen, H.J. Schellenhuber, J. Alcamo, T. Barker, D.M. Kammen, R. Leemans, D. Liverman, M. Munacinghe, B. Osman-Elasha, N. Stern, O. Waever. 2009. Climate change - global risks, challenges & decisions: synthesis report. Copenhagen, Denmark: University of Copenhagen.

Richardson, L.L. 1998. Coral diseases: What is really known? *Trends in Ecology and Evolution* 13 (11): 438-443.

Rodolfo-Metalpa, R., F. Houlbreque, E. Tambutte, F. Boisson, C. Baggini, F.P. Patti, R. Jeffree, M. Fine, A. Foggo, J.P. Gattuso, J.M. Hall-Spencer. 2011. Coral and mollusc resistance to ocean acidification adversely affected by warming. *Nature Climate Change* 1 (September): 308-312.

Rugel, K., C.R. Jackson, J.J. Romeis, S.W. Golladay, D.W. Hicks, J.F. Dowd. 2012. Effects of irrigation withdrawals on streamflows in a karst environment: Lower Flint River Basin, Georgia, USA. *Hydrological Processes* 26 (4): 523-534.

Rush, S.A., M.S. Woodrey, R.J. Cooper. 2010. Variation in the nesting habitats of clapper rails in tidal marshes of the northern Gulf of Mexico. *The Condor* 112 (2): 356-362.

Rypel, A.L. 2009. Climate-growth relationships for largemouth bass (Micropterus salmoides) across three southeastern USA states. *Ecology of Freshwater Fish* 18 (4): 620-628.

Rysgaard, S., P. Thastum, T. Dalsgaard, P.B. Christensen, N.P. Sloth. 1999. Effects of salinity on NH_4^+ adsorption capacity, nitrification, and denitrification in Danish estuarine sediments. *Estuaries and Coasts* 22 (1): 21-30.

Schindler, D.W. 1997. Widespread effects of climatic warming on freshwater ecosystems in North America. *Hydrological Processes* 11 (8): 1043-1067.

Schultheis, E.H., K.N. Hopfensperger, J.C. Brenner. 2010. Potential impacts of climate change on *Sphagnum* bogs of the southern Appalachian Mountains. *Natural Areas Journal* 30 (4): 417-424.

Scott, M.C. 2006. Winners and losers among stream fishes in relation to land use legacies and urban development in the southeastern US. *Biological Conservation* 127 (3): 301-309.

Scott, M.C. and G.S. Helfman. 2001. Native invasions, homogenization, and the mismeasure of integrity of fish assemblages. *Fisheries* 26 (11): 6-15.

Shaman, J.M., M. Stieglitz, C. Stark, S. LeBlancq, M. Cran. 2002. Using a dynamic model to predict mosquito abundances in flood and swamp water. *Emerging Infectious Disease* 8: 6-13.

Shepherd, J.M., A. Grundstein, T.A. Mote. 2007. Quantifying the contribution of tropical cyclones to extreme rainfall along the coastal southeastern United States. *Geophysical Research Letters* 34, L23810; doi:10.1029/2007GL031694.

Sherrod, C.L. and C. McMillan. 1981. Black Mangrove, *Avicennia germinans*, in Texas: Past and Present Distribution. *Contributions in Marine Science* 24 (September): 115-131.

Sherrod, C.L. and C. McMillan. 1985. The distributional history and ecology of mangrove vegetation along the northern Gulf of Mexico coastal region. *Contributions in Marine Science* 28 (September): 129-140.

Sherrod, C.L., D.L. Hockaday, C. McMillan. 1986. Survival of red mangrove, *Rhizophora mangle*, on the Gulf of Mexico coast of Texas. *Contributions in Marine Science* 29 (December): 27-36.

Silliman, B.R., J. van de Koppel, M.D. Bertness, L.E. Stanton, I.A. Mendelssohn. 2005. Drought, snails, and large-scale die-off of southern US salt marshes. *Science* 310 (5755): 1803-1806.

Slattery, M.C., P.A. Gares, J.D. Phillips. 2002. Slope-channel linkage and sediment delivery on North Carolina coastal plain cropland. *Earth Surface Processes and Landforms* 27 (13): 1377-1387.

Smith, S.J., A.M. Thomson, N.J. Rosenberg, R.C. Izaurralde, R.A. Brown, T.M.L. Wigley. 2005. Climate change impacts for the conterminous USA: an integrated assessment: 1. Scenarios and context. *Climate Change* 69 (1): 7-25.

Spalding, E.A. and M.W. Hester. 2007. Interactive effects of hydrology and salinity on oligohaline plant species productivity: Implications of relative sea-level rise. *Estuaries and Coasts* 30 (2): 214-225.

Stallins, J.A., M. Nesius, M. Smith, K. Watson. 2010. Biogeomorphic characterization of floodplain forest change in response to reduced flows along the Apalachicola River, Florida. *River Research and Applications* 26 (3): 242-260.

Stambaugh, M.C., R.P. Guyette, J.M. Marschall. 2011. Longleaf pine (*Pinus palustris* Mill) fire scars reveal new details of a frequent fire regime. *Journal of Vegetation Science* 22 (6): 1094-1104.

Stone, G.W., N. Walker, S. Hsu, A. Babin, B. Liu, B.D. Keim, W. Teague, D. Mitchel, R. Leben. 2005. Hurricane Ivan's impact along the northern Gulf of Mexico. *EOS, Transactions, American Geophysical Union* 86 (48): 497-508.

Stroh, C.L., D. De Steven, G.R. Guntenspergen. 2008. Effect of climate fluctuations on long-term vegetation dynamics in Carolina Bay wetlands. *Wetlands* 28 (1): 17-27.

Taylor, D. 2010. Biomass burning, humans and climate change in Southeast Asia. *Biodiversity Conservation* 19: 1025-1042.

Todd, M.C., R.G. Taylor, T.J. Osborn, D.G. Kingston, N.W. Arnell, S.N. Gosling. 2011. Uncertainty in climate change impacts on basin-scale freshwater resources – preface to the special issue: The QUEST-GSI methodology and synthesis of results. *Hydrology and Earth System Sciences* 15 (3): 1035-1046.

Todd, M.C., R.G. Taylor, T. Osborne, D. Kingston, N.W. Arnell, S.N. Gosling. 2010. Quantifying the impact of climate change on water resources at the basin scale on five continents a unified approach. *Hydrology and Earth System Sciences* 7 (5): 7485-7519.

Todd, M.J., R. Muneepeerakul, D. Pumo, S. Azaele, F. Miralles-Wilhelm, A. Rinaldo, I. Rodriguez-Iturbe. 2010. Hydrological drivers of wetland vegetation community distribution within Everglades National Park, Florida. *Advances in Water Resources* 33 (10): 1279-1289.

Trenberth, K.E. and D.J. Shea. 2006. Atlantic hurricanes and natural variability in 2005. *Geophysical Research Letters* 33, L12704; doi:10.1029/2006GL026894.

UNEP (United Nations Environment Programme). 2006. Marine and coastal ecosystems and human well-being: A synthesis report based on the findings of the Millennium Ecosystem Assessment. Nairobi, Kenya: UNEP.

Utley, B.C., G. Vellidis, R.R. Lowrance, M.C. Smith. 2008. Factors affecting sediment oxygen demand dynamics in blackwater streams of Georgia's coastal plain. *Journal of American Water Resources Association* 44 (3): 742-753.

van de Pol, M., B.J. Ens, D. Heg, L. Brouwer, J. Krol, M. Maier, K.M. Exo, K. Oosterbeek, T. Lok, C.M. Eising, K. Koffijberg. 2010. Do changes in the frequency, magnitude and timing of extreme climatic events threaten the population viability of coastal birds? *Journal of Applied Ecology* 47 (4): 720-730.

Vermeer, M. and S. Rahmstorf. 2009. Global sea level linked to global temperature. *Proceedings of the National Academy of Sciences of the United States of America* 106 (51): 21527-21532.

Veron, J.E.N. 2000. *Corals of the world*. Townsville, Australia: Australian Institute of Marine Science and CRR Qld Pty Ltd.

Veron, J.E.N. 2011. Ocean acidification and coral reefs: an emerging big picture. *Diversity* 3 (2): 262-274.

Veron, J.E.N., O. Hoegh-Guldberg, T.M. Lenton, J.M. Lough, D.O. Obura, P. Pearce-Kelly, C.R.C. Sheppard, M. Spalding, M.G. Stafford-Smith, A.D. Rogers. 2009. The coral reef crisis: The critical importance of <350 ppm CO_2. *Marine Pollution Bulletin* 58 (10): 1428-1436.

Vörösmarty, C.J., P. Green, J. Salisbury, R.B. Lammers. 2000. Global water resources: Vulnerability from climate change and population growth. *Science* 289 (5477): 284-288.

Waddell, J.E. and A.M. Clarke. 2008. *The state of coral reef ecosystems of the United States and Pacific freely associated states: 2008*. Silver Spring, MD: NOAA/NCCOS Center for Coastal Monitoring and Assessment's Biogeography Team.

Walker, J. and R.K. Peet. 1984. Composition and species diversity of pine-wiregrass savanna of the Green Swamp, North Carolina. *Vegetatio* 55(3): 163-179.

Walters, D.M., D.S. Leigh, A.B. Bearden. 2003. Urbanization, sedimentation, and the homogenization of fish assemblages in the Etowah River Basin, USA. *Hydrobiologia* 494 (1-3): 5-10.

Walters, D.M., M.J. Blum, B. Rashleigh, B.J. Freeman, B.A. Porter. 2008. Red shiner invasion and hybridization with blacktail shiner in the upper Coosa River, USA. *Biological Invasions* 10 (8): 1229-1242.

Wang, H.H., W.E. Grant, T.M. Swannack, J.B. Gan, W.E. Rogers, T.E. Koralewski, J.H. Miller, J.W. Taylor. 2011. Predicted range expansion of Chinese tallow tree (*Triadica sebifera*) in forestlands of the southern United States. *Diversity and Distributions* 17 (3): 552-565.

Weber, M., C. Lott, K. Fabricius. 2006. Sedimentation stress in a scleractinian coral exposed to terrestrial and marine sediments with contrasting physical, organic and geochemical properties. *Journal of Experimental Marine Biology and Ecology* 336 (1): 18-32.

Webster, P.J., G.J. Holland, J.A. Curry, H.R. Chang. 2005. Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science* 309 (5742): 1844-1846.

Weston, N.B., A.E. Giblin, G.T. Banta, C.S. Hopkinson, J. Tucker. 2010. The effects of varying salinity on ammonium exchange in estuarine sediments of the Parker River, Massachusetts. *Estuaries and Coasts* 33 (4): 985-1003.

Weston, N.B., W.P. Porubsky, V.A. Samarkin, M. Erickson, S.E. Macavoy, S.B. Joye. 2006. Porewater stoichiometry of terminal metabolic products, sulfate, and dissolved organic carbon and nitrogen in estuarine intertidal creek-bank sediments. *Biogeochemistry* 77 (3): 375-408.

Weston, N.B., M.A. Vile, S.C. Neubauer, D.J. Velinsky. 2011. Accelerated microbial organic matter mineralization following salt-water intrusion into tidal freshwater marsh soils. *Biogeochemistry* 102 (1): 135-151.

Wilkinson, C. 2008. *Status of coral reefs of the world: 2008*. Townsville, Australia: Global Coral Reef Monitoring Network Reef and Rainforest Research Centre.

Wilkinson, C. and D. Souter. 2008. *Status of Caribbean coral reefs after bleaching and hurricanes in 2005*. Townsville, Australia: Global Coral Reef Monitoring Network, and Reef and Rainforest Research Centre.

Willard, D.A. and C.E. Bernhardt. 2011. Impacts of past climate and sea level change on Everglades wetlands: Placing a century of anthropogenic change into a late-Holocene context. *Climatic Change* 107 (1): 59-80.

Winn, B., D. Swan, J. Ozier, M.J. Harris. 2008. Wood stork nesting in Georgia: 1992-2005. *Waterbirds* 31 (1): 8-11.

Yuill, B., D. Lavoie, D.J. Reed. 2009. Understanding subsidence processes in coastal Louisiana. *Journal of Coastal Research* S1, 23-36.

Zomlefer, W.B., W.S. Judd, D.E. Giannasi. 2006. Northernmost limit of Rhizophora mangle (Red mangrove; Rhizophoraceae) in St. Johns County, Florida. *Castanea* 71 (3): 239-244.

Chapter 12

Mitigation of Greenhouse Gases in the Southeast USA

LEAD AUTHOR

Kenneth L. Mitchell (mitchell.ken@epa.gov; US Environmental Protection Agency, Atlanta, Georgia)

CONTRIBUTING AUTHORS

Marilyn Brown (Georgia Institute of Technology, Atlanta, Georgia)

Ryan Brown (US Environmental Protection Agency, Atlanta, Georgia)

Diana Burk (Southface Institute, Atlanta, Georgia)

Dennis Creech (Southface, Atlanta, Georgia)

Jeffrey S. Gaffney (University of Arkansas at Little Rock, Arkansas)

Garry P. Garrett (Southern States Energy Board, Norcross, Georgia)

Daniel Garver (US Environmental Protection Agency, Atlanta, Georgia)

Stephen A. Smith (Southern Alliance for Clean Energy, Knoxville, Tennessee)

Ge Sun (Eastern Forest Environmental Threat Assessment Center, Southern Research Station, USDA Forest Service, Raleigh, North Carolina)

Although the Southeast is one of the largest emitters of CO_2 emissions in the United States, the region ranks low in policies and programs that promote efficient energy use. However, improvements are on the horizon due in part to the large potential for carbon sequestration, future cost-saving conservation efforts, and requirements of the 2009 American Recovery and Reinvestment Act.

Key Findings

- With 26% of the total population of the USA and 25% of the total CO_2 emissions, the Southeast (SE) emits more combustion-related CO_2 than any other region of the National Climate Assessment. The largest source of emissions is generation of electricity (41%) followed by transportation (35%).
- The SE has great potential for mitigating CO_2 emissions through carbon sequestration in soils and plant biomass. The average annual carbon storage in natural ecosystems is about 0.3 petagrams, 60% of which is stored in forests and the remainder in savannas. Protection of these natural carbon sinks in the face of development pressures is a critical issue for climate change mitigation in the SE.
- States in the SE consistently rank low for policies promoting energy-efficiency as is illustrated by the fact that electric utility energy efficiency program spending per capita in the SE was one-fifth the national average.
- Most states in the SE have outdated or non-existent energy code policies governing the energy efficiency of new buildings. This situation is improving, in part due to a provision of the 2009 American Recovery and Reinvestment Act that requires states receiving ARRA funds to adopt updated energy codes.
- These low energy efficiency rankings across the SE offer large potential for energy saving gains through cost-effective conservation measures. Moreover, there are several SE states that lead in energy conservation for the region and the nation. Florida, Virginia, Georgia, and North Carolina rank among the top 11 states for total numbers of Leadership in Energy and Environmental Design projects.
- Many corporations and in the SE are developing and instituting sustainability plans that include provisions to reduce their overall direct and indirect impacts on the environment through improved energy efficiency, increased use of renewable energy, and reduced GHG emissions.

12.1 Definitions

Climate change mitigation refers to activities that avoid or decrease the release of greenhouse gas (GHG) emissions from new and existing sources, or decrease atmospheric GHG concentrations, e.g., carbon storage in forests or soils, as compared to a specific historical point in time across a specific spatial boundary. This chapter briefly reviews the emissions of GHGs from sources in the SE, along with recent efforts undertaken to reduce emissions by southeastern businesses, governments, homeowners, and others. The ability of natural systems in the SE to sequester carbon is also reviewed. For purposes of this chapter, the Southeast is comprised of Louisiana, Alabama, Mississippi, Florida, Georgia, South Carolina, North Carolina, Virginia, Tennessee, Kentucky, Arkansas, Puerto Rico, and the US Virgin Islands. Unless otherwise noted, the statistics presented are focused on the 11 continental states.

12.2 Greenhouse Gas Emissions and Sinks in the Southeast

The southeastern USA is one of eight National Climate Assessment (NCA) regions, and is home to over 81 million people, which is about 26% of the USA population, including Puerto Rico and the US Virgin Islands (US Census Bureau 2012). At 25% of national emissions, the SE outpaces all other NCA regions as the largest emitter of carbon dioxide (CO_2) through combustion of fuels (Figure 12.1).

Greenhouse Gas Emissions

In 2009, southeastern sources alone were responsible for over 1,444 million metric tons (MMt) of CO_2 combustion emissions. The electric power sector accounted for 41% of these emissions, followed by the transportation sector (35%) and industrial sources (18%) as the largest contributors (Energy Information Administration 2011). A more comprehensive GHG emissions inventory for six SE states is provided in the next section. The US Environmental Protection Agency recently established a mandatory GHG Reporting Program will help stakeholders better understand where GHG emissions are coming from and will improve stakeholders' ability to make informed policy, business, and regulatory decisions (US EPA 2012a).

Among the southeastern states, all but Louisiana produce the greatest share of their combustion CO_2 emissions from the electric power and transportation sectors. Louisiana is anomalous, with industry contributing the greatest share of emissions. Florida leads all southeastern states with the greatest total amount of emissions (234 MMt CO_2 in 2009), with the majority of its emissions almost equally split between the electricity and transportation sectors (Figure 12.2).

Regional Trajectory for GHG Emissions

Of the eleven states in the SE, six—Arkansas, Florida, Kentucky, North Carolina, South Carolina, and Virginia—have begun a process to develop a climate change plan for their state, including an inventory of emissions and projections of emissions into the future, typically, for the 2020 to 2030 timeframe. Alabama's 1997 Climate Change Plan provides GHG projections only to 2010 and, so, is not included here. In most cases, these states estimated both gross emissions as well as net emissions in order to account for forestry and land use sinks. The emission sources and GHGs evaluated extend beyond those captured by Department of Energy (DOE) combustion CO_2 emission estimates discussed above. For example, state-specific estimates may have included emissions of methane (CH_4) from livestock operations and nitrogen dioxide from forest wildfires, collectively reported as carbon dioxide equivalents or CO_{2e}, a measure used to compare the emissions from various GHGs based on their global warming potential relative to CO_2. Most of these plans were developed with the assistance of the Center for Climate Strategies and a collection of these plans is available on their website (Center for Climate Strategies 2012).

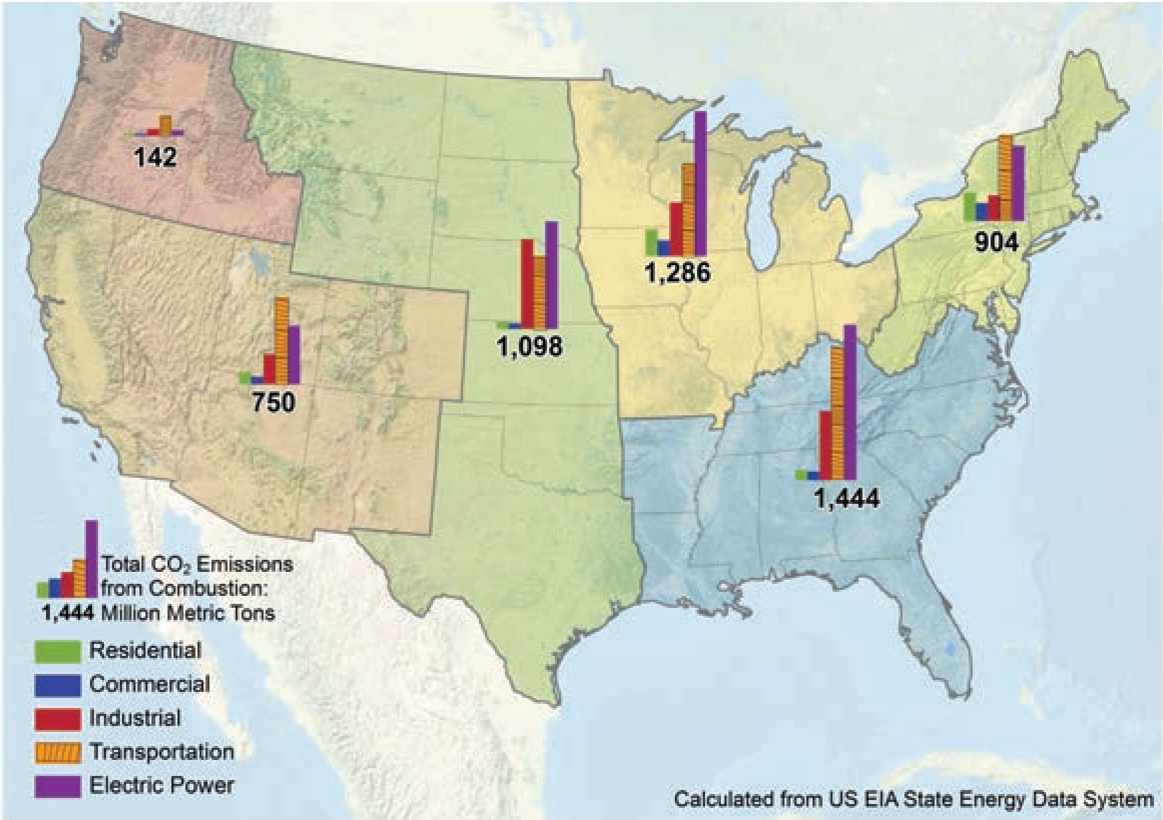


Figure 12.1 Total CO_2 emissions from combustion by sector by National Climate Assessment region (2009).

A summary of the estimated out-year GHG emissions for these six states is provided in Table 12.1 and indicates an expected increasing trend in emissions over time. In reviewing these trends, keep in mind that the numbers may not be directly comparable from state to state because of state-specific assumptions used in the development of emissions estimates. The source document for each state should be consulted to evaluate these differences. Estimates of future emissions depend upon a host of variables, ranging from changes in technology and policy to how the economy develops.

Carbon Sinks

Generally speaking, carbon sequestration measures the rate of carbon removed from the atmosphere over a finite period of time (e.g., one month or one year) within a finite unit of space (e.g., an individual plant or one acre of land), while carbon storage measures the total mass of carbon accumulated within that finite space. For example, if something sequesters at a rate of 2 Mt CO_2/year but emits at a rate of 1 Mt CO_2/year via natural processes, then its carbon storage is only 1 Mt CO_2 after year one, 2 Mt CO_2 after year two, 3 Mt CO_2 after year three, and so on, until it reaches some internal saturation point or CO_2 is released in a pulse from a disturbance like a fire.

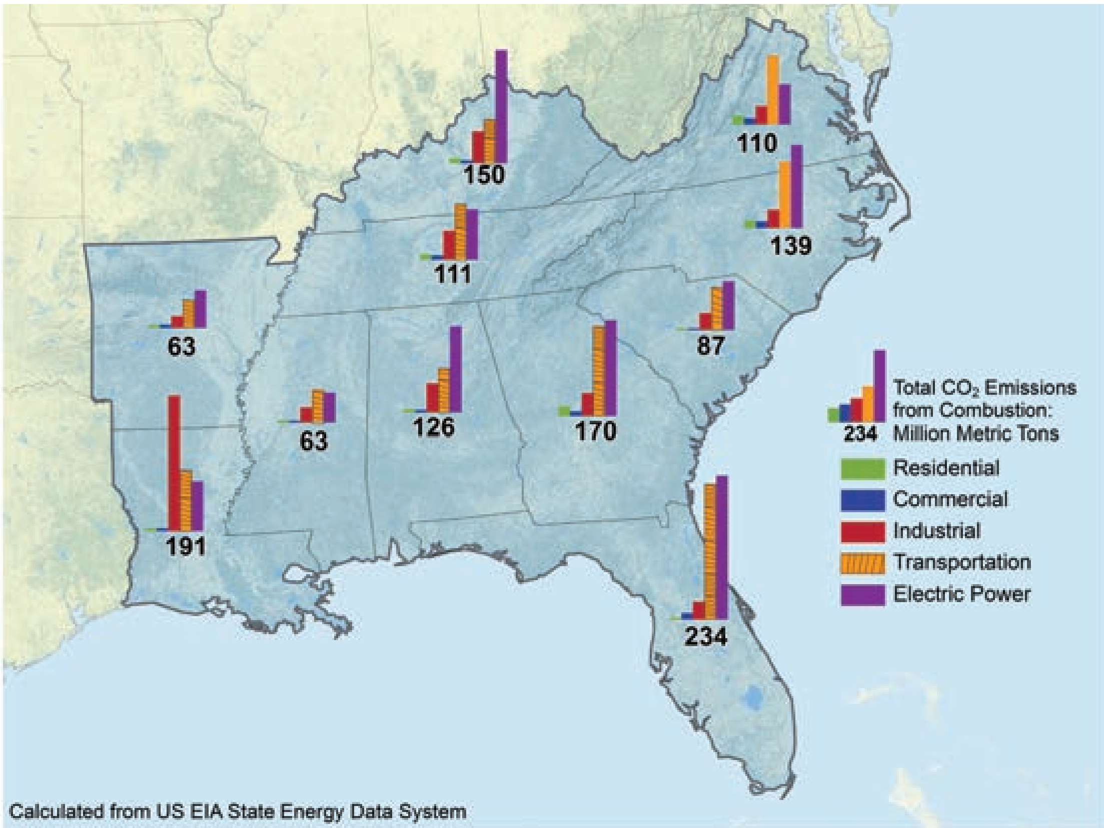


Figure 12.2 Total CO_2 emissions from combustion by sector in Southeast USA.

