19 Southeast

Federal Coordinating Lead Author
Adam Terando
U.S. Geological Survey,
Southeast Climate Adaptation Science Center

Chapter Lead
Lynne Carter
Louisiana State University

Chapter Authors
Kirstin Dow
University of South Carolina

Kevin Hiers
Tall Timbers Research Station

Kenneth E. Kunkel
North Carolina State University

Aranzazu Lascurain
North Carolina State University

Doug Marcy
National Oceanic and Atmospheric Administration

Michael Osland
U.S. Geological Survey

Paul Schramm
Centers for Disease Control and Prevention

Review Editor
Alessandra Jerolleman
Jacksonville State University

Technical Contributors are listed at the end of the chapter.

Recommended Citation for Chapter

Carter, L., A. Terando, K. Dow, K. Hiers, K.E. Kunkel, A. Lascurain, D. Marcy, M. Osland, and P. Schramm, 2018: Southeast. In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 743–808. doi: 10.7930/NCA4.2018.CH19

On the Web: https://nca2018.globalchange.gov/chapter/southeast

19 Southeast

Red mangrove in Titusville, Florida

Key Message 1

Urban Infrastructure and Health Risks

Many southeastern cities are particularly vulnerable to climate change compared to cities in other regions, with expected impacts to infrastructure and human health. The vibrancy and viability of these metropolitan areas, including the people and critical regional resources located in them, are increasingly at risk due to heat, flooding, and vector-borne disease brought about by a changing climate. Many of these urban areas are rapidly growing and offer opportunities to adopt effective adaptation efforts to prevent future negative impacts of climate change.

Key Message 2

Increasing Flood Risks in Coastal and Low-Lying Regions

The Southeast's coastal plain and inland low-lying regions support a rapidly growing population, a tourism economy, critical industries, and important cultural resources that are highly vulnerable to climate change impacts. The combined effects of changing extreme rainfall events and sea level rise are already increasing flood frequencies, which impacts property values and infrastructure viability, particularly in coastal cities. Without significant adaptation measures, these regions are projected to experience daily high tide flooding by the end of the century.

Key Message 3

Natural Ecosystems Will Be Transformed

The Southeast's diverse natural systems, which provide many benefits to society, will be transformed by climate change. Changing winter temperature extremes, wildfire patterns, sea levels, hurricanes, floods, droughts, and warming ocean temperatures are expected to redistribute species and greatly modify ecosystems. As a result, the ecological resources that people depend on for livelihood, protection, and well-being are increasingly at risk, and future generations can expect to experience and interact with natural systems that are much different than those that we see today.

Key Message 4

Economic and Health Risks for Rural Communities

Rural communities are integral to the Southeast's cultural heritage and to the strong agricultural and forest products industries across the region. More frequent extreme heat episodes and changing seasonal climates are projected to increase exposure-linked health impacts and economic vulnerabilities in the agricultural, timber, and manufacturing sectors. By the end of the century, over one-half billion labor hours could be lost from extreme heat-related impacts. Such changes would negatively impact the region's labor-intensive agricultural industry and compound existing social stresses in rural areas related to limited local community capabilities and associated with rural demography, occupations, earnings, literacy, and poverty incidence. Reduction of existing stresses can increase resilience.

Executive Summary

The Southeast includes vast expanses of coastal and inland low-lying areas, the southern portion of the Appalachian Mountains, numerous high-growth metropolitan areas, and large rural expanses. These beaches and bayous, fields and forests, and cities and small towns are all at risk from a changing climate. While some climate change impacts, such as sea level rise and extreme downpours, are being acutely felt now, others, like increasing exposure to dangerous high temperatures, humidity, and new local diseases, are expected to become more significant in the coming decades. While all regional residents and communities are potentially at risk for some impacts, some communities or populations are at greater risk due to their locations, services available to them, and economic situations.