A 2007 study of terrestrial carbon storage in the SE and South-Central USA estimated the state-level terrestrial carbon storage as teragrams of carbon (Tg C) in Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, Texas, and Virginia (Han et al. 2007). The study also projected the potential for terrestrial carbon sequestration in the region. The estimates of carbon storage for the SE are provided in Table 12.2. The estimate of annual terrestrial carbon sinks, or annual sequestration, in the SE is provided in Table 12.3. Of the southeastern states evaluated, Florida leads at nearly 25% of carbon storage, largely due to soil storage. In contrast, Arkansas leads with more than 20% of annual biomass carbon sink due to its high level of crop production.

Kentucky was not included in this evaluation and estimates of storage and annual sinks were not available for the commonwealth by the same methodology used for the other southeastern states. That said, approximately 10% of Kentucky is used for cultivated crops and 47% is covered by deciduous forests (Kentucky Renewable Energy Consortium 2009), indicating that terrestrial systems in Kentucky are expected to add substantively to the carbon sequestration totals shown in Tables 12.2 and 12.3. Other estimates of terrestrial sequestration for select southeastern states, including Kentucky, are discussed in the preceding section on regional trajectories of GHG emissions.

Table 12.1 Greenhouse Gas Inventory and Reference Case Projections (1990-2030).

$MMtCO_2e$	1990	2000	2005	2010	2015	2020	2025	2030
GROSS EMISSIONS ON A CONSUMPTION BASIS, EXCLUDING SINKS (INCREASE RELATIVE TO 1990)*								
Arkansas	65.8	86.8 (32%)	85.4 (30%)	93.5 (42%)	101.3 (54%)	107.5 (63%)	114.2 (74%)	n/c
Florida	248.8	315.0 (27%)	336.6 (35%)	362.6 (46%)	n/c	424.9 (71%)	463.3 (86%)	n/c
Kentucky	136.7	165.9 (21%)	183.1 (34%)	191.6 (40%)	205.1 (50%)	217.7 (59%)	232.3 (70%)	247.7 (81%)
North Carolina	136	180 (33%)	192 (42%)	214 (58%)	n/c	256 (88%)	n/c	n/c
South Carolina	67.2	87.8 (31%)	93.5 (39%)	102.2 (52%)	n/c	125.4 (87%)	n/c	n/c
Virginia	n/c	162.63	n/c	n/c	n/c	n/c	229.84 (41%)	n/c
NET EMISSIONS ON A CONSUMPTION BASIS, INCLUDES FORESTRY AND LAND USE SINKS (INCREASE RELATIVE TO 1990)								
Arkansas	27.3	66.0 (141%)	64.6 (136%)	72.6 (166%)	80.4 (194%)	86.6 (217%)	93.4 (242%)	n/c
Florida	230.9	288.3 (25%)	309.4 (34%)	335.3 (45%)	n/c	397.8 (72%)	436.2 (89%)	n/c
Kentucky	126.8	158.2 (25%)	175.5 (38%)	184.0 (45%)	197.6 (56%)	210.1 (66%)	224.8 (77%)	240.2 (89%)
North Carolina	112	156 (39%)	169 (50%)	191 (70%)	n/c	232 (106%)	n/c	n/c
South Carolina	34.0	56.8(67%)	62.3 (83%)	71.0 (109%)	n/c	94.1 (177%)	n/c	n/c
Virginia	n/c	n/c	n/c	n/c	n/c	n/c	n/c	n/c

* The Virginia baseline is 2000. MMtCO2e - Million metric tons of carbon dioxide equivalentn/c – Not Calculated

Sources: CAPAG 2008, Commonwealth of Virginia 2008, Strait et al. 2008a, Strait et al. 2008b, Strait et al. 2008c, Strait et al. 2010

Table 12.2 Total Terrestrial Carbon (C) Storage in the Southeast.

State	Soil Organic C	Biomass C			Total Terrestrial C
		Forest	Crop*	Pasture*	
	Tg C	Tg C	Tg C	Tg C	Tg C
Alabama	535	489	1.3	1.3	1,027
Arkansas	814	482	22	2.9	1,321
Florida	3,504	252	0.3	0.7	3,757
Georgia	1,232	514	3.7	1.6	1,751
Louisiana	1,100	376	8.7	0.7	1,485
Mississippi	457	450	7	1.3	915
North Carolina	1,761	517	7.4	1.8	2,287
South Carolina	888	262	1.9	0.7	1,153
Tenessee	408	389	5.2	4.7	807
Virginia	516	455	6.3	3.2	981
Total	**11,215**	**4,186**	**63.8**	**18.9**	**15,483.7**

*On an annual basis

While coastal wetlands have been estimated to contain about 10% of the total soil carbon (Armentano 1980, Schlesinger 1977, Schlesinger 1995), no comprehensive studies estimating the carbon sequestration and storage capabilities for the coastal areas of the NCA SE could be located.

A recent study found that the ability of SE ecosystems to act as a net carbon sink, also called Net Ecosystem Productivity (NEP), varied greatly across the region due to differences in ecosystem types and climate (Figure 12.3). NEP can be approximated by net ecosystem exchange (NEE), a research term that focuses on field measurements of ecosystem carbon sequestration. By convention, NEE = -NEP; thus, negative values of NEE represent a carbon sink, while positive values represent a carbon source. The ability to act as a net carbon sink can have large inter-annual variability due to fluctuations in precipitation and drought in the region. The mean regional NEP is about 0.3 petagrams of carbon (a carbon sink) per year, of which about 60% is from forests and the rest from lands classified as savannas (Figure 12.3, based on Xiao et al. 2011).

Table 12.3 Annual Terrestrial Biomass C Sinks in the Southeast.

State	Biomass C (Tg C/year)			Total Terrestrial C as Biomass (Tg C/year)
	Forest	Crop	Pasture	
	Tg C	Tg C	Tg C	Tg C
Alabama	8.7	1.3	1.3	11.3
Arkansas	6.5	22	2.9	31.4
Florida	5.4	0.3	0.7	6.4
Georgia	11	3.7	1.6	16.3
Louisiana	5.9	8.7	0.7	15.3
Mississippi	7.8	7	1.3	16.1
North Carolina	8.5	7.4	1.8	17.7
South Carolina	3.7	1.9	0.7	6.3
Tenessee	4.3	5.2	4.7	14.2
Virginia	6.3	6.3	3.2	15.8
Total	**68.1**	**63.8**	**18.9**	**150.8**

12.3 GHG Emission Reduction Activities

Southeastern businesses and consumers are showing an increasing interest in and ability to invest in cleaner energy options. Energy efficient home appliances, highly efficient combined heat and power technology, increasingly more stringent building energy codes, improved fuel efficiency and alternative fuel infrastructure for cars and trucks, clustered and transit oriented development, and renewable energy sources are only a few of the ways the SE is working to modernize its energy landscape and to cut its GHG emissions. In addition, federal and state policy makers, electric and gas utilities, research institutions, and others are working to identify, design, and implement clean energy policy and technology solutions that deliver important environmental and economic benefits. This section discusses some of the many activities that are helping to reduce GHG emissions in the SE over time.

Transportation

As noted in chapter 4 (Energy), the SE uses more petroleum fuel and has more vehicle miles traveled than any other NCA region. Transportation alone in the SE makes up 35% of combustion-related CO_2 emissions.

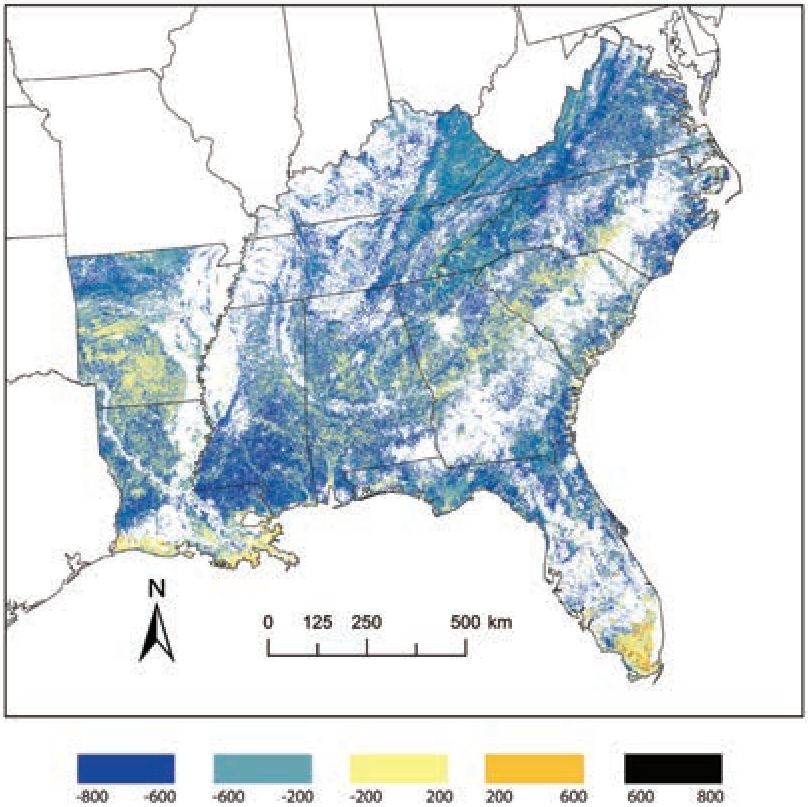


Figure 12.3 Mean annual net ecosystem exchange (NEE) for the Southeastern USA for the period 2001 to 2006. Units are $gCm^{-2}\ yr^{-1}$. Positive values indicate carbon release, and negative values indicate carbon uptake (croplands, urban areas, water bodies, and non-vegetated areas excluded).

The SE has an extensive network of highway, rail, and navigable transportation corridors and is home to five of the top 30 busiest airports in the USA by passenger boarding (FAA 2012) and seven of the top 30 freight gateways in the USA handling international merchandise, whether by water, air, or land (Research and Innovative Technology Administration 2009). A wide array of government and other stakeholders in the SE are working to improve the efficiency of the region's transportation network through such efforts as smart growth, congestion relief and commuter programs.

A noteworthy effort to reduce petroleum use in the SE is the Southeast Diesel Collaborative (SEDC 2012). The SEDC focuses on reducing the impacts of diesel emissions through strategies such as replacing older vehicles with newer, more fuel efficient vehicles, repowering existing engines to reduce emissions and to improve fuel usage, encouraging strategies to eliminate wasteful idling, and retrofitting long haul trucks with aerodynamic improvements to increase fuel economy. SEDC also works to reduce the impact of freight movement at ports and airports. For example, an SEDC project in Tennessee is installing auxiliary power units on tractor trailers to reduce fuel usage when idling. The effort is projected to save over 9 million gallons of fuel over the life of the project and eliminate over 100,000 tons of CO_2 (TDEC 2011).

Case Study: Arkansas Clean Cities Coalition

The US Department of Energy's Clean Cities Program advances the nation's economic, environmental, and energy security by supporting local actions to reduce petroleum consumption in transportation. Fourteen cities in the Southeast participate in the program.

The primary mission of the Arkansas Clean Cities Coalition is to advance the energy, economic, and environmental security of Arkansas through government-industry partnerships that contribute to the reduction of petroleum consumption in the transportation sector.

Coalition Statistics:
Population: 2,911,045
Area: 53,179 sq mi
Boundaries: Entire state of Arkansas
Designated: October 25, 1995
Alternative Fueling Stations:

- Biodiesel (B20 and above): 5
- Natural Gas: 6
- Ethanol (E85): 20
- Electric: 5
- Propane: 49

http://www1.eere.energy.gov/cleancities/ http://arkansasenergy.org/ar-clean-cities.aspx

http://www.afdc.energy.gov/cleancities/coalition/arkansas

SEDC is also working to create "green corridors" along interstates to promote the availability of less carbon intensive fuels and "idle-free" options for truckers during rest periods, e.g., truck stop electrification. SEDC is promoting this effort nationally and is working with other regional diesel collaborative organizations along the east coast to develop Interstate 95 into a green corridor. To date, the SE hosts over 1,500 alternative fuel locations, including biodiesel, compressed natural gas, propane, and E85 options (Alternative Fuels Data Center 2012).

Energy Efficiency in Buildings and Manufacturing

Energy efficiency is one of the most cost-effective ways to reduce GHG emissions of various end-use sectors, including residential, commercial, and industrial. Innovative, climate specific building designs, such as passive solar orientation, daylighting, high quality thermal and air barriers along the building envelope, and improved building occupant conservation behaviors can complement energy efficiency and help avoid new GHG emissions. While barriers to energy efficiency projects do exist, such as the upfront costs, many energy efficiency projects have a negative cost per ton of CO_2 avoided through reduced expenditures on fuel or electricity, though this negative cost depends on the temporal boundary of cost analysis and the useful life of the particular efficiency measure (McKinsey & Company 2009).

The reliable flows, estimated future stocks, high densities, and low costs of the Southeast's fossil fuel derived energy sources has made it difficult to promote energy conservation and efficiency improvements in the region. Market penetration data for energy efficient products such as Energy Star® appliances are lower-than-average and polling data suggest a weak conservation ethic in the southeastern United States (Brown et al. 2011).

According to the American Council for an Energy Efficient Economy (ACEEE 2012), states in the SE consistently rank towards the bottom of the list based on policies promoting energy-efficiency (Figure 12.4). This is illustrated by electric utility energy efficiency program spending per capita in the SE, which was just one-fifth the national average as of 2002 (Misuriello and Gillespie 2006). However, ACEEE did identify North Carolina and South Carolina as two of the most improved states in the 2012 ranking.

An exception is the ongoing implementation of the 2009 Presidential Executive Order (EO 13514) on Federal Leadership in Environmental, Energy, and Economic Performance (White House 2009). This order directs federal agencies to reduce greenhouse gas pollution, eliminate waste, improve energy and water performance, and leverage federal purchasing power to support innovation and entrepreneurship in clean energy technologies and environmentally-responsible products. The General Services Administration, along with Federal Agency partners, is working to implement this order in more than 140 federally owned buildings comprising more than 17 million rentable square feet of space in the SE USA (US General Services Administration 2012).

Although some states in the SE have already adopted fairly progressive energy codes, other states have outdated or non-existent energy code policies governing the

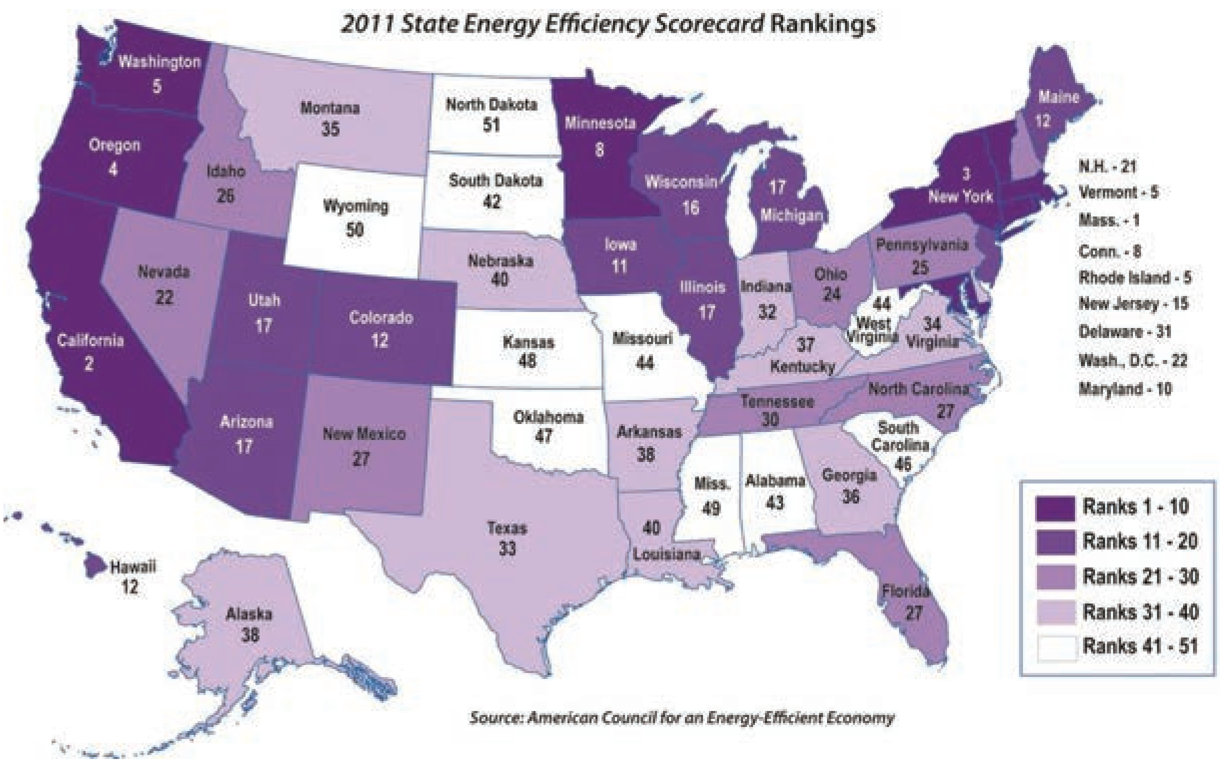


Figure 12.4 2011 ACEEE energy efficiency scorecard rankings.

energy efficiency of new buildings. This situation is improving, in part due to a provision of the 2009 American Recovery and Reinvestment Act (ARRA 2009) requiring states receiving ARRA funds to adopt updated energy codes. According to the ACEEE Scorecard, Georgia and Florida rank among the top 10 states for both the stringency of their energy codes and energy code compliance efforts. In April 2010, the Southeast Energy Efficiency Alliance was granted $20 million from the US Department of Energy Better Buildings Program to help upgrade businesses and homes in 13 cities in eight southeastern states and the US Virgin Islands. DOE expects that this project "will create program models and best practices to transform the market for energy efficiency across the Southeast" (USDOE 2012a).

Case Study: Beneficial Electrification of Motors and Vehicles

Research indicates that the electrification of transportation vehicles could provide significant benefits to the environment and the economy. Plug-in hybrid electric vehicles (PHEVs) and battery-only electric vehicles (EVs) are two types of vehicle electrification. PHEVs, unlike EVs, can operate seamlessly on gasoline or electricity. One promising technology to introduce the use of electricity as a transportation fuel is through the development of PHEVs.

The Natural Resource Defense Council (NRDC) and the Electric Power Research Institute (EPRI) recently analyzed how the deployment of PHEVs could change greenhouse gas emissions in the USA over the period 2010 to 2050. Various scenarios were evaluated which tracked the "emissions from the generation of electricity to the charging of PHEV batteries and from the production of motor fuels to their consumption in internal combustion vehicles." The scenarios represented different mixes of electric generating technologies and PHEV penetration levels. For each scenario, annual and cumulative GHG emissions were reduced. In 2050, annual reductions ranged between 163 and 612 million metric tons of GHGs. Cumulative GHG emissions reductions from 2010 to 2050 ranged from 3.4 to 10.3 billion metric tons. Each scenario reduced GHG emissions in each region of the country.

Vehicle electrification is not without challenges, which include higher vehicle costs, driven largely by the battery costs; the lack of available public charging infrastructure; the need to enable successful connection between vehicles and the electric grid; and a lack of mainstream consumer acceptance of electric powered vehicles.

For example, a growing fleet of EVs or PHEVs may bring an unusually high burden to areas of the Southeast requiring upgrades to the local utility distribution network to meet this new demand. In particular, transformers serving charging facilities may be insufficient to support the simultaneous charging of multiple vehicles. Utilities serving the Southeast will need access to information and regulatory support to deal with these and other issues.

Duvall, M. Plug-In Hybrids on the Horizon: Building a Business Case. Spring 2008. http://mydocs.epri.com/docs/CorporateDocuments/EPRI_Journal/2008-Spring/1016422_PHEV.pdf

EPRI and NRDC. "Environmental Assessment of Plug-In Hybrid Electric Vehicles Volume 1: Nationwide Greenhouse Gas Emissions." July 2007. http://mydocs.epri.com/docs/CorporateDocuments/SectorPages/Portfolio/PDM/PHEV-ExecSum-vol1.pdf

Electrification Coalition. Fleet Electrification Roadmap: Revolutionizing Transportation and Achieving Energy Security. November 2010. http://projectgetready.com/wp-content/uploads/2010/12/EC-Fleet-Roadmap-screen.pdf

An upside to these generally low energy efficiency rankings across the SE is the large untapped potential for energy saving gains through cost-effective conservation measures. This potential was illustrated in a recent study on the effect of implementing key energy efficiency polices in the industrial, residential, and commercial sectors in the SE (Brown et al. 2010). The geographic area in this study included states outside the NCA SE; the values reported below are estimates for only the NCA SE states.

The study found that policies promoting process improvements, utility plant upgrades, combined heat and power in the industrial sector, equipment standards and retrofits in the commercial sector, and home energy retrofits, building energy codes, energy-efficient appliances and an expanded residential weatherization allocation program are estimated to save 2,100 trillion BTUs (Tbtu) in 2020 (an 11% reduction in total energy consumption from a reference year of 2010) and 3,376 Tbtu in 2030 (a 16% reduction in total energy consumption from a reference year of 2010). In 2030, these energy savings are estimated to mitigate the emissions of approximately 100 MMt of CO_2. These policies would also have a net positive impact on the economy in the region, generate an estimated 220,000 jobs, avoid $24 billion of utility bills, and save 5 billion gallons of freshwater in 2020. For an example of one important energy efficiency technology that is already being used to some extent in the SE, see the following case study on combined heat and power (Kaufmann and Chittum 2011, Brown et al. 2011a, Brown et al. 2011b, Cox et al. 2011, US EPA 2012b).

Case Study: Combined Heat and Power (CHP)

Combined heat and power (CHP), also known as "cogeneration," is an efficient, clean, and reliable approach to generating power and thermal energy from a single fuel source. CHP can greatly increase a facility's operational efficiency, decrease energy costs, and decrease greenhouse gas emissions.

According to the Energy Information Administration (EIA) 2011 Annual Energy Outlook, 49% of industrial energy consumption occurs in the Southeast. CHP, therefore, is an important technology to help reduce this level of consumption. The Southeast has 416 CHP facilities that represent almost 20 GW of capacity. While bulk chemicals, food processing, and pulp and paper represent half of these CHP plants in the Southeast, a number of small applications have been added in the past ten years. The Southeast is also home to four large-scale natural gas combined cycle facilities in Alabama, Florida, Mississippi, and South Carolina.

Progressive policies that promote environmental technologies such as CHP have been shown to promote positive economic and environmental outcomes. For example, national analyses of output-based regulations and portfolio standards that include CHP have shown the potential to avoid tens of millions of tonnes of CO2 emissions, save 1.4 to 2.4 quadrillion BTUs of energy, and provide billions of dollars of net social benefits on an annual basis.

With few exceptions, such as North Carolina's 35% investment tax credit, such policies are largely nonexistent in the Southeast. For example, no Southeastern state has output-based regulations. Likewise, Arkansas and Florida both have public service commission-established energy efficiency goals, but neither includes provisions to encourage greater development of CHP.

Several southeastern states are leading in specific energy efficiency areas even though the SE as a region is lagging in overall energy-efficiency policies. According to US Green Building Council's 2010 ranking, four SE states—Florida, Virginia, Georgia, and North Carolina—rank in the top 11 of all 50 states for total number of US Green Building Council Leadership in Energy and Environmental Design (LEED) projects (US Green Building Council 2012). Georgia and Virginia are also among the top states in the country for promoting affordable green housing. Their qualified allocation plan policy provides incentives for energy efficiency, smart growth, resource conservation, and health (Global Green USA 2010). Organizations in several SE states are active in the areas of research, development, and demonstration for energy efficiency, including the Florida Solar Energy Center, the Florida Energy Systems Consortium, the North Carolina Solar Center, the Southeast Energy Efficiency Alliance, and Southface Institute, which conducts research and training on energy efficient housing and communities.

Case Study: North Carolina RPS

In 2007, the governor of North Carolina, Mike Easley, signed into law S.L. 2007-397, which establishes a Renewable Energy and Energy Efficiency Portfolio Standard for the state. By 2021, investor-owned utilities must meet 12.5% of retail electricity demand through renewable energy or energy efficiency measures. Electric membership corporations and municipalities that sell electric power in the state have to meet a standard of 10% by 2018. Resources that can be used to meet the standard include solar energy, wind energy, hydropower, geothermal energy, ocean current or wave energy, biomass resources, and energy efficiency measures.

The law also includes provisions to encourage the use of solar energy, swine and poultry wastes, as well as implementation of energy efficiency programs.

http://www.c2es.org/what_s_being_done/in_the_states/rps.cfm

Renewable Portfolio Standards

A Renewable Portfolio Standard (RPS) provides states with a mechanism to increase renewable energy generation using a market-based approach that is administratively efficient. An RPS requires electric utilities and other retail electric providers to supply a specified minimum amount of customer load with electricity from eligible renewable energy sources and other clean energy approaches, such as energy efficiency and combined heat and power. The goal of an RPS is to stimulate market and technology development so that renewable energy will eventually be economically competitive with conventional forms of electric power. States create RPS programs because of their benefits to energy security, economy, and environment, including reduction of GHG emissions (US EPA 2012c).

In the SE NCA Region, only North Carolina, Puerto Rico, and the US Virgin Islands have legally binding RPSs (North Carolina Utilities Commission 2008, Energy Affairs Administration 2010, USDOE 2012b). Several solar electricity facilities have subsequently been built, including a 17 MW solar farm in Davidson County, NC (Whitmore 2011). Two states—Virginia and Florida—have established renewable portfolio goals and Florida's Public Service Commission has approved inclusion of 110 MW of solar capacity in its ratemaking plan (Florida Public Service Commission 2008). The remaining SE states have not established either a mandatory or voluntary RPS. Additional renewable energy and energy efficiency policies and programs have likewise been established unevenly across the SE. Programs such as public benefit funds, net metering, green pricing programs, decoupling policies, energy efficiency resource standards, and various financial incentives vary from state to state (Center for Climate and Energy Solutions 2012).

Carbon Capture and Storage

Carbon capture and storage (CCS) is the process of capturing and storing CO_2 before it is emitted from stationary sources that would otherwise release CO_2 into the atmosphere. Although currently expensive and in the early stages of development, CCS technologies offer one technological solution to mitigating CO_2 emissions from stationary sources. For example, Mississippi Power's advanced integrated gasification combined cycle power plant being built in Kemper County, MS, will initially capture 65% of generated CO_2, much of which will be sold for enhanced oil recovery (Mississippi Power 2012).

Case Study: The City of Gainesville, FL

Gainesville joined the International Council for Local Environmental Initiatives the (ICLEI) Cities for Climate Protection Campaign in 2002. Three years later, the community joined cities across the nation and pledged to reduce carbon. The city's goal was to reduce carbon emissions to 7 percent below 1990 levels. Gainesville is set to reach this target in 2013.

Gainesville Regional Utilities, (GRU), a multiservice utility owned by the City of Gainesville, has played a key role in the process. As the fifth largest municipal electric utility in Florida, GRU serves approximately 90,000 retail and wholesale customers in Gainesville and surrounding areas with electric, natural gas, water, wastewater, and telecommunications services.

Strategic GRU programs and projects to reduce carbon emissions include monitoring and controlling emissions; improving energy efficiency; improving power generation efficiency, and increasing the use of renewable energy sources. GRU also has the first-in-the-nation feed-in tariff for solar electricity.

When a new local biomass power plant comes online in 2013 the city will exceed their goal of 7% below 1990 emissions for government operations, including the municipal utility (essentially all of community-wide emissions excluding transportation).

https://www.gru.com/OurCommunity/Environment/AirQuality/

It should be noted that CCS has an associated “energy penalty,” which is the fraction of fuel that must be used to run the CCS process. A recent study found that the energy penalty associated with pulverized coal power plants provided an absolute lower bound of 11%, with an easily achievable value of 40% and 29% as a “decent target value” (House et al. 2009).

The US DOE is investigating a variety of cost-effective technological approaches for CCS, including geologic carbon storage. Of particular interest is storage in saline formations, oil and gas reservoirs, coal areas that cannot be mined, organic-rich shales, and basalt formations. An example of potential deep saline geologic formations for CCS in the SE is shown in Figure 12.5 (NETL 2010).

The US DOE Carbon Sequestration Program is comprised of three key elements for CCS technology development and research: (1) core R&D, (2) infrastructure, and (3) global collaborations. The primary component of the infrastructure element is the Regional Carbon Sequestration Partnerships, a government/academic/industry cooperative effort tasked with characterizing, testing, and developing guidelines for the most suitable technologies, regulations, and infrastructure for CCS in different regions of the USA and several provinces in Canada.

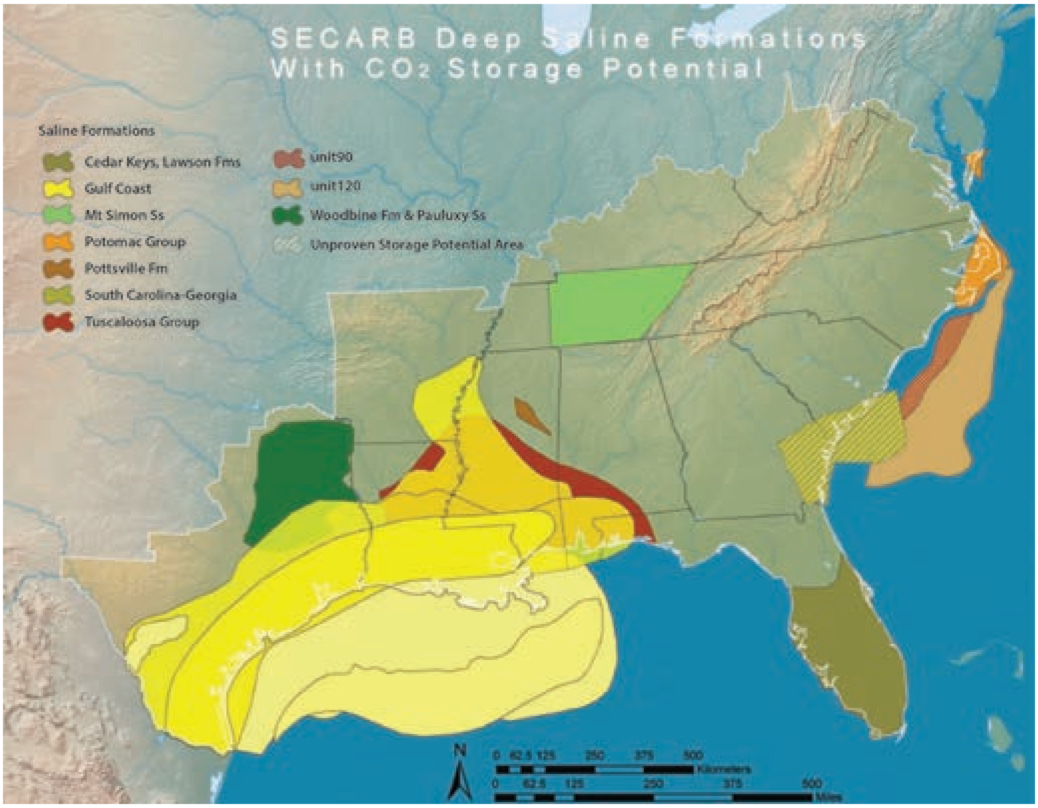


Figure 12.5 Southeast Regional Carbon Sequestration Partnership (SEACARB) map showing deep saline formations with CO_2 storage potential.

Case Study: Hickory Ridge Landfill

The Hickory Ridge Landfill in Conley, Georgia, is approximately 10 miles southeast of downtown Atlanta. The landfill opened in 1993 and is fitted with equipment to produce power from both solar photovoltaics and methane gas collection.

Hickory Ridge is one of the first landfills in the country to integrate flexible solar panels into a geomembrane cover being used to close a section of the landfill. Hickory Ridge is the largest solar landfill cover in the world, with 7,000 solar panels on 10 acres. The plant generates more than 1 million kWh of renewable electricity annually, enough to meet the needs of 224 homes. The solar project is being developed in tandem with a landfill methane-to-energy project, thereby increasing the power output of this one waste disposal facility and further reducing greenhouse gas emissions to the atmosphere.

http://www.alliedwaste.com/pr-90_000.html

http://www.georgia.gov/00/press/detail/0,2668,134245182_144576795_156569968,00.html

Photo courtesy of the Georgia Environmental Finance Authority.

The Southeast Regional Carbon Sequestration Partnership (SECARB), managed by the Southern States Energy Board, is the primary partnership investigating regional CCS opportunities (SECARB 2012). SECARB represents a 13-state region: Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, Texas, and Virginia, as well as portions of Kentucky and West Virginia. The primary goal of SECARB is to develop the necessary framework and infrastructure to conduct field tests of CCS technologies and to evaluate options and potential opportunities for the future commercialization of CCS in the region. Estimates of storage capacity in the SECARB Region are provided in Table 12.4.

SECARB is currently designing and operating four small-scale and two large-scale CCS demonstration projects across the SE. In addition, SECARB continues to characterize the region's on- and offshore geologic storage options, identify barriers and opportunities for the wide-scale construction of CO_2 pipelines to storage areas, enhanced oil recovery, and other commercial uses, monitor federal and state regulatory and legislative activities, and support local, regional, national, and international education and outreach efforts related to the SECARB initiative.

Sustainability Plans

In addition to individual projects aimed at reducing emissions of GHGs from a particular source, such as CCS for a large power plant or switching that plant to fuels with lower carbon intensities per unit of output as energy or goods, many corporations and cities are developing and instituting plans to reduce their overall direct and indirect impacts on the environment. Energy efficiency, renewable energy, and GHG emission reductions are frequently central themes in corporate and local government sustainability plans.

A number of SE cities have also developed sustainability plans to help save energy and reduce their carbon footprint. For example, 206 southeastern mayors have signed on to the US Conference of Mayor's Climate Protection Agreement. Among other things, signatories strive for a 7% reduction in GHG emissions by 2012 based on 1990 levels through actions ranging from anti-sprawl land-use policies to urban forest restoration projects to public information campaigns (Mayors Climate Protection Center 2009).

Another example, Local Governments for Sustainability (ICLEI), is working with 83 local governments in the SE to develop GHG emission inventories, set realistic goals for reduction of GHG emissions, develop and implement an action plan to achieve those reductions, and measure results (ICLEI USA 2012). The National Association of Counties, through its Green Government Initiative, also provides assistance to cities and counties through seminars, best practices, modeling, and analytical tools to increase local government plans for reducing GHG emissions (National Association of Counties 2012). A number of private sector firms are helping governments and businesses get on a path toward more quantifiable and accountable sustainability planning.

Other types of organizations, such as universities, are also engaged in developing and implementing programs to reduce GHG emissions. For example, 105 southeastern colleges and universities are signatories to the American College and University Presidents' Climate Commitment (ACUPCC), which works to "eliminate net greenhouse gas emissions from specified campus operations, and to promote the research and educational efforts of higher education to equip society to re-stabilize the earth's climate" (ACU Presidents Climate Commitment 2012). Some leaders include the University of Florida (UF 2012), in Gainesville, FL, and Agnes Scott College in Decatur, GA (Agnes Scott 2012).

Table 12.4 Estimates of CO_2 Storage Capacity in the SECARB Region.

State	CO_2 Sources (Million Metric Tons)	CO_2 Storage Resource (Million Metric Tons)				Years Storage**
	Total	Oil and Gas	Coal and Shale*	Saline*	Total	
AL	80	344	1,944	12,900	15,188	190
AR	35	250	15,675	4,304	20,229	572
FL	143	109	1,275	16,725	18,109	127
GA	90			4,909	4,909	55
KY	94	14	68	400	482	N/A
LA	102	6,781	8,325	139,497	154,603	1,520
MS	34	399	5,400	46,427	52,226	1,546
NC	77			1,352	1,352	18
SC	40			1,995	1,995	49
TN	66			500	500	8
VA	46	10	231	159	400	9
†Federal OffShore		17,754		484,996	502,750	N/A
Total	**807**	**25,661**	**32,918**	**714,164**	**772,743**	

*Low estimates used

**Years of CO_2 storage at the current emission rates (State CO_2 storage resource/State annual emissions)

†Includes storage in the Gulf of Mexico off the coast of TX

In 2006, UF was the first institution in the USA to sign the ACUPCC. Since 2001, UF has required all new buildings and major renovations to meet LEED certification, increasing the minimum certification threshold to silver in 2006, and more recently to a minimum of gold. UF now has 21 LEED certified buildings including the first platinum and gold certified buildings within Florida. In 2009, UF recycled 50% of its waste including construction debris and ambitiously aims for zero waste by 2015. Over 95% of all UF campus outdoor irrigation is supplied by reclaimed water from the university's on-campus treatment plants. UF was also named one of the nation's "Best Workplaces for Commuters" by the US EPA. Approximately 29% of all UF students, faculty, staff, and visitors travel to campus as pedestrians or bicyclists with another 39% arriving on the public bus system, which runs on a 20% biodiesel fuel blend and is partially subsidized by student fees. By 2011, UF earned the honor as the top school on the Roberts Environmental Center's sustainability reporting of the top US universities. Other aspects of the UF sustainability vision include research, curriculum, and engagement.

Agnes Scott has received funding for "green" renovations of several campus buildings, an energy audit, the purchase of utility sub-metering equipment for five buildings, the development of an energy master plan, and hiring a sustainability fellow. They are also working with the city of Decatur on sustainability initiatives in the broader community, have created an environmental and sustainability studies minor, and have established a policy that all new construction and renovation projects aim to follow LEED guidelines.

Universities are also using creative financing mechanisms such as Green Revolving Funds to promote energy efficiency improvements on campus. One example in the SE is the revolving fund at Georgia Tech, which has enabled the school to update physical plant infrastructure including boiler upgrades, efficient lights, variable-speed motors and pumps, and high-efficiency upgrades to chillers (Sustainable Endowments Institute 2011).

Additional activities. In addition to the activities discussed above, a number of additional and varied projects are in place and planned throughout the SE to reduce GHG emissions. Southeastern states, for example, currently have 135 active landfill projects under EPA's Landfill Methane Outreach Program, a voluntary assistance program that helps to reduce methane emissions from landfills by encouraging the recovery and beneficial use of landfill methane as an energy resource. In addition to the active projects, 186 additional landfills in the SE have been identified as possible candidates for methane capture (US EPA 2012d). Other examples include efforts by farmers to convert animal waste to useable energy, with 14 anaerobic digester systems currently operating at SE commercial livestock farms (US EPA 2012e), and efforts by municipalities, such as Hoover, AL and St. Johns County, FL, to collect waste grease for conversion to biodiesel (City of Hoover 2012, St. Johns County Government 2012).

12.4 Research Needs and Uncertainties

As the country moves from fossil fuels to renewable fuels, such as ethanol/gasoline blends and biodiesel, the resulting changes and impacts of radiative forcing agents need to be examined. For example, the US Congress has mandated that EPA evaluate on a three-year cycle the current and potential future environmental and resource conservation impacts associated with increased biofuel production and use, with the first report published in 2011 (US EPA 2011). Impact of emissions from biomass burning is another important consideration (Leahy et al. 2007, IPCC 2007, Marley et al. 2009, Marley et al. 2008, Gaffney and Marley 1998, Gaffney and Marley 2011).

Some of the numerous ongoing focus areas for research on GHG mitigation include the following:

- Renewable electricity conversion and delivery systems
- Renewable fuels formulation, delivery, and storage

- Efficient and integrated energy systems
- Strategic energy analysis
- Carbon capture and storage
- Vehicle electrification
- Personal and organizational behavior among the diversity of energy consumption end-use sectors
- Approaches to making substantial investments that do not lead to technology lock-in, given the uncertainties in technology development pathways and future conditions of climate, economic growth, and other factors

12.5 References

ACU Presidents Climate Commitment. 2012. http://www.presidentsclimatecommitment.org/

Agnes Scott. 2012. *Sustainability at ASC.* http://legacy.agnesscott.edu/about/sustainability

Alternative Fuels Data Center. 2012. Washington, DC. http://www.afdc.energy.gov/

American Council for an Energy Efficient Economy. 2012. *State Energy Efficiency Scorecard.* Washington, DC. http://www.aceee.org/sector/state-policy/scorecard

American Recover and Reinvestment Act. 2009. http://www.recovery.gov/About/Pages/The_Act.aspx

Armentano, T.V. 1980. Drainage of organic soils as a factor in the world carbon cycle. *BioScience,* 30 (12): 825-830.

Brown, M.A., E. Gumerman, X. Sun, Y. Baek, J. Wang, R. Cortes, D. Soumonni. 2010. *Energy Efficiency in the South*. Southeast Energy Efficiency Alliance. Atlanta, Ga.

Brown, M.A., E. Gumerman, X. Sun, G. Kim, K. Sercy 2011. Working Paper. Myths and Facts about Electricity in the U.S. South. *Energy Policy* 40: 231-241.

Brown, M.A., R. Jackson, M. Cox, R. Cortes, B. Deitchman, M.V. Lapsa. 2011a. *Making industry part of the climate solution: Policy options to promote energy efficiency*. Oak Ridge, TN: Oak Ridge National Laboratory. http://info.ornl.gov/sites/publications/Files/Pub23821.pdf

Brown, M.A., M. Cox, R. Jackson, M.V. Lapsa. 2011b. *Expanding the pool of federal policy options to promote industrial energy efficiency*. Niagara Falls, NY: American Council for an Energy-Efficient Economy. http://www.aceee.org/files/proceedings/2011/data/papers/0085-000016.pdf

CAPAG (Climate Action Plan Advisory Group). 2008. Recommended mitigation options for controlling greenhouse gas emissions. Washington, DC: Center for Climate Strategies.

Center for Climate and Energy Solutions. 2012. U.S. State Climate Policy Maps. Arlington, VA. http://www.c2es.org/what_s_being_done/in_the_states/state_action_maps.cfm

Center for Climate Strategies. 2012. State and Local Climate Blackboard. Washington, DC. http://www.climatestrategies.us/policy_tracker/state/

City of Hoover. 2012. *Fleet management*. Hoover, AL: City of Hoover. http://www.hooveral.org/Default.asp?ID=114

Commonwealth of Virginia. 2008. *Inventory and projection of greenhouse gas emissions (2000-2025).* Richmond, VA: Department of Environmental Quality–Air Division.

Cox, M., M.A. Brown, R. Jackson. 2011. *Regulatory reform to promote clean energy: The potential of output-based emissions standards*. Niagara Falls, NY: American Council for an Energy-Efficient Economy. http://www.aceee.org/files/proceedings/2011/data/papers/0085-000017.pdf

Energy Affairs Administration. 2010. *Renewable portfolio standard*. San Juan, Puerto Rico: Green Energy Fund.

EIA (Energy Information Administration). 2011. State Energy Data System, 1960-2009 Estimates. Washington, DC. http://www.eia.gov/state/seds/seds-data-complete.cfm

EIA (Energy Information Administration). 2009. *Renewable portfolio standards fact sheet*. Washington, DC: U.S. Environmental Protection Agency.

FAA (Federal Aviation Administration). 2012. Passenger Boarding (Enplanement) and All-Cargo Data for U.S. Airports. Washington, DC. http://www.faa.gov/airports/planning_capacity/passenger_allcargo_stats/passenger/

Florida Public Service Commission. 2008. *PSC approves solar projects' cost recovery eligibility*. Tallahassee, FL: Florida Public Service Commission. http://www.psc.state.fl.us/home/news/index.aspx?id=419

Gaffney, J.S. and N.A. Marley. 1998. Uncertainties of aerosol effects in global climate models. *Atmospheric Environment* 32 (16): 2873-2874.

Gaffney, J.S and N.A. Marley. 2011. Climate impacts from agricultural emissions: Greenhouse species and aerosols. In *Understanding greenhouse gas emissions from agricultural management*, ed. L. Guo, A. Gunasekara, and L. McConnell, 275-295. Washington, DC: Agricultural Research Service.

Global Green USA. 2010. *Green Building Criteria in Low-Income Housing Tax Credit Programs: 2010 analysis*. Santa Monica, CA: Global Green USA. http://globalgreen.org/docs/publication-164-1.pdf

Han, F.X., M.J. Plodinec, Y. Su, D.L. Monts, Z. Li. 2007. Terrestrial carbon pools in southeast and south-central United States. *Climatic Change* 84 (2): 191-202.

House, K.Z., C.F. Harvey, M.J. Aziz, D.P. Schrag. 2009. The energy penalty of post-combustion CO_2 capture & storage and its implications for retrofitting the U.S. installed base. *Energy & Environmental Science* 2 (2): 193-205.

ICLEI USA. 2012. http://www.icleiusa.org/about-iclei/

IPCC (Intergovernmental Panel on Climate Change). 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller. New York and United Kingdom: Cambridge University Press.

Kaufmann, N. and A. Chittum. 2011. State barriers to CHP development. Paper presented at the Proceedings of the 2011 Industrial Energy Technology conference, New Orleans, Louisiana, May 17-19, 2011. http://txspace.di.tamu.edu/bitstream/handle/1969.1/94798/ESL-IE-11-05-21.pdf?sequence=1

Kentucky Renewable Energy Consortium. 2009. *Kentucky forum on carbon sequestration through agriculture and forestry management*. Louisville, KY: KREC. https://louisville.edu/kppc/krec/krec-publications/Carbon%20Forum%20Summary%20web%2012-17-09.pdf

Leahy, L.V., T.L. Anderson, T.F. Eck, R.W. Bergstrom. 2007. A systhesis of single scattering albedo of biomass burning aerosol over southern Africa during SAFARU 2000. Geophys. Res. Lett. 34:5p.

Marley, N.A., J.S. Gaffney, M.J. Tackett, K. Hardy, N.C. Sturchio, L. Heraty, N. Martinez, A. Marchany-Rivera, T. Guilderson, A. MacMillan, K. Steelman. 2008. The impact of biogenic carbon emissions on aerosol absorption in Mexico City. *Atmospheric Chemistry and Physics* 8 (5): 18499-18530.

Marley, N.A., J.S. Gaffney, T. Castro, A. Salcido, J. Frederick. 2009. Measurements of aerosol absorption and scattering in the Mexico City metropolitan area during the MILAGRO field campaign: A comparison of results from the T0 and T1 sites. *Atmospheric Chemistry and Physics* 9 (1): 189-206.

Mayors Climate Protection Center. 2009. *Mayors Leading the Way on Climate Protection*. Washington, DC: U.S. Conference of Mayors. http://www.usmayors.org/climateprotection/revised/

McKinsey&Company. 2009. *Pathways to a low carbon economy: Version 2 of the global greenhouse gas abatement curve--January 2009*. Washington, DC: McKinsey&Company.

Mississippi Power. 2012. *Kemper Energy Facility.* http://www.mississippipower.com/kemper/home.asp

Misuriello, H. and K. Gillespie. 2006. *New energy efficiency policy initiatives and advances in the southeast United States*. Niagara Falls, NY: American Council for an Energy-Efficient Economy. http://www.eceee.org/conference_proceedings/ACEEE_buildings/2006/Panel_8/p8_16/paper

National Association of Counties. 2012. *Green government initiative*. Washington, DC: NASo. http://www.naco.org/programs/csd/pages/greengovernmentinitiative.aspx

NETL (National Energy Technology Laboratory). 2010. *2010 carbon sequestration atlas of the United States and Canada: Third edition*. Washington, DC: US Department of Energy.

North Carolina Utilities Commission. 2008. *Renewable energy and energy efficiency portfolio standard*. Raleigh, NC: NC Utilities Commission.

Research and Innovative Technology Administration. 2009. *America's freight transportation gateways 2009*. Washington, DC: US Department of Transportation. http://www.bts.gov/publications/americas_freight_transportation_gateways/2009/pdf/entire.pdf

Schlesinger, W.H. 1977. Carbon balance in terrestrial detritus. *Annual Review of Ecology and Systematics* 8 (November): 51-81.

Schlesinger, W.H. 1995. An overview of the C cycle. In *Advances in soil science: Soils and global change,* ed. R. Lal, J.M. Kimble, E. Levine and B.A. Stewart, 9-26. Boca Raton, FL: CRC-Press.