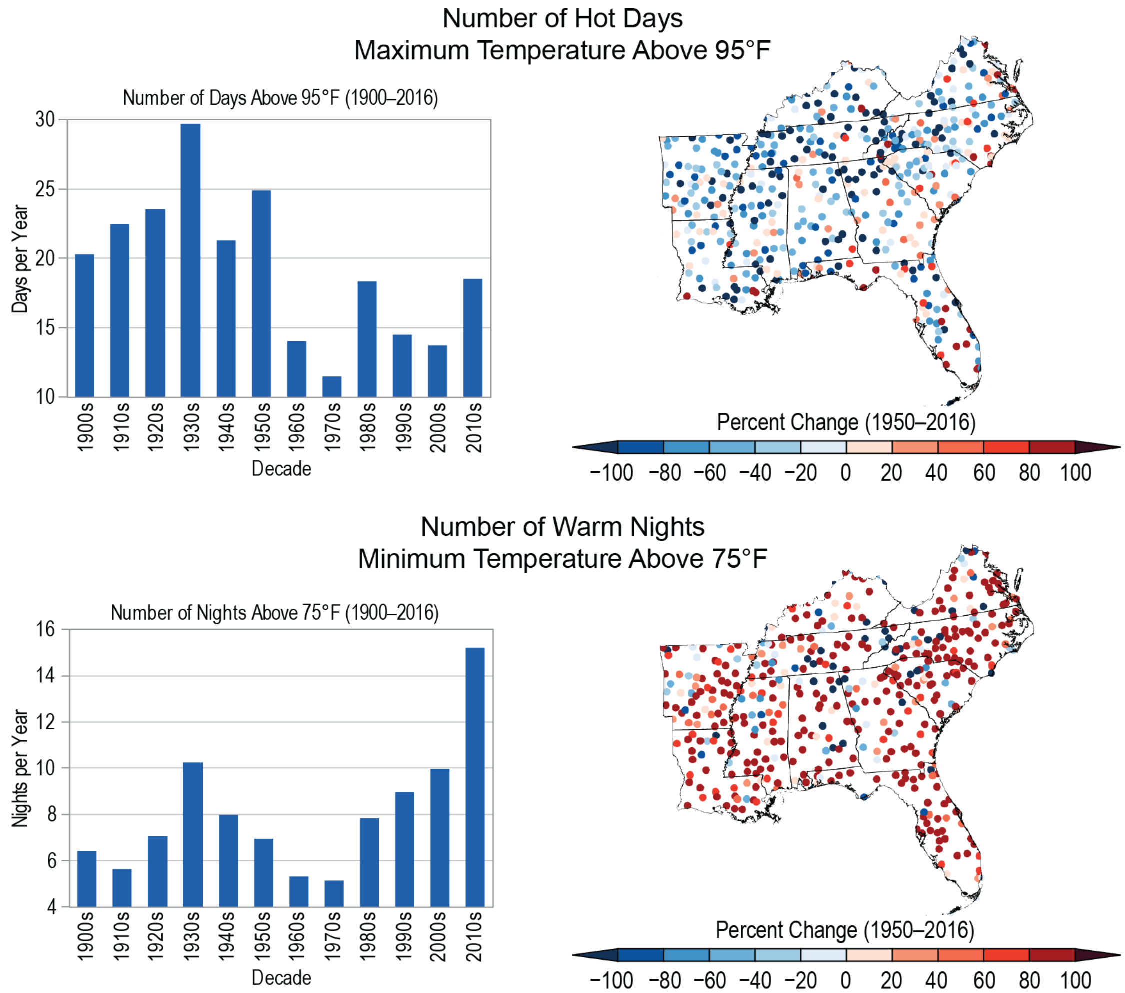
Observed warming since the mid-20th century has been uneven in the Southeast region, with average daily minimum temperatures increasing three times faster than average daily maximum temperatures. The number of extreme rainfall events is increasing. Climate model simulations of future conditions project increases in both temperature and extreme precipitation.