SECARB (Southeast Regional Carbon Sequestration Partnership). 2012. http://www.secarbon.org/

SEDC (Southeast Energy Efficiency Alliance). 2010. Southeast Diesel Collaborative. 2012. Atlanta, GA http://southeastdiesel.org/

St. Johns County Government. 2012. *Biodiesel fuel program*. St. Augustine, FL: Biodiesel Fuel Department. http://www.co.st-johns.fl.us/PublicWorks/Biodiesel.aspx

Strait, R., M. Mullen, B. Dougherty, A. Bollman, R. Anderson, H. Lindquist, L. Williams, M. Salhotra, J. Schreiber. 2008a. *Final Arkansas greenhouse gas inventory and reference case projections, 1990-2025.* Washington, DC: Center for Climate Strategies.

Strait. 2008b. *Final Florida greenhouse gas inventory and reference case projections, 1990-2025.* Washington, DC: Center for Climate Strategies.

Strait, R., S. Roe, B. Dougherty, A. Bollman, H. Lindquist. 2008c. *Final draft South Carolina greenhouse gas inventory and reference case projections, 1990-2020.* Washington, DC: Center for Climate Strategies.

Strait, R., M. Mullen, B. Dougherty, R. Anderson, A. Bollman, V. Glenn, J. Maldonado, S. Roe, J. Schreiber, B. Strode, K. Pasko. 2010. *Final Kentucky greenhouse gas inventory and reference case projections, 1990-2030.* Washington, DC: Center for Climate Strategies.

Sustainable Endowments Institute. 2011. *Greening the bottom line: The trend toward green revolving funds on campus*. Cambridge, MA: Sustainable Endowments Institute. http://www.endowmentinstitute.org/gbl/Greening_the_Bottom_Line.pdf

TDEC (Tennessee Department of Environment and Conservation). 2011. APU Rebate Program. Final Report. Table 2 – Actual Results. Grant 2D-95422009.

UF (University of Florida). No Date. Reaching the Vision - Sustainable U.F. Gainesville, FL: UF Office of Sustainability. http://sustainable.ufl.edu/docs/ReachingtheVision-final.pdf

US Census Bureau. 2012. Washington, DC: US Department of Commerce. http://www.census.gov

USDOE (US Department of Energy). 2012a. Better Buildings Neighborhood Program. *Southeast Energy Efficiency Alliance--The Southeast Makes a Wise Investment in Energy Efficiency.* Washington, DC. http://www1.eere.energy.gov/buildings/betterbuildings/neighborhoods/seea_profile.html

USDOE (US Department of Energy). 2012b. U.S. Virgin Islands--Renewables Portfolio Targets. Washington, DC. http://energy.gov/savings/us-virgin-islands-renewables-portfolio-targets

US EPA (US Environmental Protection Agency). 2011. National Center for Environmental Assessment. *Biofuels and the environment: The first triennial report to Congress*. Washington, DC. http://cfpub.epa.gov/ncea/biofuels/recordisplay.cfm?deid=235881

US EPA (US Environmental Protection Agency). 2012a. Greenhouse Gas Reporting Program. Washington, DC. http://www.epa.gov/ghgreporting/index.html

US EPA (US Environmental Protection Agency). 2012b. Combined Heat and Power Partnership. *Environmental Benefits*. Washington, DC. http://epa.gov/chp/basic/environmental.html

US EPA (US Environmental Protection Agency). 2012c. Combined Heat and Power Partnership. *Renewable Portfolio Standards Fact Sheet*. Washington, DC. http://www.epa.gov/chp/state-policy/renewable_fs.html#fn1

US EPA (US Environmental Protection Agency). 2012d. Landfill Methane Outreach Program. Washington, DC. http://epa.gov/lmop/

US EPA (US Environmental Protection Agency). 2012e. AgStar Program. Washington, DC. http://epa.gov/agstar/

US General Services Administration. 2012. *Federal buildings/facilities*. Washington, DC: GSA. http://www.gsa.gov/portal/category/21459

US Green Building Council. 2012. *Top 10 U.S. states ranked by total number of LEED projects*. Washington, DC: U.S. Green Building Council. http://www.usgbc.org/ShowFile.aspx?DocumentID=7744

Virgin Islands Energy Office. 2009. Renewable Portfolio Standard.

White House. 2009. *Executive Order 13514 on Federal Leadership in Environmental, Energy, and Economic Performance*.http://sustainability.performance.gov/

Whitmore, C. Davidson county solar farm, North Carolina. *PV-Tech*, January 27, 2011. http://www.pv-tech.org/project_focus/davidson_county_solar_farm_north_carolina

Xiao, J., Q.Zhuang, B.E. Law, D.D. Baldocchi, J. Chen, A.D. Richardson, J.M. Melillo, et al. 2011. Assessing net ecosystem carbon exchange of U.S. terrestrial ecosystems by integrating eddy covariance flux measurements and satellite observations. *Agricultural and Forest Meteorology* 151 (1): 60-69.

Chapter 13

Climate Adaptations in the Southeast USA

LEAD AUTHORS

Kirstin Dow (Carolinas Integrated Sciences and Assessments; Department of Geography, University of South Carolina, Columbia, South Carolina)

Lynne Carter (Southern Climate Impacts Planning Program and Coastal

Sustainability Studio, Louisiana State University, Baton Rouge, Louisiana)

CONTRIBUTING AUTHORS

Ashley Brosius (Carolinas Integrated Sciences and Assessments, Columbia, South Carolina)

Ernesto Diaz (Puerto Rico Coastal Zone Management Program, San Juan, Puerto Rico)

Rick Durbrow (Region 4, Environmental Protection Agency, Atlanta, Georgia)

Rhonda Evans (Region 4, Environmental Protection Agency, Atlanta, Georgia)

Stephanie Fauver (NOAA Coastal Services Center, Charleston, South Carolina)

Tim Hayden (Engineer Research Development Center–CERL, U.S. Army Corps of Engineers, Champaign, Illinois)

Bob Howard (Region 4, Environmental Protection Agency, Atlanta, Georgia)

Kasey Jacobs (Puerto Rico Coastal Zone Management Program, San Juan, Puerto Rico)

Glenn Landers (U.S. Army Corps of Engineers, Jacksonville, Florida)

Steve McNulty (Eastern Forest Environmental Threat Assessment Center, Raleigh, North Carolina)

Janine Nicholson (Climate Change Strategies Program, NC Department of Environment and Natural Resources, Raleigh, North Carolina)

Dale Quattrochi (NASA Marshall Space Flight Center, Huntsville, Alabama)

Linda Rimer (Region 4, Environmental Protection Agency, Durham, North Carolina)

Scott Shuford (City of Fayetteville, Fayetteville, North Carolina)

Skip Stiles (Wetlands Watch, Norfolk, Virginia)

Adam Terando (Department of Biology, North Carolina State University, Raleigh, North Carolina)

Climate adaptation activities are currently under way around the Southeast (SE). Efforts by local, state, and federal agencies include identification of relevant climate impacts, assessment of significant risks and vulnerabilities, and the creation of partnerships to support planning. In addition to specific projects, adaptive capacity also is being established through monitoring, research, and outreach. This analysis draws on multiple efforts to inventory adaptation in the SE. The authors of this chapter identified few advanced examples of plans and projects that have been implemented. However because of the number of efforts, diversity of groups involved, the mainstreaming of efforts, and the differences in how those efforts disseminated, this review may not fully represent adaptation activity in the SE.

The majority of current efforts are aimed at identification of relevant climate risks and assessment of risk and vulnerability. Coastal areas, where risks of severe storms and sea level rise (SLR) are highly salient, are frequently the focus of attention. Efforts to bring climate change adaptation strategies and methods into mainstream activities often are done through projects that focus on resilience and sustainability. The adaptation process is complex and must include partnerships for cross-disciplinary coordinated response from many sectors including financial, technical, governance, and social.

In the future, as groups move from risk and vulnerability assessments to strategic adaptation planning and implementation, the authors anticipate a shift in activities and information needs that place great emphasis on costs, benefits, and co-benefits of adaptations. As efforts advance, evaluation of adaptation efforts will become important in decision making.

This review of climate adaptation programs and activities in the SE begins with an introduction to broad adaptation research questions and then introduces major stresses currently confronting regional adaptation needs. Existing stresses likely will increase the potential negative impacts of future climate changes. This summary picks up from the 2009 National Assessment report (Karl et al. 2009) that included some discussion around adaptation efforts in this region and the nation, and provides an overview of recent adaptation activities and example case studies.

Key Findings

- Although many climate adaptation efforts are underway throughout the Southeast, it is difficult to document the full extent because of increasing levels of involvement, the diversity of entities involved, and integration of adaptation into other planning processes.
- Adaptation activities cross all scales of planning from nongovernmental organizations (NGOs) to local communities, states, regions, and federal agencies.
- Many adaptation efforts are being included into other processes. As a result, adaptation is taking place in the context of resilience and sustainability efforts.
- To the extent that current adaptation catalogs and databases accurately represent ongoing activities, the present focus of adaptation in the SE is on identifying relevant climate impacts and building partnerships to foster coordinated responses and sharing of resources. These partnerships foster additional aspects of adaptive capacity.

- Adaptation planning projects that have reached the stage of risk and vulnerability assessment are mostly focused on sea level rise and severe storm threats facing coastal areas and communities.
- Examples of undertaking full adaptive management approaches to the threats and uncertainty are limited.
- There is little information on the costs, benefits and co-benefits of adaptations to guide adaptation planning.

13.1 Definition of Adaptation

Climate adaptation can be defined as the "adjustment in natural or human systems to a new or changing environment that exploits beneficial opportunities or moderates negative effects" (NRC 2010a). Questions that lead to an understanding of the adaptation process initially are descriptive: Who is adapting or not? To what are they adapting? How, when, and why are they adapting? Answers to these questions provide a foundation for further questions including the following:

- How does the understanding of climate change and potential consequences or opportunities motivate a response?
- How do other stresses interact with potential climate impacts and influence adaptation options?
- How do individuals, sectors, groups, and governments differ in their capacity to adapt?
- How are adaptation options being evaluated?
- What are the barriers, constraints, and limits to adaptation and how can they be overcome?

Adaptive responses can vary in several ways, including by what motivates them. Some responses are "anticipatory" or planned in response to real or perceived information about expected climate changes. Other responses are "autonomous" adaptations taken in response to indirect signals such as changes in regulations or markets.

The process of adaptation can be conceptualized as a series of steps moving from developing an understanding of current and future climate changes related to the system of interest, assessing vulnerabilities and risks, evaluating management options, implementing strategies, monitoring outcomes, and re-evaluating those analyses and decisions (Figure 13.1). The process generally prescribes multiple iterations to incorporate new information and changing conditions. The emphasis on risk management and identification of opportunities and co-benefits differs among frameworks, but there is good consistency at the conceptual level that this is a critical piece to adaptation (e.g., NRC 2011, NRC 2010b, UKCIP 2012).

Practical applications of adaptation rarely proceed in the tidy, sequential manner of a concept diagram such as Figure 13.1. Because multiple groups of people are involved steps must be repeated to account for differences in planning schedules, organizational timelines, and priorities. Some activities may be out of step with others at any specific time. Examples of the ongoing processes for these steps are outlined later in the chapter.

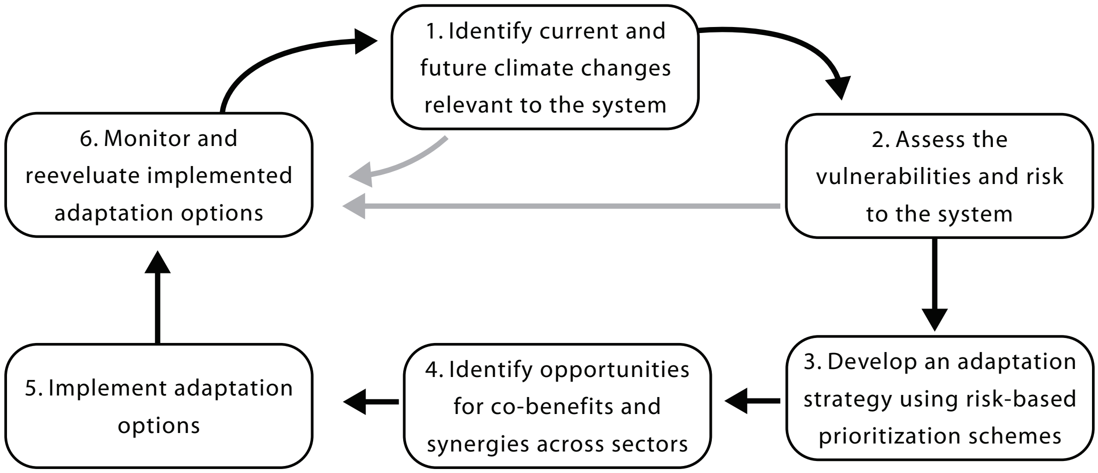


Figure 13.1 Adaptation planning is envisioned as a cyclical, iterative process incorporating these six steps (NRC 2010a).

While not focused on the southeastern USA, there is substantial research literature associated with each of these six steps (for example, NRC 2010a). However, because interest in climate adaptation is relatively recent, for each subsequent step in the process, the fraction of empirical work on climate change adaptation becomes substantially thinner and that of conceptual contributions and insights garnered from related or analogous topics swell.

Efforts are ongoing to engage stakeholders of all types in assessing the significance of climate to their areas of interests. Information about stakeholder needs is integral for research projects as well as for making decisions about adaptation to climate change effects.

When making risk and vulnerability assessments, researchers and planners need to consider other stresses, such as population growth and land development, which likely will interact with climate change in shaping vulnerabilities. Identification of relevant impacts and analysis of risks and vulnerabilities are important foundations to setting risk-based priorities. In addition, processes for risk-based priority setting and analysis of opportunities for co-benefits frequently require information from socioeconomic scenarios and climate projections as well as institutional and economic analyses. While several studies have considered potential losses to SLR, there is less consideration of economic evaluations of adaptation alternatives (Bin et al. 2011).

Other research addresses the arrows connecting the steps highlighted in Figure 13.1. These projects seek to understand the processes that influence the pace, difficulty, and resources required to move from one step to the next. For example, some of the practical complexity is related to the diversity of actors and sectors working at different social and geographical scales and institutional needs for coordination (NRC 2010a and 2010b). Another significant body of work focuses on understanding the factors that increase the capacity to adapt. These include governance, financial, technological, and social resources, and are sometimes expressed through the creation of networks.

Some strategies emphasize the value of incorporating new adaptation activities and policies into existing planning and management efforts, a process called mainstreaming. Mainstreaming is especially valuable when climate change may exacerbate extant stresses. In the SE, mainstreaming might include strategies that address population growth, hurricanes, tropical storms, SLR, land subsidence, and drought. Mainstreaming is often recommended because it offers the option to reduce current risks while increasing preparedness for potential future risks. Benefits also include using existing institutions to avoid duplication of efforts, to increase coordination, and to build on existing support and networks across levels of organizations and governments. Note though, that mainstreaming faces the challenges and limitations faced by existing institutions. The following section provides a brief review of the current climate and related stresses in the Southeast and situates the subsequent discussion of adaptation efforts.

13.2 Major Stresses on the Southeast

The Southeast is vulnerable to a number of direct and indirect impacts from the current range of climate variability and the significant challenges posed by climate change (Karl et al. 2009, and also see Chapter 2 of this report). Adaptation is complicated by other changes within the region and internationally, such as population issues, agricultural markets, changes to natural ecosystems, and economic fluctuations. Four major regional challenges facing multiple sectors are discussed in the following paragraphs.

Population Growth

The southeastern region's moderate climate has been a population-growth driver since the development of air conditioning (Svart 1976, Graves 1980). The region is vulnerable to rising summer temperatures that ncrease energy demand, which is already high during summer months due to demands for residential and commercial cooling (Karl et al. 2009, also see Chapter 2). The population is also at risk to potential spread of disease vectors with changing climate conditions (e.g., Morens and Fauci 2008; Karl et al. 2009; also see Chapter 3).

Residential and business development has typically increased populations in coastal areas and major metropolitan centers (US Census Bureau 2011). These areas are vulnerable to climate change effects, such as sea level rise, droughts, floods, stronger hurricanes, and unstable weather patterns (Karl et al. 2009). Miami, according to one set of climate predictions, ranks internationally as the number one metropolitan area likely to be exposed to coastal flooding by 2070 (Hanson et al. 2011). In the same analysis, New Orleans is ranked number 12 and Virginia Beach number 19. For coastal areas, retreat from SLR may prove difficult. For example, retreat by the City of Satellite Beach, Florida, will be restrained because 98% of the land is developed and there is no room for expansion away from encroaching sea level (Parkinson and McCue 2011).

Research on land use planning along the Atlantic coast indicates that many state and local governments experience high development pressures in low lying coastal areas, which is unlikely to change as coastal regions are desirable locations for residents and businesses (Table 13.1). In addition, local governments benefit from the higher property taxes of coastal properties, so there is little financial incentive to curtail development.

Table 13.1 Intensity of Development of Land along Atlantic Coast (USA) Land within 1m above High Water.

	Likelihood of shore protection[a] High ↔ Low						
	Percent of dry land, by land use type[b]				Area		
State	Developed (%)	Intermediate (%)	Undeveloped (%)	Conservation (%)	Dry land (km^2)	Non-tidal Wetlands (km^2)	Tidal Wetlands (km^2)
MA	26	29	22	23	110	24	325
RI	36	11	48	5	8	1	29
CT	80	8	7	5	30	2	74
NY	73	18	4	6	165	10	149
NJ	66	15	12	7	275	172	980
PA	49	21	26	4	24	3	6
DE	27	26	23	24	126	32	357
MD	19	16	56	9	449	122	1116
DC	82	5	14	0	4	0	1
VA	39	22	32	7	365	148	1272
NC	28	14	55	3	1362	3050	1272
SC	28	21	41	10	341	272	2229
GA	27	16	23	34	133	349	1511
FL	65	10	12	13	1286	2125	3213
Total	**42**	**15**	**33**	**9**	**4665**	**6314**	**12882**

[a] High and low refer to the likelihood that a type of land may already be, or will be, protected by shore protection measures. Developed areas are more likely to be protected by bulkheads, dikes, or beachfill, while conservation areas are more likely to be allowed to respond naturally to shore processes.

[b] Calculated as the statewide area of a given land use category divided by the area of dry land in the study area. Percentages may not add up to 100% due to rounding

(Adapted from Titus et al. 2009, Table 1, p. 5)

Tourism

The economic importance of tourism in the Southeast complicates adaptation efforts (e.g., Evans 2004, Murley et al. 2005, North Carolina Department of Commerce 2012). In the Gulf Coast region, for example, 8% of jobs are in the tourism and recreation industry. Consequently, public infrastructure and private investment are geared toward a combination of permanent and seasonal populations along the coastline. Such investment increases exposure to losses due to SLR, storm surge, and wind damage from tropical storm systems. Exposure to risk is also increased due to the geomorphic characteristics of the most populated coastal areas. The majority of Atlantic coastline areas that

Box 13.1

Process for Identifying Adaptation Activities in the Southeast

These observations are based on an extensive investigation to identify adaptation activities taking place in the Southeast. The following summary is based on a compilation of adaptation actions identified by the Georgetown Climate Center Adaptation Clearinghouse, (Georgetown Climate Center 2012); the NOAA Coastal Services Center database of Coastal Climate Adaptation/Action Plans (NOAA CSC 2012), case studies in the CAKE database (Climate Adaptation Knowledge Exchange 2012), the Gulf of Mexico Climate Change Adaptation Inventory (NOAA Gulf Coast Services Center 2012), contributions from researchers contributing to the Southeastern Region Technical Input to the National Climate Assessment, and additional research conducted by Regional Integrated Sciences and Assessments teams in the Southeast. The types of documents represented included planning documents, government reports, workshop reports, peer-reviewed publications, research reports (not peer reviewed), and website reports. This body of information represents the triangulation of efforts across the groups of researchers mentioned above. The cases presented represent publicly available information and are likely to under represent actual adaptive efforts on-going in the region for at least three reasons. First, the documents reviewed are publicly available and they likely under represent efforts undertaken by private entities or organizations, such as energy or manufacturing businesses. A second reason is that the cases represented are biased towards planned rather than autonomous forms of adaptation. Finally, reluctance of some groups to publicly engage with the climate change controversies is a potential source of under representing of adaptation activities in the Southeast. Research by Carolinas Integrated Sciences Assessments (2012 draft in preparation for the National Climate Assessment) indicates that while some entities are undertaking climate adaptation activities, they consciously avoid publicly identifying these activities as adaptation actions in order to avoid political controversy around climate change. Instead, some highlight co-benefits, such as reduction of risks to current hazards, which might build resilience, water efficiency, and energy efficiency.

experienced the greatest population increase are historically rapidly shifting and highly dynamic barrier island systems (Culver et al. 2011). The large investment in infrastructure and employment tied to coastal tourism could hinder the ability to adapt rapidly to tipping points and threshold responses in the climate system (Frazier et al. 2010).

Sea Level Rise and Land Subsidence

The geomorphic setting and the length of the coastline in the SE and Caribbean mean that SLR is likely to be one of the most immediate, widespread, and potentially damaging impacts of climate change (Thieler and Hammar-Klose 1999, Titus and Richman 2001). Many of the southeastern coastal areas are low in elevation and vulnerable to SLR. Additionally, many areas are prone to land subsidence due to the presence of organic soils and water soluble rock substrates. Extensive withdrawals of groundwater for drinking and for industrial processes exacerbate hydrologic conditions. Withdrawal of oil and gas promote further subsidence, which enhances the vulnerability to present and future sea level rise. In some cases, subsidence is the primary cause of relative changes between land surface elevation and sea level (Dixon et al. 2006).

Vulnerability to SLR is also enhanced by storm surge from tropical cyclones. As sea level rises, storm surge likely will move further inland along low-lying coastal areas (Mousavi et al. 2011). Many communities along the southeastern coast are built on soils that are highly porous and permeable, which means that hard barriers, such as levees and seawalls, will not be effective because SLR will increase hydrostatic pressure and force water to flow beneath or behind the structures (Parkinson and McCue 2011). Barriers also potentially create a false sense of security that could encourage continued building and place more people and property at risk from events that may exceed infrastructure design as we saw when Hurricane Katrina broke the levees in New Orleans.

Advance warning systems and improved evacuation procedures and infrastructure are crucial for human safety. Under climate change projections, property and infrastructure damages likely will increase substantially, affecting cost and availability of insurance, energy, property; as well as changes in local, state, and federal policies (Irish et al. 2010, Bin et al. 2011, Neumann et al. 2011). Increases in tropical storm intensity as opposed to frequency have been projected by recent climate models (Knutson et al. 2010). Globally tropical storm intensity is projected to increase by 2% to 11% by 2100 and associated rainfall by roughly 20% (Knutson et al. 2010). Globally, the frequency of intense hurricanes also is expected to increase (Knutson et al. 2010).

Drought and Water Supply

Climate-related issues likely will challenge adaptation by threatening water supplies in the SE. Many large metropolitan areas depend on surface water supplies to meet potable and industrial water needs. Many other cities, including Charlotte, NC, and Atlanta, GA, rely on rivers and associated reservoirs. Urban groundwater resources are also at risk. For example, the Southeast Florida Regional Climate Change Compact includes threats to drinking water supply due to salinity intrusion among its priorities (http://www.southeastfloridaclimatecompact.org/).

Drought conditions exacerbated by climate change likely will affect the reliability of water sources. The National Integrated Drought Information System (NIDIS) has been working with stakeholders, including state and federal agencies, to pilot a drought early warning system for the ACF basin (NIDIS 2012). Other strategies will need to be developed in the SE to appropriate water fairly and efficiently.

13.3 Adaptation in the Southeast

Adaptation efforts in the SE either focus on the early stages of identifying climate risks relevant to communities, ecosystems, and businesses or on assessing risks and vulnerabilities. Much activity focuses on coastal areas and existing stresses. Despite the review and search efforts undertaken and described in Box 13.1, we believe that the identified information is an indicative, rather than comprehensive, summary of overall trends in the Southeast.

This review of adaptation activities in the SE uses the six-step process of adaptation (Figure 13.1) as an organizational framework for assessing the current status of efforts.

In the figure, the boxes mark a step in the process while the arrows represent the efforts needed to achieve each step. Our assessment provides numerous case study examples of the projects that mark achievement of a step as well as the process-related activities represented by the arrows. In the absence of a significant body of peer-reviewed research or other broad adaptation assessments, case studies are used extensively to illustrate the types of activities taking place. Various efforts are also underway to support the development of adaptive capacity in the region by developing educational outreach programs (Chapter 14), tools, and organizational resources. Along with the case studies are descriptions of a few of the many tools that have been developed by researchers and practitioners that are applicable to the southeast region. This section concludes with short descriptions of some organizations located in the region whose goals include assisting the region to adapt better to a changing climate. The review of tools and organizations is not exhaustive but indicative of the diversity of actors and efforts.

Step 1: Identify Current and Future Climate Changes Relevant to the System

Many entities in the region have recognized that current climate variability and future climate changes will require adaptation planning, although the planning may be in a very early stage or not yet formally underway. A wide variety of entities are involved in organizing conferences, workshops, listening sessions, and other forums for identifying concerns. For example, the National Conference of State Legislatures published a series of reports on potential risks to states, including Georgia, North Carolina, and Tennessee (National Conference of State Legislatures, 2008a, 2008b, 2008c). Listening sessions held along the Albemarle Sound elicited concerns of residents about climate change impacts on culture and livelihoods as well as physical changes (Brown et al. 2010).

Ongoing monitoring together with associated outreach and research efforts by federal agencies such as the National Weather Service, the National Atmospheric and Oceanic Administration, and the United States Geological Survey support the identification of current trends and risks. EPA Region 4 convened a workshop on adaptation in the Southeast which brought together over 200 representatives of federal government; state, tribal, and local governments; academia; the private sector; and nongovernmental organizations (NGOs) in February 2010 (Stratus Consulting 2010b). Other examples of federal efforts are included in the following sections.

Among the eleven SE states, Puerto Rico and US Virgin Islands, six have completed climate action plans (The Center for Climate Strategies 2012). Five of the six with climate action plans, Arkansas, Kentucky, North Carolina, South Carolina, and Virginia, have been recommended to start adaptation planning as part of their comprehensive climate action plan (The Center for Climate Strategies 2012). Florida's climate action plan included a section on adaptation (The Center for Climate Strategies 2012).

An analysis of 48 cities in the SE with populations greater than 100,000 found that six of these large cities have also recommended adaptation planning as a part of their climate change plans although those plans were not complete. These cities included Miami and St. Petersburg, FL; Atlanta, GA; Louisville, KY; New Orleans, LA; and Greensboro, NC. Since the time of that study, Greensboro, NC has integrated climate issues into their sustainability plan (Community Sustainability Council 2010); Miami is a member of the Southeast Florida Climate Change Compact and has completed a city plan that calls for adaptation planning (Community Sustainability Council 2010). It is likely that there are other communities whose actions are not yet integrated. For example, the comprehensive plan for Beaufort, SC calls for addressing SLR (Beaufort County South Carolina 2010).

A 2008 survey of experts and decision-makers working in the Florida Keys reported widespread concern about climate-related impacts. At that time only 5% of those surveyed reported that their organization or agency had a climate adaptation plan and less than 1% reported having participated in community discussions, state, or federal climate change. Since the time of that study, other initiatives, including the Southeast Florida Climate Change Compact (see discussion following) and the Climate Action Plan for Florida Reef (The Nature Conservancy 2010) have increased engagement in this area.

Step 2: Assess the Vulnerabilities and Risk to the System

Several efforts are underway to conduct risk and vulnerability assessments to inform adaptation processes. Multi-sectoral vulnerability analyses to inform adaptation are underway in Puerto Rico (see discussion following) and North Carolina (see Step 4). Many efforts reflect existing pressures on coastal areas and give particular attention to tropical storms and SLR (Stratus Consulting Inc. 2010a). Louisiana is updating its Coastal Master Plan to incorporate both planning and action-ready projects that among other things address resilience to rising sea levels 50 years into the future (http://www.coastalmasterplan.louisiana.gov). The Southeast Florida Regional Climate Change Compact addresses water resources and includes a substantial effort to develop a shared regional understanding of local SLR scenarios to underpin developing adaptation plans.

Other efforts include work by government agencies, private sector, and non-governmental organizations. For example, America's Energy Coast, Entergy, and America's Wetland Foundation undertook the development of a framework and a fact base that allowed the quantification of the climate risks for energy infrastructure in the US Gulf Coast. They also developed an economic analysis of the costs to secure/adapt that energy infrastructure (America's Energy Coast 2010). Work by the Department of Defense illustrates a case-based approach designed to inform a broader vulnerability assessment of military facilities in the SE to be conducted in the future. NASA is assessing local risks and vulnerabilities to inform adaptation at five facilities in the Southeast. Both of these federal efforts recognize the substantial facilities along the coast. There are several conservation-oriented efforts including the USGS Southeast Regional Assessment Project, the Florida Reef action plan, the North Carolina Coastal Habitat plan, and the Kentucky wildlife plan (Dalton and Jones 2010, The Nature Conservancy 2010, Kentucky Department of Fish and Wildlife Resources 2010, North Carolina Department of Environment and Natural Resources 2010).

The Puerto Rico Coastal Adaptation Project and the Puerto Rico Climate Change Council. The Puerto Rico Coastal Adaptation Project, PRCAP, is a two-year effort from 2010 to 2012 that was initiated to collect and synthesize information about climate change risks to Puerto Rico through increasing coordination of efforts and compiling all best available scientific and local knowledge (Puerto Rico Coastal Management Program 2011). PRCAP is a partnership of the Puerto Rico Department of Natural and Environmental Resources and Coastal Zone Management Division (PRCZMP), and involves more than 130 scientists, planners, practitioners, and communication experts. It is developing a comprehensive climate change vulnerability assessment and recommended adaptation strategies for Puerto Rico. The project supported the establishment of the Puerto Rico Climate Change Council (PRCCC) in November 2010. The PRCCC is working to accurately assess vulnerability of life and property and to identify and assess feasible adaptation strategies for government, the private sector, non-profit organizations, and civil society.

The PRCCC collaboration is working towards the following objectives:

- To use the best available scientific knowledge to identify the communities and ecosystems most at risk from coastal hazards and climate change.
- To identify, assess, develop, and prioritize effective adaptation strategies and policies that could be implemented in Puerto Rico.
- To communicate findings, consensuses, and recommendations to government, civil society, the media, and the private sector.
- To cultivate a well-informed Puerto Rican society about coastal hazards, climate change adaptation, and mitigation.

The PRCCC identified communication and sharing of information as an early priority. Their newly created Puerto Rico Climate Research Library has more than 480 documents related to climate change and the Caribbean and they have established a PR-CC-Listserv for announcements and sharing of relevant publications.

Southeast Florida Regional Climate Change Compact. The Southeast Florida Regional Climate Change Compact (referred to as the Compact) (http://www.southeastfloridaclimatecompact.org/) was signed in 2009 by Broward, Miami-Dade, Palm Beach, and Monroe Counties and is an example of the development of a regional resilience perspective and response to issues of climate concern that will impact the region as a whole and not just a particular county or community. The Compact has four major purposes: (1) to develop a regional cooperative response strategy to climate changes; (2) to encourage federal funding to support regional action plans; (3) to respond to proposed state and federal climate policies and legislation; and (4) to devote resources including staff time to support the development of the Southeast Florida Regional Climate Change Action Plan, including both mitigation and adaptation strategies.

Managing water resources is a primary focus of the Compact and that includes freshwater supply (considering changes in rainfall patterns) and storm water management (especially under the potential for stronger storms). SLR is also a critical stressor for the cooperating counties.

There are numerous successes as a result of the Compact in the areas of governance, policy, planning, and communication, as well as in unified positions on state and federal legislation and appropriations. Also a new amendment to Florida Statues now allows for the creation of “Adaptation Action Areas” where local governments may implement special policies for areas that are particularly vulnerable to SLR and coastal flooding.

Another success was achieved through a series of consultations and technical input resulting in the four cooperating counties agreeing to a unified SLR projection out to 2060 that they will use for planning and communications. They have also established a suggested trend and range of future SLR projections out to 2110, and while these further projections are not being put up for immediate adoption they will provide a sense of future trends for longer term and large scale investments in the region.

The white paper discussing the unified SLR projections can be found online at: http://www.broward.org/NaturalResources/ClimateChange/Documents/SE%20FL%20Sea%20Level%20Rise%20White%20Paper%20April%202011%20ADA%20FINAL.pdf

Adaptation efforts by the Department of Defense. The Department of Defense (DoD) recognizes that climate change presents increased challenges for current and future missions, built infrastructure, and natural ecosystems on military lands. The 2010 Quadrennial Defense Review (DoD 2010) states that “the Department (of Defense) must complete a comprehensive assessment of all installations to assess the potential impacts of climate change on its missions and adapt as required.” DoD increasingly is focusing on the need to develop adaptation approaches for identified climate change vulnerabilities and impacts. Several research projects are currently underway on southeastern USA installations that will support vulnerability and impact assessment and adaptation planning for climate change. Current adaptation research and planning initiatives for the SE NCA region are administered by the DoD Strategic Environmental Research and Development Program (SERDP). These efforts consider both built and natural infrastructure. More information is available through SERDP (2012), USACE (2010), and US Navy (2012).

Climate adaptation at NASA Centers in the Southeastern USA. The National Aeronautics and Space Administration (NASA) is concerned about the possible impacts that climate change will have on NASA Centers across the USA and has many facilities of concern in the SE. As a proactive measure, NASA has implemented a Climate Adaptation and Science Investigation (CASI) wherein each NASA Center is assessing its risk and vulnerability to climate change, and developing adaptation measures and plans for potential climate-induced threats. The five NASA Centers in the SE are: Stennis Space Center (SSC), MS; Kennedy Space Center (KSC), FL; Langley Research Center (LaRC), VA; Wallops Flight Facility WFF), VA; and Marshall Space Flight Center (MSFC), AL. Three of these Centers, KSC, LaRC, and WFF, are located on the Atlantic Ocean; SSC is located very near the Gulf of Mexico. Consequently, the major climate change threats to these Centers are SLR, flooding caused by severe storms (principally hurricanes), and in the case of LaRC and WFF, land subsidence. For each Center, CASI efforts have developed projections for the 2020s, 2050s, and 2080s—these projections include average temperature, average precipitation, SLR, SLR under a rapid ice melt scenario, days with maximum temperatures over 90°F and days with minimum temperatures at or below 40°F or 32°F (Rosenzweig and Brown 2009, Rosenzweig et al 2011).

Given these projections, each Center is developing plans for implementation of adaptation strategies to mitigate the overall effect of climate change impacts on facilities, property, the workforce and the environment. Personnel at the five SE NASA Centers are conducting research under the aegis of CASI that further elucidates the potential impacts that climate change will have on the respective Centers as a foundation for constructing adaptation strategies.

Southeast Regional Assessment Project (SERAP). The Southeast Regional Assessment Project (SERAP) is a prototype for the type of studies that the Department of Interior Climate Science Centers will develop to explore and project ecological responses to climate change and inform natural resource managers on strategies for conserving wildlife and cultural resources. SERAP is working in the southeastern USA in an area that includes all or parts of 15 states. Work began in 2009, and SERAP is scheduled to complete most products during 2012. This section summarizes a report on SERAP (Dalton and Jones 2010).

SERAP takes a multi-disciplinary approach that includes modeling of key physical, ecological, and socioeconomic processes to aid the development of robust adaptation strategies. Improving the robustness of decisions is primarily achieved by identifying and quantifying the sources of uncertainty in model projections, and propagating this uncertainty through to the different modeling components. Physical processes that are modeled include local climate change impacts, shoreline change due to SLR, fire frequency, and streamflow conditions. Social and economic changes are simulated by modeling urban growth. Ecological responses are simulated through projections of vegetation dynamics that are used to predict species specific habitat changes through time and models of species distributions for birds, fish, and mussels. The end product for managers will be the development of spatially explicit, conservation strategies that are more robust to a range of future climatic changes.

Downscaled climate projections of temperature and precipitation will be used as inputs to ecological process models. Avian range dynamics are being developed for the entire study area, SLR modeling is focused in the Gulf coast of Alabama, Florida, and Mississippi, and aquatic ecosystem responses will be evaluated in the Apalachicola-Chattahoochee-Flint River Basin in Alabama, Florida, and Georgia. All the assessments will project changes through 2100.

Climate adaptation strategies developed through SERAP will be provided to interested stakeholder groups including federal, state, and local agencies and NGOs. A primary stakeholder is the US Fish and Wildlife Service (USFWS) Landscape Conservation Cooperatives (LCCs). The conservation strategies are being developed through an interactive process with wildlife management agencies and will include a diverse portfolio of actions. The goal is to provide information that can help decision-makers and managers to plan for the potential impacts of climate and landscape changes using strategic habitat conservation and a process of adaptive management.

North Carolina Sea Level Rise Risk Management Study and iRisk Tool for the Integrated Hazard Risk Management. North Carolina has significant vulnerability to SLR. In recognition of this hazard, the North Carolina Office of Geospatial and Technology Management Floodplain Mapping Program received a $5 million grant from FEMA to develop a comprehensive study on climate change effects on risks to built and living systems, and to develop science-based mitigation and adaptation strategies that will pro-actively reduce future risk. The NC Sea Level Rise Risk Management Study (SLR-RMS) will evaluate the potential changes in coastal flooding hazards due to SLR and changes in storm frequency and intensity on a system-wide basis inclusive of societal and economic impacts. This assessment will include future vulnerability to both temporary and permanent flooding, land loss, and account for dynamic interactions and feedback between receptor systems.

The Integrated Hazard Risk Management (IHRM) program is designed to complement the SLRRMS by helping the public, private sector, and governments (local, state, and federal) manage their risk from natural hazards. IHRM damage assessment methods extend and enhance calculations and data from several commonly used models, including FEMA's HAZUS-MH and benefit-cost analysis. In particular, IHRM focused on collecting asset information for buildings and other critical infrastructure at the parcel or individual asset level. Methods to define qualitative hazard ratings as High, Medium, or Low were defined at both the building level and the county level. Hazard ratings consider risk as well as the individual components of risk: hazard probability, consequences, and vulnerability.

IHRM provides this information through a web-based visualization tool, iRISK, so users can educate themselves about their risk and make informed decisions that will help save lives, decrease property damage, and improve resiliency to natural disasters. Four pilot counties in North Carolina will be the first to demonstrate the revised planning approach and the associated computer-based tools, including Durham, Edgecombe, Macon, and New Hanover.

Step 3: Develop an Adaptation Strategy Using Risk-based Prioritization Schemes

Adaptation efforts furthest advanced in developing and implementing plans are often at smaller scales, individual communities or a system, such as Spartanburg's water system in South Carolina (EPA 2011a). The Hampton Roads area of Virginia has also undertaken several efforts (see the discussion of Wetlands Watch). These include the communities of Wilmington and Greensboro, NC (Community Sustainability Council 2010, Prete 2010). At the state level, the Florida climate action plan gives explicit consideration to adaptation strategies and options (Governor's Action Team on Energy and Climate Change 2008).

Some research is assessing the value of different types of community engagement for adaptation planning. Broad outreach has supported advancing adaptation activities on Bald Head Island, NC. Frazier et al. (2010) report positive outcomes from using scenarios in a day-long workshop setting in Sarasota, FL. A number of efforts support increasing community resilience to hazards and integrating climate change issues in their guidance. For example, the *Louisiana Coastal Hazard Mitigation Guidebook* suggests strategies that, if implemented, would reduce but not completely eliminate the risks from coastal natural hazards including subsidence and SLR, storm surge, and other flooding (Wilkins et al. 2008). The approaches are designed to address current stresses and to provide additional protection from those hazards. The guidebook also demonstrates methods that communities can use to adopt a flexible approach to hazard planning and include a wide range of attitudes around restricting the use of property when necessary to mitigate hazards.

Lee County, FL, has completed a vulnerability assessment that assessed potential impacts of climate stability, sea level, hydrology, geomorphology, natural habitats and species, land use changes, economy, human health, human infrastructure, and variable risk projects with respect to multiple goals, including implementation of a comprehensive plan, perceived current impacts, habitat loss, and proximity in time (Beever et al. 2009). Rankings were used to create a priority matrix for climate change vulnerabilities, which placed alterations to hydrology as the top priority followed by climate variability and changes in storm severity (Beever et al. 2009).

Several regional efforts to develop climate adaptation strategies have been undertaken with significant support from federal agencies. The US Environmental Protection Agency (EPA) and the Federal Emergency Management Agency (FEMA) are partnering to explore the intersection of climate change adaptation and local planning in North Carolina through technical assistance to two coastal communities facing impacts from SLR, more intense coastal storms, and changes in precipitation. New Orleans recovery efforts are increasing the resilience of the city to hurricanes (Natural Resources Defense Council 2011). Terrebonne Parish, LA has established a plan to develop a strategic decision-making tool to help guide their response to wetlands loss and restoration, including the threats of SLR (Suazo 2010).

Two other efforts were supported by the Climate Ready Estuaries program (described below). In 2008, Charlotte Harbor National Estuary Program (CHNEP) collaborated with the City of Punta Gorda, FL to develop a climate change adaptation plan. CHNEP and the Southwest Florida Regional Planning Council also prepared a Southwest Florida Climate Change Vulnerability Assessment (Beever et al. 2009). In order to support the adaptation plan, they are working to develop climate change indicators and a monitoring plan for estuarine systems. Indian River Lagoon NEP and the City of Satellite Beach, FL began collaboration in 2009 on a SLR vulnerability assessment, which helped identify options for reducing risk, planning for adaptation, and educating local decision makers (Parkinson and McCue 2011).

There are also many efforts underway to support the development of adaptation plans, such as assessment of existing regulatory authorities (Silton and Grannis 2010, Farber 2009) and development of methods for decision-making (Julius et al. 2010). These efforts assemble substantial resources from local, private, non-governmental, and federal while synchronizing tasks and decisions that allow the process to move quickly. Several of the following case studies point to the importance and value of building new forms of regional coordination and organizational authority in support of climate adaptation (Sheffer 2010).

Climate Ready Estuaries. The Climate Ready Estuaries program within the US Environmental Protection Agency is a partnership among the National Estuary Programs (NEPs) and other EPA divisions to address climate change in coastal areas. The NEP is a network of voluntary community-based programs focused on the conservation and management of estuaries. NEP is a place-based effort and each NEP has a Management Conference made up of stakeholders including citizens, local, state, and Federal agencies, as well as non-profit and private sector entities. Since 2008, Climate Ready Estuaries has been assisting NEPs and coastal communities in becoming "climate ready" by providing tools and assistance to assess climate change vulnerability and to plan for adaptation. Activities are taking place at the Albemarle-Pamlico Estuary Program (EP), Charlotte Harbor EP, Indian River Lagoon EP, Tampa Bay EP, and the City of Satellite

Beach, Florida, in conjunction with an EP in the Southwest region, the Coastal Bend Bays and EP in Texas.

Two programs in particular are strongly oriented to transferring knowledge from these place-based efforts. Sarasota Bay EP developed an adaptation plan that includes public outreach and participation in updates to local comprehensive plans to integrate adaptation measures. Associated research to support this effort includes the use of Light Detection and Ranging (LiDAR) data, the development of a web-based SLR visualization tool, development of a technical report including maps, and a guide with tips and early lessons. In 2011, Tampa Bay EP and Coastal Bend Bays and EP focused on publication and distribution of the "Gulf Coast Community Handbook" for incorporating resiliency into habitat restoration and protection plans to communities around the Gulf of Mexico.

Wetlands Watch, Norfolk, Virginia. Wetlands Watch, a nonprofit environmental advocacy group, based in Norfolk, VA, has been working with local governments on SLR adaptation for five years (Wetlands Watch 2012). Their adaptation work grew out of a session held with the Center for Coastal Resources Management at the Virginia Institute of Marine Sciences, after which they realized the benefits of their conventional wetlands advocacy work would be overwhelmed by SLR impacts to the coastal ecosystem (S. Stiles, personal communication).

In 2007 Wetlands Watch began a campaign focused on making local government long-range planning, floodplain and post-hazard mitigation planning, zoning and ordinance codes, capital improvement funding, and permitting processes to account for SLR. Wetlands Watch has formed partnerships with academic institutions, government agencies, military programs, businesses, and faith communities to address these issues (Wetlands Watch 2012).

Gulf of Mexico Climate Change Adaptation Inventory. The Climate Change Adaptation Inventory is a compilation of climate adaptation activities and research initiatives taking place at the federal, state, and local levels in communities adjacent to the Gulf of Mexico. The inventory focuses specifically on those projects and efforts that address climate change or SLR. Research activities captured by the inventory are limited to those projects that have applications to coastal communities, particularly planning and development, land management, and socioeconomic initiatives. Currently available online as a document with links to a variety of websites and online resources, the inventory will be upgraded to an interactive database so users can input their own adaptation efforts.

The inventory's intended audience includes National Oceanic and Atmospheric Administration (NOAA) staff members and other stakeholders. It is a living document that will be maintained by the NOAA Gulf Coast Services Center. Addenda to listed project information and new project suggestions for the inventory are encouraged (NOAA Gulf Coast Services Center 2011).

Template to Assess Climate Change Impact and Management Options (TACCIMO). Since its creation in 1905, the USDA Forest Service has overseen the care of US public forests and grasslands. That area now exceeds 193 million acres (USDA Forest Service 2009) and 13.1 million acres in the Southern region (the southeastern states considered in this report plus Oklahoma and Texas). The Forest Service has faced many challenges in its 100+ year history and like other federal agencies is now attempting to address the management issues created or amplified by a changing climate with a goal of identifying options to assure ecosystem sustainability (USDA Forest Service 2009).

All National Forests operate under management plans specifically designed for each National Forest. The National Forest Management Act of 1976 requires that all National Forests are managed for multiple uses (NFMA 1976), but each forest has unique challenges and attributes. These goals are called the *desired future conditions* of the forest. Periodically, these management plans are re-evaluated to see if desired future conditions have or should be modified. During the past two years, Forest Service scientists and land planners have collaborated to develop a web-based management and adaptation tool called the Template to Assess Climate Change Impact and Management Options (TACCIMO) is a result of that collaboration (http://www.sgcp.ncsu.edu:8090/, Solomon et al. 2009).

TACCIMO has been parameterized with National Forest Plans for Region 8 (southern region) and can be used for state and private forest use. In the Southern region, the user can select their location (county, state, or region) for an assessment of general climate change impacts and management options. The core of TACCIMO is hundreds of scientifically reviewed papers on climate change impacts and management options. TACCIMO compares the desired future conditions outlined in each forest plan with the cataloged climate change impacts to assess whether various aspects of climate change (e.g., wildfire risk, drought, SLR) could pose a new or enhanced threat to the National Forest desired future conditions. TACCIMO cross references the climate change impacts with cataloged management options to provide land managers with potential choices to minimize negative change. Finally, TACCIMO generates a report that includes the forest plan, potential climate change impacts and management options.

Leveraging Federal programs for natural resource protection in the Albemarle-Pamlico Estuary. Adaptation to climate change along the North Carolina coast is the focus of an interagency pilot project to build resilience into the natural landscape, integrate partnership priorities and leverage existing Federal resources. The project is being directed through the Southeast Natural Resource Leaders Group (SENRLG) (EPA 2011b). SENRLG is comprised of regional Federal agency leaders across the SE with natural resource mission responsibilities. The SENRLG Landscape Conservation and Restoration Pilot Project (LCRPP) identified the Albemarle-Pamlico Estuary as the initial location to illustrate the co-benefits of targeting Federal program resources and to outline an innovative approach to address environmental challenges in long-term natural resource protection. The outcomes of the LCRPP are designed to demonstrate that collaborative, on-the-ground climate risk-related conservation, restoration, and resilience-building work produces results that exceed those that could be achieved through individual agency efforts.

Public access to the Targeted Resource Implementation Plan (TRIP) and online decision support tools is scheduled for October 2012. The tools will include a web portal to access the documents and a Geographical Information System viewer to access the data used during the project. When complete, the TRIP will do the following:

- Identify a landscape where agencies may collaborate and leverage resources that promote resilience of the landscape and improved capacity to adapt to climate change within the estuary.
- Support collaboration with external stakeholders that obtain co-benefits through targeted funding of restoration and conservation projects.
- Provide a set of performance metrics to evaluate co-benefits of resource accomplishments for on-the-ground work.
- The decision support tools will identify Federal resources available to support locally driven landscape conservation efforts that address climate change adaptation. The TRIP products will be transferable to other internal and external partnerships across the SE.

Step 4: Identify Opportunities for Co-benefits and Synergies Across Sectors

Many current planning efforts focus on identification of risks and vulnerabilities in order to inform adaptation strategies. Some vulnerability assessment and adaptation planning processes, such as the Puerto Rico example given earlier, are being conducted as one integrated effort. Still, reports of efforts to identify co-benefits and synergies across sectors are sparse. A reef restoration project off the coast of Alabama is one example of implementing an adaptation strategy that provides protection from storm surge and increases habitat (The Nature Conservancy 2010). A guidebook aimed at helping governments assess the economic value of adaptation is available that comments on the potential to incorporate additional societal benefits in cost-benefit analyses, but the treatment is very brief (The Economics of Climate Change Adaptation Working Group 2009). The North Carolina effort described below illustrates one effort to identify adaptation strategies with broad benefits across sectors.