Trends towards a more urbanized and denser Southeast are expected to continue, creating new climate vulnerabilities. Cities across the Southeast are experiencing more and longer summer heat waves. Vector-borne diseases pose a greater risk in cities than in rural areas because of higher population densities and other human factors, and the major urban centers in the Southeast are already impacted by poor air quality during warmer months. Increasing precipitation and extreme weather events will likely impact roads, freight rail, and passenger rail, which will likely have cascading effects across the region. Infrastructure related to drinking water and wastewater treatment also has the potential to be compromised by climate-related events. Increases in extreme rainfall events and high tide coastal floods due to future climate change will impact the quality of life of permanent residents as well as tourists visiting the low-lying and coastal regions of the Southeast. Sea level rise is contributing to increased coastal flooding in the Southeast, and high tide flooding already poses daily risks to businesses, neighborhoods, infrastructure, transportation, and ecosystems in the region.[1,2] There have been numerous instances of intense rainfall events that have had devastating impacts on inland communities in recent years.

The ecological resources that people depend on for livelihoods, protection, and well-being are increasingly at risk from the impacts of climate change. Sea level rise will result in the rapid conversion of coastal, terrestrial, and freshwater ecosystems to tidal saline habitats. Reductions in the frequency and intensity of cold winter temperature extremes are already allowing tropical and subtropical species to move northward and replace more temperate species. Warmer winter temperatures are also expected to facilitate the northward movement of problematic invasive species, which could transform natural systems north of their current distribution. In the future, rising temperatures and increases in the duration and intensity of drought are expected to increase wildfire occurrence and also reduce the effectiveness of prescribed fire practices.[3,4,5,6]

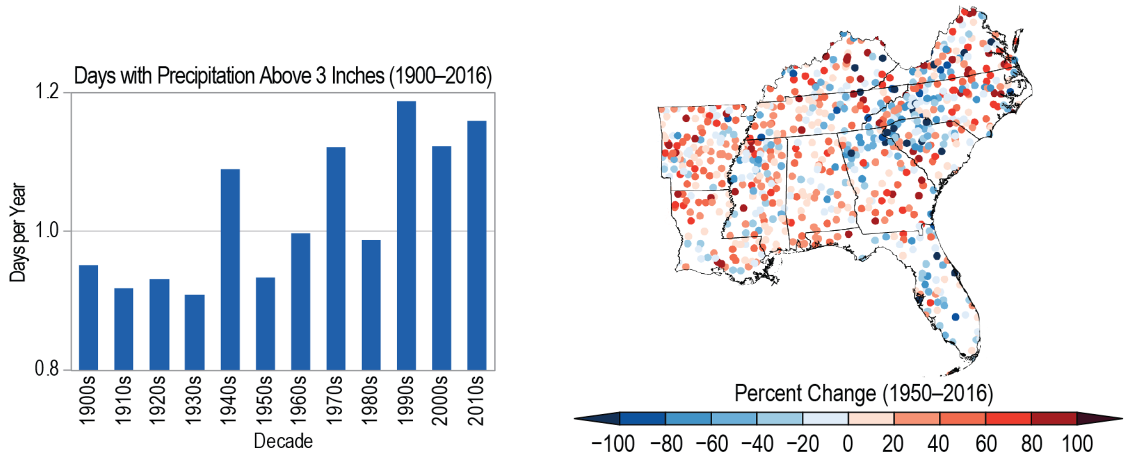
Many in rural communities are maintaining connections to traditional livelihoods and relying on natural resources that are inherently vulnerable to climate changes. Climate trends and possible climate futures show patterns that are already impacting—and are projected to further impact—rural sectors, from agriculture and forestry to human health and labor productivity. Future temperature increases are projected to pose challenges to human health. Increases in temperatures, water stress, freeze-free days, drought, and wildfire risks, together with changing conditions for invasive species and the movement of diseases, create a number of potential risks for existing agricultural systems.[7] Rural communities tend to be more vulnerable to these changes due to factors such as demography, occupations, earnings, literacy, and poverty incidence.[8,9,10] In fact, a recent economic study using a higher scenario (RCP8.5)[11] suggests that the southern and midwestern populations are likely to suffer the largest losses from future climate changes in the United States. Climate change tends to compound existing vulnerabilities and exacerbate existing inequities. Already poor regions, including those found in the Southeast, are expected to continue incurring greater losses than elsewhere in the United States.