Using vulnerability assessment to inform adaptation strategies. The North Carolina Interagency Leadership Team, (ILT) led by the North Carolina Department of Environment and Natural Resources, assessed North Carolina's vulnerability to the impacts of climate change in order to inform adaptive strategies that will reduce risk and increase resilience to projected future changes. Federal agencies involved include EPA, USACE, NOAA, Federal Highway Administration, and US Fish and Wildlife Service. North Carolina state agencies include Departments of Transportation, Environment and Natural Resources, Commerce, Cultural Resources, and Agriculture and Consumer Services; as well as the Wildlife Resources Commission.

The effort focused on major climate change threats to North Carolina including increased air and water temperatures, inundation from SLR, more frequent and intense heat waves, increased tropical cyclone intensity, and altered rainfall patterns resulting, paradoxically, in more droughts and more floods.

A Climate Change Working Group developed a prototype for climate vulnerability assessments across multiple sectors and statewide and regional scales. Sectors assessed included: Transportation, Natural Ecosystems, Water Resources, Coastal and Marine Resources, Human Health and Welfare, Agriculture and Forestry, Energy Production and Use, Human Social Systems, Land Resources, and Air Quality. This vulnerability assessment phase was critical to inform adaptation responses, within and across sectors and regions of the state.

The NC Climate Adaptation Framework initially focuses on broad overarching strategies that emphasize cross-sector, integrated efforts within three major categories: (1) policy integration and creation; (2) promotion and facilitation of adaptive behaviors; and (3) research and education.

The ILT agencies and their partners are concentrating early efforts on adaptive responses that can make progress within three to five years. To leverage limited resources, initial strategies will focus on no- or low-cost actions that address multiple or particularly vulnerable systems. Early efforts emphasize "no-regrets" actions that provide multiple benefits and are good to do for reasons beyond climate adaptation.

These strategies provide common themes designed to guide future efforts to prepare for climate impacts across multiple levels–state, regional, or local:

- Collaborate with partners to provide information that informs decisions.
- Promote comprehensive adaptation planning among state agencies.
- Facilitate communication and education to support local, regional, and state planning efforts.
- Refine adaptation strategies as science advances and tools improve.
- Encourage broad collaboration and partnerships to leverage resources.
- Partner with communities to facilitate local climate adaptation efforts.

Steps 5 and 6: Implement, Monitor, and Re-evaluate Implemented Adaptation Options

The implementation, monitoring, and regular re-evaluation of adaptation options are steps of adaptive management strategies incorporated into climate adaptation recommendations. The approach is intended to support ongoing social learning in the context of uncertainty. In practice, the process of adaptive management confronts several challenges in application (Gregory et al. 2006) including tolerance for delay during the experiment. One example of applying adaptive management strategies to coastal conservation management that is well documented and advanced is that of the Alligator River National Wildlife Refuge.

Adaptive management in the Alligator River National Wildlife Refuge. The Alligator River National Wildlife Refuge encompasses about 154,000 acres in the Albemarle-Pamlico Estuary, Dare and Hyde Counties, NC. The US Fish and Wildlife Service (USFWS) and North Carolina Chapter of The Nature Conservancy (TNC) are working together to evaluate the effects of different adaptive management strategies that might contribute to the resilience and stability of wetland ecosystems on areas affected, or likely to be affected, by SLR. Successes would include reductions in the rates of ecosystem change, shoreline erosion, saltwater intrusion, land subsidence, and an increase in the growth and survival of salt-tolerant vegetation. Adaptation strategies include:

- Using oyster reefs to dissipate wave energy, slow currents, and reduce shoreline erosion. Added benefits are that these reefs sequester carbon and provide habitat for a variety of species.

- Using ditch plugs or water control structures equipped with flashboard risers and tide gates to restore the hydrologic regime and prevent saltwater intrusion.
- Planting salt-tolerant vegetation, such as bald cypress and brackish marsh grasses, to enhance future shoreline stability and combat expected biodiversity and habitat loss.

In addition, the project aims to establish migration corridors for species to move inland and upland from low lying areas. TNC and USFWS have already implemented these strategies in several locations. Marl, a calcium carbonate fossil rock, and oyster shell bags have been used to construct oyster reefs to buffer the shoreline, ditch plugs and water control structures have been strategically placed in areas to restore the region back to a sheet flow system, and 40 acres of salt-tolerant vegetation have been planted. Monitoring is underway to track the progress of each project. The projects have begun adaptation efforts in other nearby conservation areas, including the Swan Quarter National Wildlife Refuge, and plan to expand efforts to all nine North Carolina Coastal Plain refuges.

13.4 Supporting Adaptive Capacity

The many specific adaptation efforts in the SE are supported more generally by an expanding set of programs and centers that support adaption planning at all stages. The expertise and resources provided by these groups ranges from original research on the climate of the SE, to development of climate datasets, geospatial datasets, and analysis tools, to direct assistance with adaptation planning. Some programs engage with many sectors while others focus on specific needs, such as coasts, forestry, water resources, or conservation. Though not exhaustive, below is a sample list of the existing and developing programs in the region.

Climate Ready Estuaries (www.epa.gov/cre/live.html)

Five of the EPA's Climate Ready Estuary Programs are located in the SE USA. The Climate Ready Estuaries program together with the EPA National Estuary Programs works with coastal managers and others: 1) to determine vulnerabilities to climate change; 2) to create and apply adaptation strategies; 3) to interact and educate stakeholders; and 4) to disseminate the lessons learned. The Climate Ready Estuaries website contains information on climate change impacts to various estuary regions, provides resources and tools important to monitor changes, and material to support development of adaptation plans for coastal communities and their related estuaries.

Climate Science Centers (www.doi.gov/csc/southeast/index.cfm)

Two (southeast and south central) of the newly developing Department of Interior Climate Science Centers will serve the SE/Gulf Coast region of the USA. The mission for all of the Science Centers is to make scientific information, tools, and techniques available to assist wildlife managers and others to anticipate, observe and measure, and adapt to a changing climate.

CSC: Coastal Services Center (www.csc.noaa.gov)

The Coastal Services Center (CSC) of NOAA assists local and state organizations responsible for coastal resource management by providing technology, information, management strategies, tools, data, publications, training, and a wide variety of options that address today's complex coastal issues (NOAA CSC 2012). The CSC offerings support the economic, social, and environmental well being of the coast by linking information, people, and technology.

National Estuarine Research Reserves (NERRs) (www.nerrs.noaa.gov; gulfalliancetraining.org)

There are 10 National Estuarine Research Reserves (NERRs) sites in the SE. These reserves are living laboratories to investigate coastal concerns, including climate change and building resilience. The five Gulf Coast NERRs Coastal Training Programs established a partnership in 2007 that addresses adaptation through the framework of the Gulf of Mexico Alliance (National Ocean Service, NOAA 2008). This regional collaboration supports adaptation-planning workshops hosted by each Gulf NERR. Intended for local decision-makers, workshops have and will feature regional climate-science experts and highlight local climate efforts.

Regional Integrated Science Assessment (RISA), National Oceanic and Atmospheric Administration (NOAA)

There are three RISA teams serving the SE.

- **CISA: Carolinas Integrated Science and Assessments (www.cisa.sc.edu).** For North and South Carolina, the CISA program focuses on improving the quality, range, relevance, and accessibility of climate information that is used for resource management and other decision-making efforts, particularly related to coastal and water resources, human health and adaptation. In collaboration with regional stakeholders, CISA researchers work to identify and create effective methods of providing climate data, science, and education.
- **SCIPP: Southern Climate Impacts Planning Program (www.southernclimate.org).** The SCIPP focus is on research, education, and tool development around climate change and hazards in the south central USA through interaction with a wide variety of regional efforts. The mission of SCIPP is to build resiliency in the region and increase preparedness for present and future weather extremes. The SCIPP region includes: Oklahoma, Texas, Arkansas, Louisiana, Tennessee, and Mississippi.
- **SECC: Southeast Climate Consortium (www.seclimate.org).** The Southeast Climate Consortium's mission is to use progress in climate sciences, including improved climate forecast capabilities–both seasonal and long-term climate change–to develop scientifically sound information and tools for decision-making. These tools are for application to a variety of ecosystems in the SE USA including: agricultural, forests and other terrestrial ecosystems, and coastal. The most advanced of these decision support systems is AgroClimate (AgroClimate.

org), which focuses on the agricultural and forest sectors but also includes climate information at the county level that is valuable to many other sectors.

- **Sea Grant Programs (www.seagrant.noaa.gov).** There are 32 Sea Grant Programs nationwide that address issues and create products and tools for the coastal region of the USA. The Texas, Louisiana, Mississippi/Alabama, and Florida Sea Grant programs have developed individually as well as cooperated on developing a variety of outreach, education, and tools that focus on building resilience in the coastal zone. North and South Carolina Sea Grant programs were the first to place a full time regional climate extension specialist on staff. There are many tools and educational resources developed and in process through the various Sea Grant programs.

13.5 Summary

Adaptation efforts are underway in the SE. Work to understand the relevant climate impacts, to assess the significant risks and vulnerabilities, and to build partnerships and resources to support planning is taking place at all levels–from small communities to NGOs, states, and federal agencies. Many of these groups are supporting broad efforts to build adaptive capacity as well as individual projects. Given the growing numbers and diversity of groups involved, the mainstreaming of adaptation planning, and the rapid advancement of adaptation efforts, this review and the existing catalogs and databases are likely to be incomplete representations of the full scope of effort.

Currently, most efforts aim to identify the relevant climate risks and conduct risk and vulnerability assessments. Coastal areas, where risks of severe storms and SLR are highly visible, are the focus of much of this attention. Many of the efforts are working to mainstream climate adaptation into existing institutions and processes. Partly as a consequence of that mainstreaming approach, adaptation efforts are being conducted under a variety of different names and terminologies, including resilience and sustainability. The adaptation process is much more complex and less linear than conveyed by basic models. Significant effort is going into building necessary partnerships for coordinated response of the authorities and resources.

In the future, as more entities move from risk and vulnerability assessment to strategic adaptation planning and implementation, we anticipate a greater demand for more information on the costs, benefits and co-benefits of adaptations. As efforts advance, support for evaluation of adaptation efforts will need to increase.

13.6 References

America's Energy Coast, America's Wetland Foundation, Entergy Corporation. 2010. *Building a resilient energy Gulf Coast: Executive Report*. New Orleans, LA: Entergy Corporation. http://www.entergy.com/content/our_community/environment/GulfCoastAdaptation/Building_a_Resilient_Gulf_Coast.pdf

Beaufort County South Carolina. 2010. 2010 Comprehensive Plan. Beaufort, SC: Beaufort County.

Beever III, J.W., W. Gray, D. Trescott, D. Cobb, J. Utley, L.B. Beever. 2009. *Comprehensive southwest Florida/ Charlotte harbor climate change vulnerability assessment*. Fort Myers, FL: Southwest Florida Regional Planning Council and Charlotte Harbor National Estuary Program. http://

www.cakex.org/sites/default/files/Climate%20Change%20Vulnerability%20Assessment%20CHNEP.pdf

Bin, O., C. Dumas, J. Whitehead, B. Poulter. 2007. *Measuring the impacts of climate change on North Carolina costal resources*. Washington, DC: National Commission on Energy Policy.

Bin, O., B. Poulter, C. Dumas, J. Whitehead. 2011. Measuring the impact of sea-level rise on coastal real estate: A hedonic property model approach. *Journal of Regional Science* 51 (4): 751-767.

Brown, C., S. Campbell, L.R. Henry, M.M. Robinson. 2010. *Public listening sessions: Sea level rise and population growth in North Carolina*. Raleigh, NC: The Albemarle-Pamlico Conservation and Communities Collaborative and The Albemarle-Pamlico National Estuary Program. http://www.cakex.org/sites/default/files/Public%20Listening%20Sessions%20in%20North%20Carolina.pdf.

Climate Adaptation Knowledge Exchange. 2012. *Case Studies* [Accessed March 26, 2012]. Available from http://www.cakex.org/case-studies.

Community Sustainability Council. 2010. *Sustainability Action Plan Greensboro, North Carolina*. Greensboro, NC: City of Greensboro. http://www.greensboro-nc.gov/modules/showdocument.aspx?documentid=1194.

Culver, S.J., K.M. Farrell, D.J. Mallinson, D.A. Willard, B.P. Horton, S.R. Riggs, E.R. Thieler, J.F. Wehmiller, P. Parham, S.W. Snyder, C. Hillier. 2011. Micropaleontologic record of quaternary paleoenvironments in the central Albemarle Embayment, North Carolina, U.S.A. *Palaeogeography, Palaeoclimatology, Palaeoecology* 305 (1–4): 227-249.

Dalton, M.S. and S.A. Jones. 2010. *Southeast regional assessment project for the National Climate Change and Wildlife Center, US Geological Survey*. Washington, DC: US Geological Survey. http://serap.er.usgs.gov/docs/SerapOFR2010_1213.pdf.

Dixon, T.H., F. Amelung, A. Ferretti, F. Novali, F. Rocca, R. Dokkas, G. Sella, S.-W. Kim, S. Wdowinski, D. Whitman. 2006. Space geodesy: Subsidence and flooding in New Orleans. *Nature* 441 (7093): 587-588.

DoD (Department of Defense). 2010. *Quadrennial defense review report*. Washington, DC: US Department of Defense.

EPA (US Environmental Protection Agency). 2011a. *Climate change vulnerability assessments: Four case studies of water utility practices*. Washington, DC: US Environmental Protection Agency. http://oaspub.epa.gov/eims/eimscomm.getfile?p_download_id=501095.

EPA (US Environmental Protection Agency). 2011b. *Southeast natural resources leaders.* Washington, DC: US Environmental Protection Agency. http://www.epa.gov/region4/topics/envmanagement/senrlg/index.htm.

Evans, R.L. 2004. Rising Sea Levels and Moving Shorelines. *Oceanus* 43 (1): 1-6.

Farber, D.A. 2009. *A legal framework for climate adaptation assessment*. Washington, DC: Resources for the Future. http://www.rff.org/rff/documents/RFF-IB-09-14.pdf.

Frazier, T.G., N. Wood, B. Yarnal, D.H. Bauer. 2010. Influence of potential sea level rise on societal vulnerability to hurricane storm-surge hazards, Sarasota County, Florida. *Applied Geography* 30 (4): 490-505.

Georgetown Climate Center. 2012. *Adaptation Clearinghouse* [Accessed March 26, 2012]. Available from http://www.georgetownclimate.org/adaptation/clearinghouse.

Gibson, C.A., J.L. Meyer, N.L. Poff, L.E. Hay, A. Georgakakos. 2005. Flow regime alterations under changing climate in two river basins: Implications for freshwater ecosystems. *River Research and Applications* 21 (8): 849-864.

Governor's Action Team on Energy and Climate Change. 2008. *Florida energy and climate change action plan*. Tallahassee, FL: Governor's Action Team on Energy and Climate Change. http://www.flclimatechange.us/documents.cfm

Graves, P.E. 1980. Migration and climate. *Journal of Regional Science* 20 (2): 227-237.

Gregory, R., D. Ohlson, J. Arvai. 2006. Deconstructing adaptive management: Criteria for applications to environmental management. *Ecological Applications* 16 (6): 2411-2425.

Hanson, S., R. Nicholls, N. Ranger, S. Hallegatte, J. Corfee-Morlot, C. Herweijer, J. Chateau. 2011. A global ranking of port cities with high exposure to climate extremes. *Climatic Change* 104 (1): 89-111.

Irish, J.L., A.E. Frey, J.D. Rosati, F. Olivera, L.M. Dunkin, J.M. Kaihatu, C.M. Ferreira, B.L. Edge. 2010. Potential implications of global warming and barrier island degradation on future hurricane inundation, property damages, and population impacted. *Ocean & Coastal Management* 53 (10): 645-657.

Julius, S., B. Bierwagen, C. Pyke, J.R. Freed, S. Asam. 2010. *A method to assess climate-relevant decisions: Application in the Chesapeake Bay*. Washington, DC: US Environmental Protection Agency. http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=227483.

Karl, T.R., J.M. Melillo, T.C. Peterson. 2009. *Global climate change impacts in the United States*. New York, NY: Cambridge University Press.

Kentucky Department of Fish and Wildlife Resources. 2010. *Action plan to respond to climate change in Kentucky: A strategy of resilience*. Frankfort, KY: Kentucky Department of Fish and Wildlife Resources. http://fw.ky.gov/kfwis/stwg/2010Update/Climate_Change_Chapter.pdf.

Knutson, T.R., J.L. McBride, J. Chan, K. Emanuel, G. Holland, C. Landsea, I. Held, J.P. Kossin, A.K. Srivastava, M. Sugi. 2010. Tropical cyclones and climate change. *Nature Geoscience* 3 (3): 157-163.

Morens, D.M. and A.S. Fauci. 2008. Dengue and hemorrhagic fever–A potential threat to public health in the United States. *Journal of the American Medical Association* 299 (2): 214-216.

Mousavi, M., J. Irish, A. Frey, F. Olivera, B. Edge. 2011. Global warming and hurricanes: The potential impact of hurricane intensification and sea level rise on coastal flooding. *Climatic Change* 104 (3): 575-597.

Murley, J., L. Alpert, W.B. Stronge. 2005. Tourism in paradise: The economic impact of Florida beaches. Paper read at 14th Biennial Coastal Zone Conference, July 17th, 2005, New Orleans, Louisiana.

National Conference of State Legislatures. 2008a. *Georgia: Assessing the costs of climate change.* Washington, DC: NCSL. http://www.ncsl.org/Portals/1/documents/environ/ClimateChangeGA.pdf.

National Conference of State Legislatures. 2008b. *North Carolina: Assessing the costs of climate change*. Washington, DC: NCSL. http://www.ncsl.org/print/environ/ClimateChangeNC.pdf.

National Conference of State Legislatures. 2008c. *Tennessee: Assessing the costs of climate change*. Washington, DC: NCSL. http://www.ncsl.org/print/environ/ClimateChangeTN.pdf.

Natural Resources Defense Council. 2011. *New Orleans, Louisiana: Identifying and becoming more resilient to impacts of climate change*. New York, NY: NRDC. http://www.nrdc.org/water/files/ClimateWaterFS_NewOrleansLA.pdf.

Neumann, J., D. Hudgens, J. Herter, J. Martinich. 2011. The economics of adaptation along developed coastlines. *Wiley Interdisciplinary Reviews: Climate Change* 2 (1): 89-98.

NFMA (National Forest Management Act). 1976. National Forest Management Act of 1976. Washington, DC: US Forest Service. http://www.wilderness.net/NWPS/documents/publiclaws/PDF/94-588.pdf

NIDIS (National Integrated Drought Information System). 2012. *Regional Drought Early Warning System: Apalachicola-Chattahochee-Flint (SCF) River Basin* [Accessed 18 February 2012]. Available from http://www.drought.gov/portal/server.pt/community/acfrb.

NOAA CSC (Coastal Services Center). 2012. *Coastal Climate Adaptation* [Accessed March 26, 2012]. Available from http://collaborate.csc.noaa.gov/climateadaptation/default.aspx.

NOAA Gulf Coast Services Center. 2011. *Gulf of Mexico climate change adaptation inventory*. Washington, DC: National Oceanic and Atmospheric Administration. http://masgc.org/climate/cop/Documents/GoM_ClimateChangeAdaptationInventory_Report.pdf.

North Carolina Department of Commerce. 2012. *Tourism*. Raleigh, NC: N.C. Department of Commerce. http://www.nccommerce.com/tourism/.

North Carolina Department of Environment and Natural Resources. 2010. *North Carolina ecosystem response to climate change: DENR assessment of effects and adaptation measures*. Raleigh, NC: North Carolina Department of Environment and Natural Resources.

NRC (National Research Council). 2010a. *Adapting to the Impacts of Climate Change*. Washington, DC: National Academies Press.

NRC (National Research Council). 2010b. *Informing an Effective Response to Climate Change*. Washington, DC: National Academies Press.

NRC. 2011. *America's Climate Choices*. Washington, DC: National Academies Press.

Parkinson, R.W. and T. McCue. 2011. Assessing municipal vulnerability to predicted sea level rise: City of Satellite Beach, Florida. *Climatic Change* 107 (1-2): 203-223.

Prete, P. 2010. *Sea level rise adaptation report for the City of Wilmington, North Carolina*. Wilmington, NC: N.C. Development Services.

Puerto Rico Coastal Management Program. 2011. *Puerto Rico coastal adaptation project 2010-2012*. San Jose, Puerto Rico: Programa de Manejo de la Zona Costanera, Departamento de Recursos Naturales y Ambientales. http://www.drna.gobierno.pr/oficinas/arn/recursosvivientes/costasreservasrefugios/pmzc/riesgos-costeros-1/FactSheet_OnePage_FINAL_2side.pdf.

Rosenzweig, C. and M. Brown. 2009. Space agency workshop considers effect of climate change on infrastructure: Climate change impacts and adaptation: NASA mission and infrastructure; Kennedy Space Center, Florida, 28-30 July 2009. *EOS, Transactions American Geophysical Union* 90 (40): 352.

Rosenzweig, C., R. Horton, I.S. Higuchi, C. Hudson. 2011. NASA's CASI: Building Climate-Resilient NASA Centers. *livebetter* 15 (December).

SERDP (Strategic Environmental Research and Development Program). 2012. *Resource Conservation and Climate Change*. Alexandria, VA: SERDP. http://serdp.org/Program-Areas/Resource-Conservation-and-Climate-Change.

Sheffer, T. 2010. *The key role of regional coastal adaptation planning in the United States*. Blacksburg, VA: Virginia Polytechnic Institute and State University. http://www.cakex.org/sites/default/files/Thomas%20Sheffer%20Paper.pdf.

Silton, A.C. and J. Grannis. 2010. *Virginia case study: Stemming the tide: How local governments can manage rising flood risks*. Washington, DC: Georgetown Climate Center. http://www.law.unc.edu/documents/clear/vacasestudy.pdf.

Solomon, A., R. Birdsey, L. Joyce, J. Hayes. 2009. *Forest service global change research strategy 2009-2019*. Washington, DC: US Department of Agriculture, Forest Service Research and Development, FS-917a.

Stratus Consulting Inc. 2010a. *Overview of climate change adaptation in the southeastern United States with a focus on water and coastal resources*. Boulder, CO: Stratus Consulting, Inc.

Stratus Consulting Inc. 2010b. *Report on the U.S. EPA southeast climate change adaptation planning workshop*. Boulder, CO: Stratus Consulting, Inc.

Suazo, L. 2010. *Systematically prioritizing restoration projects in Terrebonne Parish, Louisiana*. Houma, LA: Coastal Restoration and Preservation. http://www.cakex.org/case-studies/582.

Svart, L.M. 1976. Environmental preference migration: A review. *Geographical Review* 66 (3): 314-330.

The Center for Climate Strategies. 2012. *State and Local Climate Blackboard* http://www.climatestrategies.us/policy_tracker/state/index.

The Economics of Climate Adaptation Working Group. 2009. *Shaping climate-resilient development: A framework for decision-making*. Economics of Climate Adaptation Working Group. http://ccsl.iccip.net/climate_resilient.pdf.

The Nature Conservancy. 2010. *Climate change action plan for the Florida reef system 2010-2015*. Arlington, VA: The Nature Conservancy.

http://www.cakex.org/sites/default/files/FL%20Reef%20Action%20Plan.pdf

Thieler, E.R. and E.S. Hammar-Klose. 1999. *National assessment of coastal vulnerability to sea-level rise: Preliminary results for the U.S. Atlantic coast*. Washington, DC: US Geological Survey.

Titus, J., D. Hudgens, D. Trescott, M. Craghan, W. Nuckols, C. Hershner, J. Kassaklan, C. Linn, P. Merritt, T. McCue, J. O'Connell, J. Tanskl, J. Wang. 2009. State and local governments plan for development of most land vulnerable to rising sea level along the US Atlantic coast. *Environmental Research Letters* 4, 044008; doi:10.1088/1748-9326/4/4/044008.

Titus, J.G. and C. Richman. 2001. Maps of lands vulnerable to sea level rise: Modeled elevations along the US Atlantic and Gulf coasts. *Climate Research* 18 (3): 205-228.

UKCIP (United Kingdom Climate Impacts Programme). 2012. *Adaptation wizard*. Oxford, United Kingdom: Environmental Change Institute (ECI). http://www.ukcip.org.uk/wizard/.

USACE (U.S. Army Corps of Engineers). 2010. Chief of engineers' environmental advisory board meeting minutes, 22 January 2010. Mobile, AL: Environmental Advisory Board. http://www.usace.army.mil/Portals/2/docs/Environmental/mins_22jan10.pdf

US Census Bureau. 2011. *Statistical abstract of the United States: 2012.* Washington, DC: US Census Bureau.

USDA Forest Service. 2009. *The U.S. Forest Service–An Overview.* Washington, DC: US Forest Service. http://www.fs.fed.us/documents/USFS_An_Overview_0106MJS.pdf.

US Navy. 2012. *Climate Change*. Washington, DC: Office of the Secretary of the Navy. http://greenfleet.dodlive.mil/climate-change/.

Wetlands Watch. 2012. *Sea Level Rise Adaptation.* Norfolk, VA: Wetlands Watch Inc. http://www.wetlandswatch.org/WetlandScience/SeaLevelRise/SeaLevelRiseAdaptation.aspx.

Wilkins, J.G., R.E. Emmer, D. Hwang, G.P. Kemp, B. Kennedy, H. Mashriqui, B. Sharky. 2008. *Louisiana Coastal Hazard Mitigation Guidebook*. Baton Rouge, LA: Louisiana Sea Grant College Program. http://www.lsu.edu/sglegal/pdfs/LaCoastalHazMitGuidebook.pdf.

Chapter 14

Southeast USA Regional Climate Extension, Outreach, Education, and Training

LEAD AUTHOR

LaDon Swann (swanndl@auburn.edu; Mississippi-Alabama Sea Grant Consortium and Auburn University Marine Extension and Research Center, Mobile, Alabama)

CONTRIBUTING AUTHORS

Julian Carroll (Mississippi State University, Starkville, Mississippi)

Lynne Carter (Southern Climate Impacts Planning Program, Louisiana State University, Baton Rouge, Louisiana)

Stuart Foster (Western Kentucky University, Bowling Green, Kentucky)

Suzanne VanParreren (Sapelo Island National Estuarine Research Reserve, Darien, Georgia)

Extension, outreach, education, and training (EOET) programs have been and will continue to be essential in addressing the climate change needs facing the Southeast (SE) United States. This chapter, developed by professionals working in the EOET field as practitioners, provides an introduction and details for planning, delivering, and evaluating climate change programs.

Connecting science to societal problems is a difficult task, especially with respect to the implications that climate change education seeks to change behaviors. From a human behavior perspective, "global warming" implies a cataclysmic ending while "climate change" conveys something more manageable. Both are true, and EOET programs must be tailored to fit the desired behavior change whether it is reduction of greenhouse gas emissions or climate adaptation strategies for a coastal community. Using the best available science delivered by credible and trusted educators is critical for successful implementation of mitigation and adaptation strategies.

Because climate change science has become highly politicized in the policy arena and in education, programs must be thoughtfully created to inform without alienating. Climate scientists and EOET professionals will benefit from collaboration with each other to craft simple, clear, and consistent messages necessary to build trust and encourage behavior changes. Climate change education will require a cross-disciplinary approach, combining instruction with education, social, behavioral, and economic sciences as well as earth systems science. Climate change programs must be designed for specific audiences and should include formal, nonformal, and informal options for all student grade levels. Programs also need to be established for state and local governments, nongovernmental organizations, industry, and the general public.

The Southeast (SE) has a strong contingent of EOET professionals familiar with effective program planning, implementation, and program evaluation. The current EOET programs in the SE have good relationships with target audiences and will be even more effective with increased performance-based funding. Coordination among federal agencies, nongovernmental organizations, and businesses invested in climate change education will avoid duplicate efforts that waste limited resources. Coordination, funding, and open communication between agencies and people across levels are required to build stronger climate change education programs in the SE.

Key Findings

- There is significant EOET capacity in the SE.
- Formal, nonformal, and informal education have complementary roles in climate education.
- EOET programs are largely uncoordinated.
- Better integration is needed between the biophysical sciences and education.
- Recognition that adults learn differently than youth will improve EOET programs for both groups.
- EOET programs would be more effective if they more closely followed instructional design models.

- Trust in the science and the individual or group delivering the instruction influences the effectiveness of the instruction.
- Trust has to be established over time.
- Most effective EOET programs have excellent engagement with the intended audience and utilize joint fact finding principles.
- Performance based funding is needed to expand climate education to all audiences.

14.1 Why Climate Education is an Essential Part of Climate Science

Education influences environmental choices and behaviors through internal and external mechanisms (Carter 1998, Coyle 2005, Knowles 1980, Tyson and Hurd 2009). The stabilization of the human caused changes to Earth's ecosystems requires a large proportion of the population to change their behavior and support critical mitigation and adaptation policies and regulations. Because the climate issue is complex, long-lived, and likely will produce even more impacts in the future, it is critical that human behaviors change and that those changes are sustainable. Research shows that permanent change depends largely upon internal factors such as personal insight, commitment, confidence, a feeling of control, and personal responsibility (Carter 1998). All of these can be built through gaining knowledge about an issue in ways that resonate with a specific audience (Carter 1998, McCright and Dunlap 2011).

According to a recent study by the American Psychological Association (APA 2010), "people's understandings of climate change underlie their willingness to act, and to support public policies, in response." Logically then increasing the public's understanding in a way that personalizes climate change impacts should lead to an increase in willingness to make the necessary changes in behavior and support for mitigation and individual, business, and governmental adaptation strategies. The following questions are useful in developing programs to educate people about climate and corresponding appropriate action:

1. What are the audience's motivations/attitudes?
2. How will their viewpoints be addressed?
3. What information do people need and for what purposes?
4. Does everyone need or want the same information?
5. How will the target audiences be approached?
6. Who do different audiences trust when delivering information?
7. How will the content be delivered?
8. How will the success of a program be measured?

In other words, public education involves the right information, in the right communication format, at the right time to the right audience.

Research on the various interpretations of and responses to a changing climate has identified six "publics" in the USA (Leiserowitz et al. 2011). They are categorized along a continuum of acceptance of the reality and critical nature of a changing climate. The continuum ranges from those seriously concerned (Alarmed and Concerned), to those who doubt (Doubtful) or completely deny it is occurring (Dismissive). There are two categories of publics in between these extremes: Cautious and Disengaged. The Knowledge of Climate Change Across Global Warming's Six Americas study found a great deal of public uncertainty on the issue of a changing climate. Many members of the identified publics said they needed more information. If such information could be provided it might help "more than a third of Americans . . . change their minds about global warming--especially those in the Disengaged (73%) and Cautious (58%) segments." (Editor's note: Numbers in parentheses refer to the portion of people within the category that changed their mind from one survey to the next.) One explanation for the lack of broad public acceptance of the science around climate change is the failure of scientists to craft simple, clear, and consistent messages and repeat them often (Somerville and Hassol 2011). The excessive detail and unfamiliar language of science communications make it difficult for nonscientists to sort out what is important and relevant to them (Leiserowitz et al. 2011).

Many respondents in the Six Americas study identified a number of specific questions about climate, which include the following:

1. How do the experts know human activities are the problem rather than natural variability?
2. How do they know what they know?
3. What are the likely impacts?
4. What can we do in response?

In addition, many members of the public believe there is still major disagreement among the science community about the reality of climate change. They do not know that 100% of the climatologists believe climate is changing and 97% of publishing climate scientists are convinced that human induced activities are responsible for recently detected climate trends (Shah 2012).

14.2 A Starting Point for Climate Education: Climate versus Weather

A person who has lived in a single place for many years develops an organic awareness of the local climate, as well as an appreciation for the inherent variability of the climate from year to year. Depending on the region, one may experience combinations of heat and cold waves; droughts and floods; hurricanes, snow and ice storms; severe thunderstorms, tornadoes, and other types of hazardous weather that characterize a region's climate. With time, expectations emerge about the types of weather typical for the various seasons of a year. This composite view, which includes both a sense of what type of weather is typical and an awareness of the variability of weather, is a representation of climate.

14.3 Context for Climate Extension, Outreach, Education, and Training

Understanding why and how adults learn is a prerequisite to any program for adult audiences described later in this chapter. Practitioners of climate education programs should utilize instructional design model such as Dick et al. (2011). Their Systems Approach Model includes the following components:

- Identify Instructional Goal(s): goal statement describes a skill, knowledge or attitude (SKA) that a learner will be expected to acquire.
- Conduct Instructional Analysis: Identify what a learner must recall and identify what a learner must be able to do to perform a particular task.
- Analyze Learners and Contexts: Identify general characteristics of the target audience including prior skills, prior experience, and basic demographics; identify characteristics directly related to the skill to be taught; and perform analysis of the performance and learning settings.
- Write Performance Objectives: Objectives consist of a description of the behavior, the condition and criteria. The component of an objective that describes the criteria that will be used to judge the learner's performance.
- Develop Assessment Instruments: Purpose of entry behavior testing, purpose of pretesting, purpose of post-testing, purpose of practice items/practice problems.
- Develop Instructional Strategy: Pre-instructional activities, content presentation, learner participation, assessment.
- Develop and Select Instructional Materials.
- Design and Conduct Formative Evaluation of Instruction: Designer try to identify areas of the instructional materials that are in need of improvement.
- Revise Instruction: To identify poor test items and to identify poor instruction.
- Design and Conduct Summative Evaluation.

Three Classifications of Education

Understanding classifications of educational methods and the intended audiences are essential to effectively design, deliver, and evaluate climate EOET programs. There are three classifications of education: formal, nonformal, and informal.

1. **Formal education** is normally associated with kindergarten through twelfth grade (K-12) and higher education where there is a hierarchically structured, chronologically graded educational system (Coombs 1973).
2. **Nonformal education** is any intentional and systematic educational enterprise, usually outside of a traditional school, in which content is adapted to the unique needs of the audiences or unique situations in order to maximize learning (Etllng 1993). Nonformal education is more learner-centered than most formal education. In general, nonformal education has less structure and therefore more flexibility than formal education.

3. **Informal education** is the third classification and deals with everyday experiences which are not planned and do not have formal learning objectives (Etllng 1993). The unstructured approach of informal education lends itself well to incidental learning through aquaria, zoos, and other settings with passive learning opportunities.

Adult education often uses nonformal methods, as does youth education is some cases, for example, 4-H programs. Successful implementation of adult education programs requires an effective instructor who understands how adults learn best. Compared with youths, adults have special needs and requirements as learners. Malcom Knowles, who pioneered the field of adult learning using nonformal methods, identified the following characteristics of adult learners:

1. Adults are autonomous and self-directed. They need to be free to direct themselves. Their teachers must actively involve adult participants in the learning process and serve as facilitators for them. Specifically, teachers must get participants' perspectives about what topics to cover and let them work on projects that reflect their interests. Teachers should allow the participants to assume responsibility for presentations and group leadership. Teachers should act as facilitators, guiding participants to their own knowledge rather than supplying them with facts. Finally, teachers should show participants how the education program will allow them to reach their goals.
2. Adults have accumulated a foundation of life experiences and knowledge that includes work-related activities, family responsibilities, and previous education. They need to connect learning to this knowledge and experience base. To help them do so, teachers should draw out participants' experience and knowledge relevant to the topic. Teachers must relate theories and concepts to the participants and recognize the value of experience in learning.
3. Adults are goal-oriented. Upon enrolling in an education program, they usually know what goal they want to attain. Adults, therefore, appreciate an educational program that is organized and has clearly defined elements. Instructors must show adult participants how an education program will help them attain their goals. This classification of goals and course objectives must be done early in the course.
4. Adults are relevancy-oriented. They must see a reason for learning something. Learning has to be applicable to their work or other responsibilities to be of value to them. Therefore, instructors must identify objectives for adult participants before the course begins. This need for relevance also means that theories and concepts must be related to a setting familiar to participants. This need can be fulfilled by letting participants choose projects that reflect their own interests.
5. Adults are practical, focusing on the aspects of a lesson most useful to them in their work. They may not be interested in knowledge for its own sake. Instructors should tell participants explicitly how the lesson will be useful to them on the job.

6. As with all learners, adults need to be shown respect. Instructors must acknowledge the wealth of experiences that adult participants bring to an education program. These adults should be treated as equals in experience and knowledge and allowed to voice opinions freely.

Engagement in the Climate Discussion

Organizations that implement EOET programs at the community level will be more effective when they engage constituents and respond to their needs. Sustained community engagement by EOET professionals lays the foundation for climate change discussions with communities. Ultimately, meaningful engagement will lead to planning efforts with desired outcomes to mitigate against and adapt to climate change. The Kellogg Commission's report "Returning to Our Roots: The Engaged Institution" (APLU 1999) includes a seven-part test through which universities and other adult education programs can measure engagement with constituents.

The seven standards to measure constituent engagement are as follows:

1. Responsiveness. Does the organization listen to its constituents and respond to their needs?
2. Respect for Partners. Does the organization understand that it can improve its services and learn from its partners? Does it respect the skills and capacities of its partners in collaborative projects?
3. Intellectual Neutrality. Does the organization's research present data and analysis that informs constituents about important and controversial issues in a factual and timely manner?
4. Accessibility. Does the organization help constituents and partners find appropriate personnel or solutions within the organization? Is the organization's expertise accessible to those who can best utilize it?
5. Integration. In addressing opportunities with its partners, has the organization developed ways of integrating its diverse areas of expertise to address the multidisciplinary problems of society?
6. Coordination. Is the organization prepared to maximize its internal resources and capabilities? Do the organization's employees understand and appreciate all of the products and services of the organization?
7. Resource Partnerships. Does the organization make a serious effort to partner with other organizations to address the problems of society in the interest of fulfilling its mission and achieving its vision?

EOET and Downscaling of Climate Information

Numerous educational and informational groups have identified the public's need for and request of climate change information (Carter 1998, Culver et al. 2010, Booz Allen Hamilton 2010, National Ocean Council 2012, NOAA 2008a, National Research Council 2011). Requested information includes basic climate literacy, basics of climate change, suggested adaptation options for specific sectors (e.g. farmers, foresters, human health, infrastructure, dwellings), and projections of climate impacts for which communities might need to prepare. The Southern Climate Impacts Planning Program (SCIPP) at Louisiana State University (Needham and Carter 2012) recently conducted 62 one-hour interviews along the Gulf Coast focused on coastal climate information needs. The number one request from the respondents for what SCIPP could provide to assist participants was climate information applicable to their local areas. SCIPP interprets this as a need to provide climate projections that are down-scaled to be appropriately useful for residents of specific locations in creating mitigation and adaptation strategies. The next most common requests were for instructions on where to find trustworthy climate information and for training on how to interpret climate information products. Climate EOET needs are complex and by necessity will vary with audience. For example, a farmer in central Florida will have different needs than a commercial fisherman in south Louisiana or a beachfront community in North Carolina.

Who are the Current Audiences?

Climate EOET programs can and should encompass all audiences. These audiences include internal training for EOET professionals and outreach for K-12 and adult audiences, including focus on the general public, industry, governmental planners, and resources managers.

As part of the process to design effective EOET programs, the four Gulf of Mexico Sea Grant Programs are undertaking a survey to determine climate perceptions of more than 3,000 Gulf of Mexico coastal residents to determine how they perceive climate is affecting community resilience (Goidel et al. 2012). The results of the survey will be used to refine EOET through the Gulf of Mexico Climate Outreach Community of Practice, which is described further below (Capps et al. 2010). Among other potential applications, these data will be used to establish a climate perception baseline dataset among Gulf of Mexico residents for use with data from qualitative methods to create and implement a community-based social marketing (CBSM) campaign (Pickens 2002). The CBSM will aide planners in building broad community support for local governments to include climate adaptation strategies in hazard mitigation plans.

In 2010, the Coastal Services Center of the National Oceanic and Atmospheric Administration studied the perceived benefits and barriers in hazard and resiliency planning. The study results are useful in planning climate information needs because some impacts from climate change will be reflected as increased strength or frequency of present hazards (Booz Allen Hamilton 2010). The initial recommendation called for working with local planners and community leaders to identify specific data and information needs that would help communities organize and take action to adapt to or mitigate climate change impact. For instance, data needs for Gulf Coast audience might include maps of projected relative sea level rise overlaying vulnerable infrastructure and neighborhoods.

Another important audience is K-12 teachers and their students. Improving climate literacy in K-12 education programs lays the foundation for long-term improvements in understanding the consequences of individual choices. National Oceanic Atmospheric Administration (NOAA) (2008a and 2009) defined a climate literate person as someone who has the following expertise:

1. Understands the essential principles of all aspects of the Earth system governing climate patterns.
2. Knows how to gather information about climate and weather, and how to distinguish credible from non-credible scientific sources on the subject.
3. Communicates about climate and climate change in a meaningful way.
4. Makes scientifically informed and responsible decisions regarding climate.

What Is Success and How Should It Be Measured

Climate change education programs must be evaluated in order to be responsive to and useful for individuals, communities, and organizations impacted by climate change. Regardless of the audience (youth or adult) and classification (formal, nonformal, or informal), an evaluation plan is necessary to measure its effectiveness in reaching program goals and objectives (Dick et al. 2011, Friedman 2008). Program assessments should include formative and summative evaluations and when possible a confirmative evaluation (Russell and Hellebrandt 1993).

The purpose of formative evaluation is to validate or ensure that the instruction goals are achieved and to improve the instruction through identification and remediation of any problems (Friedman 2008). Instructional content developed for climate education programs should undergo a formative evaluation to determine age-appropriateness and to ensure that the content is valid and reliable. Formative evaluations are also used to improve instructor skills and to correct management procedures such as audience accessibility. The return on the instructional investment should be calculated during the formative stage of the program.

Summative evaluations provide information on the program's efficacy and its ability to do what it was designed to do (Dick et al. 2011). Summative evaluations are typically conducted by an external evaluator. A widely used tool for summative evaluation is the pretest/post-test design, which assumes that changes in the audience's reflexive control are due to the instruction. In practice a post-test only design is common but is only useful with reflexive controls that assume little variation between treatment groups receiving the instruction and the control group not receiving the instruction.

Implementation of adaptation plans, changes in behavior, policy changes, and climate literacy are just a few indicators that might be used to measure the success of climate education programs. Resiliency and adaptation to climate change and ocean acidification, for example, is one of the nine national priorities set forth in the National Ocean Policy (NOP) draft implementation plan (National Ocean Council 2012). This plan requires the development and implementation of adaptation strategies for coastal communities to reduce vulnerability to sea level rise based on climate change projections and vulnerability assessments. The NOP implementation plan also recognizes the importance of organizations, such as Sea Grant Extension agents, to translate and communicate the science and adaptation-relevant information to practitioners.

Role of Credible Science in EOET

Joint fact finding (JFF) is a collaborative process that adds insight in solving a problem by including an additional component; local knowledge. JFF refers to a procedure or set of best practices that have evolved over the past decade or so for ensuring that science and politics are appropriately balanced in environmental decision making at the federal, state, and local levels (Karl 2007). Because JFF promotes and improves constituent engagement through shared learning, it helps create knowledge that is technically credible, publicly legitimate, and especially relevant to policy and management decisions. JFF involves people affected by policy decisions in a continual process of generating and analyzing information needed to shape scientific inquiry and to make sense of scientific findings. Local and cultural knowledge as well as expert knowledge are considered relevant components of JFF.

EOET practitioners can help scientists become more comfortable when engaging with constituents through internal training programs that define collaborative JFF, how it works, why scientists should be involved in JFF, and how scientists can effectively contribute to JFF without losing their credibility (Karl 2007, Hinkey 2005). For example, the scientific process frames a question as a test of significant difference between two alternatives. Possible answers through the scientific method can only be that results did or did not differ from the hypothesis tested. The scientific method does not conclude with a "right" answer but with an answer that is either not wrong or different from the proposed answer (hypothesis). The collaborative JFF process asks "*How* do we solve this problem?" Through JFF science, logic, and reasoning are combined to inform solutions and actions rather than just to define a single right or wrong hypothesis.

Trust, Risk, and Credible Science Climate Education and Communication

One definition of risk is the probability or threat of damage, injury, liability, loss, or other negative occurrence that is caused by external or internal vulnerabilities. Risk management can be based on either quantitative or qualitative representations of likelihood and consequence. However, a written, traceable account to sources used to establish quantitative judgments and the rationale behind qualitative judgments must be provided. In order to ensure a transparent, traceable account of recommended actions, it is important to have a guideline that accounts for uncertainty in estimates of the likelihood of various outcomes. Risk management actions typically progress from observation to implementation of mitigation of or adaptation to climate change impacts.

As a tool for risk management and communication, trust is important in judging appropriate conclusions about the acceptability of the hazard and management policies (Siegrist et al. 2007). Judgments of trustworthiness are based on representations of salient value similarities among similar groups. Strategic trust in climate EOET programs has the potential for mutual gains as groups work together to solve a problem. Strategic trust can be defined as "A trusts B to the extent that A will do X; where A is an individual, industry, or planner, B is a scientist, educator, risk communicator, or policy maker, and X is a recommended action or change of behavior (Hardin 1992, Siegrist et al. 2007). Strategic trust is built on experience and goodwill, and reduces transaction costs needed to take action in response to new information.

Education broadens people's perspectives on the world by providing new information to increase knowledge, awareness, skills, and motivation. Increased learning can sharply increase trust through the establishment of a similar value system among EOET professionals and EOET program participants (Uslaner and Badescu 2002). The average American adult, regardless of age, income, or education, generally does not grasp essential aspects of environmental science, important cause-effect relationships, or concepts such as runoff pollution, power generation and fuel use, or water flow patterns (Coyle 2005). Moreover, Coyle found, the opinions of 80% of Americans are heavily influenced by incorrect or outdated information, and only 12% of Americans can pass a basic quiz on awareness of energy topics.

Social trust refers to willingness to rely on others whose values are compatible with our own main goals (Siegrist et al. 2007). There is no significant correlation between social trust and judged risks and benefits for hazards with which people are familiar, whereas there is strong correlation between these variables with people who have little familiarity of the hazard (Siegrist and Cvetkovich 2000). A mental model proposed by Morgan et al. (2002) suggests that solutions for some risk management problems may be identified by comparing the understanding of a risk among different groups of people, such as the general public, scientific experts, risk managers, and EOET practitioners. The mental model approach offers a method for understanding self-assessed knowledge and how to design EOET programs to correct any gaps or errors in the self-assessed knowledge (Siegrist et al. 2007). Morgan explained further that laypeople rank the degree of risk from a hazard based on how well the risk is distributed across the population, how well an individual can control the risk they face, and whether the risk is assumed to be voluntary or imposed on people without their approval.

Needs Based Content

Effective EOET programs are built around program planning models (Dick et al. 2011), for which audience needs assessment or gap analysis is central. Many state and regional EOET programs have conducted needs assessments and market analysis to identify educational and informational needs (Culver et al. 2010; SCIPP, in press; Capps et al. 2010). One example by Culver et al. (2010) identified an exhaustive list of needs for climate education. Needs relevant to this discussion include the following:

1. Establish climate education inventories that can be used to develop an inventory of plans, lessons learned, and best management practices.
2. Establish a clear vocabulary on climate science that is understandable by disparate audiences.
3. Develop reliable and consistent information to frame messages.
4. Set standards for what a climate-literate citizen should know.
5. Develop transparent and participatory approaches to the selection of materials for educational programs.
6. Support ongoing information clearinghouses.
7. Address gaps in climate change projections with specific education, outreach, extension and training programs.
8. Perform additional socioeconomic impact, risk, and cost-benefit analyses.
9. Sustain mechanisms for regional collaboration.
10. Address issues of scale.
11. Facilitate cooperation among states, federal agencies, and regional associations.

More than half of USA citizens live in a jurisdiction that has enacted a greenhouse gas (GHG) emissions reduction goal (National Research Council 2010). Growing numbers of people and organizations responding to climate change have increased demands for climate information and justify the need for an effective national capacity to respond to climate change. The National Research Council (2010) report, "Informing an Effective Response to Climate Change" identified three key lessons from these GHG reduction experiences:

1. A broad range of tailored information and tools is needed for the diversity of decision makers and to engage new constituencies.
2. Most decision makers will need to make climate choices in the context of other responsibilities, competing priorities, and resource constraints.
3. There is a critical need to coordinate a national response that builds on existing efforts, provides a heuristic approach to successes and failures, reduces burdens on any one region or sector, and ensures the credibility and comprehensiveness of information and policy.

Data from needs assessments conducted with target audiences are used to determine if the identified needs can be solved through EOET program. Needs that can be addressed through an EOET program undergo an instructional design process beginning with instructional goals and desired outcomes, and culminating with a summative evaluation of the instructional strategy used to reach the identified goals. Through the needs assessments that have been conducted (Needham and Carter 2012), organizations are implementing instructional programs to present an understandable, acceptable, and effective climate EOET programs to constituents in ways that draws participation from partners and the public. These partnerships include federal, state, and county agencies as well as academia, nongovernmental, private, and community groups.

State STEM Education Standards

Science, technology, engineering, and mathematics (STEM) initiatives started as a way to promote education in physical sciences so that students would be prepared to study STEM fields in college and pursue STEM-related careers (Jones 2008). Schools with a strong emphasis on STEM education often integrate science, technology, engineering, and mathematics into the entire curriculum. Jones provided five recommendations for strengthening STEM education:

1. Obtain societal support for STEM education.
2. Expose students to STEM careers.
3. Provide ongoing and sustainable STEM professional development.
4. Encourage STEM pre-service teacher training.
5. Recruit and retain STEM teachers.

Though a consensus process, federal agency and nongovernmental organizations concluded that climate is an ideal interdisciplinary theme for education (National Research Council 2011). Incorporating climate change into state education science standards is increasing and provides early evidence of success (National Research Council 2011). To support STEM, the NOAA 2009-2029 Education Strategic Plan (NOAA 2009) recommended an environmentally literate public be supported by a continuum of lifelong formal and informal education and outreach opportunities in ocean, coastal, Great Lakes, weather, and climate sciences.

14.4 Delivery Methods

Program delivery is the mechanism to meet EOET goals and objectives. Organizations providing EOET use various delivery methods to reach their target audiences. This section describes some key delivery mechanisms for EOET (NOAA 2008b, Baker et al. 2001, Etllng 1993).

Traditional Delivery

Traditional delivery methods such as newsletters, publications, field tours, video, workshops, seminars, symposia, evening meetings, short courses, and formal classes have been extremely effective as an education tool. State Land Grant and Sea Grant Extension programs have historically used these delivery methods for programs since their inception. Designers of these nonformal education programs understand the need to develop and adopt methods delivery methods that are most appropriate for adult and youth learners. For example, Seger (2011) recommended a blend of delivery methods in learning opportunities by mixing new technology with traditional on-site educational activities.

Role of Media in Climate Education Delivery

Media in any form provide a powerful tool for climate education. A study conducted by Pew Internet and American Life Project found that, when asked specifically about news habits on a "typical day," 99% of American adults surveyed said they get news from a local or national print newspaper, a local or national television news broadcast, radio, or the Internet. The Internet has surpassed newspapers and radio in popularity as a news platform and now ranks just behind television (Purcell et al. 2010).

Cooperative Extension organizations have identified Internet social media as a diverse online tool for reaching audiences—especially for adult education. Such programs are easily accessible and often provided free through a personal computer, smartphone, or web-enabled television. In 2010, Americans spent 23% of their Internet time using social media (O'Neill et al. 2011). Social media sites, such as Facebook, Twitter, YouTube, Flicker, and Blogger, are popular sources of news and communications. Facebook, for instance, had more than 800 million subscribers in 2011 (O'Neill et al. 2011). The accessibility of social media tools and the ability to share across platforms creates an environment primed for quick and widespread distribution of information (Cornelisse et al. 2011). A social media post theoretically can be spread worldwide and viewed by millions within minutes, if not seconds. The use of social media as a delivery platform for formal and nonformal education programs for adults and youth offers tremendous potential for climate education when programs are based on the best available climate science.

The downside of the explosive growth in the use of social media for education is the low level of credibility of information often provided by such the sites. Credibility of an information source can be evaluated with metrics from the University of Oregon Libraries (http://libweb.uoregon.edu/guides/findarticles/credibility.html):

1. Authority of the author and the publisher: Are they well qualified to speak to the topic at hand?
2. Objectivity of the author.
3. Quality of the work.
4. Coverage of the work.
5. Currency: How recently is the research and publication?

14.5 Program Integration

Many state and local agencies, professional organizations, and other groups in the SE are becoming increasingly aware of the importance and the crucial value of partnerships and program integration. For this chapter program integration is defined as the intra- and interagency integration of scientists and EOET professionals with the public. The National Oceanic Atmospheric Administration (NOAA) Coastal Services Center has created a central hub for information and reports (http://www.csc.noaa.gov/climate/). The Gulf of Mexico Climate Community of Practice (CoP) is another example of collaborative program integration (Capps et al. 2010), which recognizes the value in leveraging the diverse set of assets among federal, state, and local partners when working with local communities to develop and implement climate adaptation strategies. Efforts like these address key impediments to effective delivery of climate education programs such as a tight coupling between science and policy; improved federal, regional, and state coordination; and funding (Culver et al. 2010, National Research Council 2010 and 2011)

Mandates

The America COMPETES Act assigns NOAA responsibility for advancing and coordinating mission-related STEM education and stewardship efforts and for participating in interagency education efforts. At the local level, however, there are few mandates for climate education. Most mandates are driven at the federal level. NOAA 2009-2029 acknowledges that NOAA has a climate education mandate through its climate literacy program.

The National Aeronautics and Space Administration (NASA), NOAA, and the National Science Foundation (NSF) have formed a partnership to streamline climate education into a program that is relevant, recognizable, and effective. With mandates from the US Congress to increase global climate change literacy among educators and students, federal agencies have begun the process of implementing programs and awarding cooperative agreements and grants to further climate science education.

14.6 Barriers to Extension, Outreach, Education, and Training Regarding Climate Change

The National Research Council (2011) identified various barriers to climate change education including the following:

1. Resistance to the behavior change model. Connecting science with society is a difficult task, especially with respect to the implications that climate change education is currently aimed solely at changing people's behavior.
2. Lack of technical support provided at the right time and in the right format to implement mitigation and adaptation strategies.
3. Overcoming distrust of those identified in the Six Americas study as being doubtful, disengaged, or dismissive of climate change (Leiserowitz et al. 2011).
4. The need for a cross-disciplinary approach, blending education with the learning, social, behavioral, and economic sciences as well as earth systems science.
5. The lack of a forum for coordination, cooperation, and alignment of overall education strategies among myriad federal agencies, nongovernmental organizations, and businesses invested in climate change education might duplicate efforts and waste limited resources.
6. Climate change science has become highly politicized in the policy arena and in education institutions in some regions and sectors. Often people's willingness to learn depends on their attitude toward the issue itself (Gardner and Stern 2008, Leiserowitz et al. 2011).

Culver et al. (2010) identified the lack of research funding to investigate local impacts, create adaptation plans, and then implement those plans as barriers to EOET at the community level. As a result, Culver et al. recommended case studies and partnerships with practitioners knowledgeable in developing frameworks to overcome previously identified barriers. In addition, the inclusion of participants from federal, regional, and local agencies would create broad ownership in the planning process. Finally, a communication strategy and outreach plan was suggested as a way to open doors, engage stakeholders, and obtain funding to implement actions from the plan.

14.7 Ongoing Education, Outreach, Extension and Training Programs

In response to these and other expressed climate EOET needs, many groups within the SE have developed a wide range of education and communication programming, hands-on activities, online tools for decision makers, short and long courses, teacher training, publications, websites, online programs, handouts, topical brochures, and other outreach efforts through a variety of mechanisms. Programs include formal K-12 and university level courses; informal training and topic specific options; options for businesses, such as insurance information; and federally supported programs. This section provides examples of climate education outreach extension and training programs in the SE. These programs were identified during October and November 2011 through an online survey (Climate Education and Outreach Survey 2012) that was disseminated to members of the Southeast Regional Technical Report team and other groups known to deliver climate EOET programs. The survey is a step forward in developing an inventory of these types of services.

Alabama Office of the State Climatologist

The office provides information to legislative, governmental, industrial, agricultural, and ducational institutions regarding all aspects of climate. The office performs fundamental climate research from local to global aspects, and provides solicited testimony before numerous state legislative bodies, US Congress, Federal Agencies, and Federal Courts regarding climate and climate change issues. **Website:** http://vortex.nsstc.uah.edu/aosc/

Animal Agriculture and Climate Change

America's livestock and poultry production are impacted by changes in climate. This USDA Cooperative Extension System Web-based collection of information has been developed for dairy, beef, swine, broiler, layer, and turkey farmers and ranchers on the topics of climate change, carbon footprints, greenhouse gases, and effects of climatic changes. **Website:** http://www.extension.org/pages/60702/animal-agriculture-and-climate-change

Center for Coastal Ecology

The center works primarily in outreach to working scientists, agency staff, NGOs, and the general public on Florida-specific issues relating to sea level and sea-level rise. **Website:** http://www.mote.org

CHARM–Community Health and Resource Management

Addresses climate adaptation issues through a no-regrets approach of good planning for existing coastal hazards. **Website:** http://www.urban-nature.org

Climate Change in the Gulf of Mexico

The program goal is to educate K-16 teachers and informal educators about various aspects of climate change and to explore activities with them that they can use in their classroom or laboratory to help communicate these topics to their students. **Website:** http://dhp.disl.org/teachertraining.htm

Climate Community of Practice in the Gulf of Mexico

The Climate Community of Practice brings together extension, outreach and education professionals to learn how coastal communities along the Gulf can adapt to sea level rise and other climate-related issues. Through participation in the community, extension, outreach, and education professionals become better equipped to provide community leaders with reliable information and science-based guidance regarding the level of risk to their communities and strategies they can use to adapt to climate change. **Website:** http://www.masgc.org/cop.

Climate Literacy Education and Research

This program combines climate information with information from the natural, built, human and economic sectors and relays this information to decision makers. Rather than one-way web communication, the program starts with outreach and active listening, improves prototypes, and provides true tools to support decision making at a variety of scales. **Website:** http://nemac.unca.edu/climate-literacy

Climate Resilient Communities Program

The program goal is to help local governments build more resilient communities, through greater resilience of social, environmental, and economic systems. The program aggregates and develops information needed for local governments to understand climate change, to understand their vulnerabilities, to identify strategies appropriate for their unique vulnerabilities and opportunities from a changing climate, to assist them with implementing the actions, and then to assist with monitoring and verifying success. **Website:** http://www.icleiusa.org/adaptation

Georgia Interfaith Power & Light

The organization's goal is to educate and engage communities of faith across Georgia with respect to our responsibility as people of faith to care for the planet as well as to communicate the realities of climate change and how we can make a difference. **Website:** http://www.gipl.org

Gulf Coast Community Handbook, Tampa Bay Estuary Program

This program will develop and distribute a Gulf Coast Community Handbook for incorporating resiliency into habitat restoration and protection plans to communities around the Gulf of Mexico. The Handbook will incorporate "case studies" of habitat restoration resiliency examples from communities around the Gulf. This effort will contribute to climate change adaptation in the estuary by providing on-the-ground examples of how local communities around the Gulf area are incorporating resiliency into habitat restoration and protection strategies, including a summary of best practices. **Website:** http:://www.tbep.org

Kentucky Climate Center

The center serves as the State Climate Office for Kentucky. The main outreach education and outreach activities include hosting a website with a database for Kentucky's climate, filling individual requests for data and advice regarding climate, and operating a mesonet to support both operational and research needs. **Website:** http://www.kyclimate.org

King Tide Photo Documentary Project

This project raises awareness of sea-level rise in the local community through the opportunity to be part of a photo documentary activity. Community members take pictures of areas receiving higher than usual water during the King Tides each year and submit them to on-line sharing websites. **Website:** http://www.tbep.org

Pine Integrated Network: Education, Mitigation, and Adaptation project (PINEMAP)

This program conducts research, education, and outreach on climate change and pine–both pine adaptations to climate change and using pine to mitigate change. The education activities include a graduate course, an undergraduate internship program, a secondary project learning tree module, and a host of extension materials and programs to reach SE forest landowners. Each project will have specific objectives, of course. **Website:** http://pinemap.org

Public Water Supply Utilities Climate Impacts Working Group (PWSU-CIWG)

The PWSU-CIWG focuses on making climate science more useable for planning and operational needs related to both the supply of and demand for water. It provides a collaborative forum for public water suppliers, water resource managers, climate, hydrologic and social scientists to promote shared knowledge, data, models, decision-making tools, strategies and adaptations relevant to the dynamic and changing conditions affecting water supply reliability. The working group is interested in opportunities to support the collaborative development of new industry-relevant tools that have been vetted through the academic, public water supply and regulatory communities in Florida. **Website:** http://waterinstitute.ufl.edu/workshops_panels/PWSU-CIWG.html

Sapelo Island National Estuarine Research Reserve (SINERR) Coastal Training Program

The SINERR Coastal Training Program provides support and information to elected officials and professionals so they can better manage the coastal resources so vital to their economies and way of life. The program responds to individuals, businesses and communities by providing information on topics ranging from waste removal systems to shoreline erosion and shellfish habitat. The program targets the entire coastline of Georgia with partners and collaborators from many agencies and organizations. **Website:** http://www.sapeloislandnerr-ctp.org/

Southeast Climate Consortium (SECC)

The consortium includes about 70 participating research and extension members from eight universities and five southeastern states. The SECC conducts research and extension to develop and apply climate information in partnership with information users and other education and outreach programs. Target audiences of the SECC currently emphasize agricultural and water resource managers. **Websites:** http://SEClimate.org; http://AgroClimate.org

Southern Climate Impacts Planning Program (SCIPP)

The Southern Climate Impacts Planning Program (SCIPP) is one of the NOAA RISA (Regional Integrated Science Assessment) programs (see Chapter 13). The tools/data products on the SCIPP website at present include: Southern US drought tool; Average Monthly Temperature and Precipitation tool; Historical Climate Trends tool; Climograph tool; and Historical Gulf Coast surge map. **Website:** http://www.southernclimate.org

State Climate Office of North Carolina

The office mission has three components: research, extension, and education. The outreach and education goals are to increase public and professional understanding of climate science, monitoring, and prediction and to build capacity for sectoral professionals to better use climate information and science. **Website:** http://nc-climate.ncsu.edu

Tennessee Climatological Service

Although not a designated State Climate Office, this outreach effort by three universities (UTK, UTM, and TTU) provides climate data and services to the state of Tennessee. **Website:** http://climate.tennessee.edu/

14.8 Conclusions

Climate extension, outreach, education and training (EOET) programs have been and will continue to be essential in addressing the climate change needs facing the SE region of the United States. EOET program design, delivery, and evaluation must be tailored to the audience needs, whether through formal, nonformal, or informal programs for K-12 education, higher education, state or local governments, or for the general public. Targeted programs are essential to reach the desired program goals or outcomes including improving climate literacy, adaptation strategies, or climate-friendly behavior changes. Existing and nascent climate EOET programs should be inventoried and evaluated against local, regional and national climate program goals and objectives to determine ways to improve their effectiveness and establish best practices for future EOET programs. Inadequate funding is always an issue, regardless of the type of EOET program. In the absence of increased funding better integration among existing climate EOET programs and sponsors of climate education should be encouraged.

14.9 References

APA (American Psychological Association Task Force). 2010. *Psychology and global climate change: Addressing a multifaceted phenomenon and set of challenges*. Washington, DC: American Psychological Association. http://www.apa.org/science/about/publications/climate-change-booklet.pdf

APLU (Association of Land Grant Universities, formerly National Association of State Universities and Land Grant Colleges). 1999. *Returning to our roots: The engaged institution*. Washington, DC: Kellogg Commission on the Future of State and Land-Grant Universities. http://www.aplu.org/NetCommunity/Document.Doc?id=183.

Baker, D.R., J. Murray, B. Wilkins, M. Spranger, J. Lemus, B. Branca. 2001. *Fundamentals of a sea grant extension program*. Oakland, CA: University of California Libraries. http://www-csgc.ucsd.edu/BOOKSTORE/Resources/COMP_PUBS/sgfundext.pdf

Booz Allen Hamilton. 2010. *Hazard and resiliency planning: Perceived benefits and barriers among land use planners: Final research report*. National Oceanic and Atmospheric Administration Coastal Services Center. McLean, VA: Booz Allen Hamilton.

Capps, M., L. Swann, K. Havens, M. Schneider, C. Wilson, R. Stickney, T. Sempier, S. Sempier. 2010. *Climate outreach in the Gulf of Mexico region: Awareness and action tools for the climate outreach community of practice*. Washington, DC: National Sea Grant Office.

Carter, L.M. 1998. Global environmental change: Modifying human contributions through education. *Journal of Science Education and Technology* 7 (4): 297-309.

Climate Education and Outreach Survey. 2012 (http://surveymonkey.com/s climate_education_outreach)

Coombs, P. 1973. *New paths to learning for rural children and youth*. New York, NY: International Council for Educational Development.

Cornelisse, S., J. Hyde, C. Raines, K. Kelly, D. Ollendyke, J. Remcheck. 2011. Entrepreneurial extension conducted via social media. *Journal of Extension* 49 (6): 6TOT1. http://www.joe.org/joe/2011december/tt1.php.

Coyle, K. 2005. Environmental literacy in America: What ten years of research says about environmental literacy in the U.S. Washington, DC: The National Environmental Education and Training Foundation. http://www.neefusa.org/pdf/ELR2005.pdf.

Culver, M.E., J.R. Schubel, M.A. Davidson, J. Haines, K.C. Texeira. 2010. Proceedings from the sea level rise and inundation community workshop, Lansdowne, MD, Dec 3-5, 2009. Sponsored by the National Oceanic and Atmospheric Administration and U.S. Geological Survey.

Dick, W., L. Carey, J.O. Carey. 2011. *The systematic design of instruction*. Upper Saddle River, NJ: Pearson Education.

Etllng, A. 1993. What is nonformal education? *Journal of Agricultural Education* 34 (4). http://pubs.aged.tamu.edu/jae/pdf/Vol34/34-04-72.pdf.

Friedman, A., ed. 2008. *Framework for evaluating impacts of informal science education projects*. Arlington VA: The National Science Foundation. http://insci.org/resources/Eval_Framework.pdf.

Gardner, G.T. and P.C. Stern. 2009. The Short List: The Most Effective Actions U.S. Households Can Take to Curb Climate Change. *Environment: Science and Policy for Sustainable Development.* http://www.environmentmagazine.org/Archives/Back%20Issues/September-October%202008/gardner-stern-full.html.

Goidel K., M. Climek, C. Kenny, M. Means, M. Schneider, T. Sempier, L. Swann. 2012. Climate perceptions of residents living on the coast of the Gulf of Mexico Executive Summary. Mississippi-Alabama Sea Grant Consortium. http://masgc.org/pdf/masgp/12-036.pdf.

Hinkey, L.M., K.T. Ellenberg, B. Kessler. 2005. Strategies for engaging scientists in collaborative processes. *Journal of Extension* 43 (1): 1FEA3. http://www.joe.org/joe/2005february/a3.php

Hardin, R. 1992. The street-level epistemology of trust. *Analyse and Kritik* 14 (1992): 152-176. http://www.analyse-und-kritik.net/1992-2/AK_Hardin_1992.pdf

Jones, R.B. 2008. *Science, technology, engineering and math*. Glen Burnie, MD: State Educational Technology Directors Association (SETDA). http://www.setda.org/c/document_library/get_file?folderId=270&name=DLFE-257.pdf.

Karl, H.A., L.E. Susskind, K.H. Wallace. 2007. A dialogue, not a diatribe: Effective integration of science and policy through joint fact finding. *Environment* 49 (1): 20-34.

Knowles, M.S. 1980. *The modern practice of adult education: Andragogy versus pedagogy*. New York, NY: Association Press.

Leiserowitz, A., E. Maibach, C. Roser-Renouf, N. Smith. 2011. *Climate change in the American mind: Americans' global warming beliefs and attitudes in May 2011*. New Haven, CT: Yale Project on Climate Change Communication. http://environment.yale.edu/climate/files/ClimateBeliefs-May2011.pdf.

Leiserowitz, A., E. Maibach, C. Roser-Renouf, N. Smith. 2011. *Global warming's six America's, May 2011*. New Haven, CT: Yale Project on Climate Communication. http://environment.yale.edu/climate/files/SixAmericasMay2011.pdf.

McCright, A.M. and R.E. Dunlap. 2011. The politicization of climate change and polarization in the American public's views of global warming, 2001-2010. *The Sociological Quarterly* 52 (2): 155-194.

Morgan, M.G., B. Fishchhoff, A. Bostrom, C.J. Atman. 2002. *Risk communication: A mental models approach*. Cambridge, United Kingdom: Cambridge University Press.

National Ocean Council. 2012. *Draft national ocean policy implementation plan*. Washington, DC: National Ocean Council. http://www.whitehouse.gov/sites/default/files/microsites/ceq/national_ocean_policy_draft_implementation_plan_01-12-12.pdf.

NOAA (National Oceanic and Atmospheric Administration). 2008a. *Essential principles of climate literacy*. Washington, DC: NOAA. http://www.climate.noaa.gov/education/pdfs/climate_literacy_poster-final.pdf.

NOAA (National Oceanic and Atmospheric Administration). 2008b. *Engaging NOAA constituents: A report from the NOAA Science Advisory Board*. Washington, DC: NOAA. http://www.sab.noaa.gov/Reports/EOEWG/EOEWG_Final_Report_03_20_08.pdf.

NOAA (National Oceanic and Atmospheric Administration). 2009*. Education strategic plan 2009-2029*. Washington, DC: NOAA. http://www.education.noaa.gov/plan/index.html.

National Research Council. 2011. *Climate change education: Goals, audiences, and strategies*. Washington, DC: The National Academies Press.

National Research Council. 2010. *Informing an effective response to climate change*. Washington, DC: The National Academies Press. http://www.nap.edu/catalog.php?record_id=12784.

Needham, H. and L. Carter. 2012. *Gulf coast climate information needs assessment*. Norman, OK: Southern Climate Impacts Planning Program. http://www.southernclimate.org/publications/Gulf_Coast_Assessment_Final.pdf

O'Neill, B., A. Zumwalt, J. Bechman. 2011. Social media use of cooperative extension family economics educators: Online survey results and implications. *Journal of Extension* 49 (6): 6RIB2. http://www.joe.org/joe/2011december/rb2.php.

Pickens, P.M. 2002. *Community-based social marketing as a planning tool: Community and regional planning masters project*. Eugene, OR: University of Oregon-Architecture and Allied Arts Department.

Purcell, K., L. Rainie, A. Mitchell, T. Rosenstiel, K. Olmstead. 2010. *Understanding the participatory news consumer: How Internet and cell phone users have turned news into a social experience*. Washington, DC: Pew Research Center. http://www.pewinternet.org/~/media//Files/Reports/2010/PIP_Understanding_the_Participatory_News_Consumer.pdf

Russell, J.D. and J. Hellebrandt. 1993. Confirmative evaluation of instructional materials and learners. *Performance & Instruction* 32 (6): 22-27.

Siegrist, M., G. Cvetkovich. 2000. Perception of hazards: The role of social trust and knowledge. *Risk Analysis* 20 (5) :713-719.

Siegrist, M. and T.C. Earle, H. Gutscher. 2007. *Trust in risk management: Uncertainty and skepticism in the public mind*. Oxford, United Kingdom: Earthscan.

Shah, A. 2012. Global Warming, Spin and Media. Global Issues. http://www.globalissues.org/print/article/710.

Somerville, R.C.J., S.J. Hassol. 2011. Communicating the science of climate change. *Physics Today* 64 (10): 48-53.

Seger, J. 2011. The new digital [st]age: Barriers to the adoption and adaptation of new technologies to deliver extension programming and how to address them. *Journal of Extension* 49 (1): 1FEA1. http://www.joe.org/joe/2011february/a1.php.

Tyson, B. and D.M. Hurd. 2009. *Social marketing environmental issues*. Bloomington, IN: iUniverse.

Uslaner, E.M., G. Badescu. 2002. *The moral foundations of trust*. New York, NY: Cambridge University Press.

Climate of the Southeast United States: Variability, Change, Impacts, and Vulnerability is based on one of a series of regional technical reports prepared for the Third National Climate Assessment. This report is the work of more than 100 experts in climate science, economics, ecology, engineering, geography, hydrology, planning, resource management, agriculture, aquaculture, health, and other disciplines that reviewed and analyzed the latest scientific research, current and historical trends, and projections of how climate change is likely to impact the Southeast USA. Climate variability has strong physical, biological, and social impacts for the southeastern states of Arkansas, Alabama, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, and Virginia, as well as Puerto Rico and the Virgin Islands. Questions and issues about how climate variability and change may affect the social and economic well-being of people and communities are addressed along with processes for mitigation and potential solutions for adaptation to climate variability, which may include uneven changes in precipitation resulting in more frequent droughts or floods, damages from sea level rise, and increased intensity of tropical storms. This book, along with the other National Climate Assessment documents, is an important tool for decision makers and stakeholders as communities work together to make scientifically informed choices for making the Southeast region sustainable and prosperous for the present and future generations.

Cover design: Maureen Gately
Book design: Livia Kent

ISBN 13: 978-1-61091-439-0
ISBN 10: 1-61091-439-2
90000 >
9 781610 914390

ISLANDPRESS
Washington | Covelo | London
www.islandpress.org
All Island Press books are printed on recycled, acid-free paper.