Historical Changes in Hot Days and Warm Nights



Sixty-one percent of major Southeast cities are exhibiting some aspects of worsening heat waves, which is a higher percentage than any other region of the country.[12] Hot days and warm nights together impact human comfort and health and result in the need for increased cooling efforts. Agriculture is also impacted by a lack of nighttime cooling. Variability and change in (top) the annual number of hot days and (bottom) warm nights are shown. The bar charts show averages over the region by decade for 1900–2016, while the maps show the trends for 1950–2016 for individual weather stations. Average summer temperatures during the most recent 10 years have been the warmest on record, with very large increases in nighttime temperatures and more modest increases in daytime temperatures, as indicated by contrasting changes in hot days and warm nights. (top left) The annual number of hot days (maximum temperature above 95°F) has been lower since 1960 than the average during the first half of the 20th century; (top right) trends in hot days since 1950 are generally downward except along the south Atlantic coast and in Florida due to high numbers during the 1950s but have been slightly upward since 1960, following a gradual increase in average daytime maximum temperatures during that time. (bottom left) Conversely, the number of warm nights (minimum temperature above 75°F) has doubled on average compared to the first half of the 20th century and (bottom right) locally has increased at most stations. *From Figure 19.1 (Sources: NOAA NCEI and CICS-NC).*

Historical Change in Heavy Precipitation



The figure shows variability and change in (left) the annual number of days with precipitation greater than 3 inches (1900–2016) averaged over the Southeast by decade and (right) individual station trends (1950–2016). The number of days with heavy precipitation has increased at most stations, particularly since the 1980s. *From Figure 19.3 (Sources: NOAA NCEI and CICS-NC)*

Background

Throughout the southeastern United States, the impacts of sea level rise, increasing temperatures, extreme heat events, heavy precipitation, and decreased water availability continue to have numerous consequences for human health, the built environment, and the natural world. This assessment builds on the above concerns described in the Third National Climate Assessment (NCA3) and includes impacts to urban and rural landscapes as well as natural systems. The impacts from these changes are becoming visible as 1) flooding increases stress on infrastructure, ecosystems, and populations; 2) warming temperatures affect human health and bring about temporal and geographic shifts in the natural environment and landscapes; and 3) wildfires and growing wildfire risk create challenges for natural resource managers and impacted communities.

The Southeast includes vast expanses of coastal and inland low-lying areas, the southern (and highest) portion of the Appalachian Mountains, numerous high-growth metropolitan areas, and large rural expanses. Embedded in these land- and seascapes is a rich cultural history developed over generations by the many communities that call this region home. However, these beaches and bayous, fields and forests, and cities and small towns are all at risk from a changing climate. These risks vary in type and magnitude from place to place, and while some climate change impacts, such as sea level rise and extreme downpours, are being acutely felt now, others, like increasing exposure to dangerously high temperatures—often accompanied by high humidity—and new local diseases, are expected to become more significant in the coming decades. While all regional residents and communities are potentially at risk for some impacts, some communities or populations are at greater risk due to their locations, services available, and economic situations. In fact, a recent economic study using a higher scenario (RCP8.5)[11] suggests that the southern and midwestern populations are likely to suffer the largest losses from projected climate changes in the United States. According to the article, "[b]ecause losses are largest in regions that are already poorer on average, climate change tends to increase preexisting inequality in the United States."[11] Understanding the demographic and socioeconomic composition of racial and ethnic groups in the region is important, because these characteristics are associated with health risk factors, disease prevalence, and access to care, which in turn may influence the degree of impact from climate-related threats.

Historical Climate and Possible Future Climates

The Southeast region experienced high annual average temperatures in the 1920s and 1930s, followed by cooler temperatures until the 1970s. Since then, annual average temperatures have warmed to levels above the 1930s; the decade of the 2010s through 2017 has been warmer than any previous decade (App 5: FAQs, Figure A5.14), both for average daily maximum and average daily minimum temperature. Seasonal warming has varied. The decade of the 2010s through 2017 is the warmest in all seasons for average daily minimum temperature and in winter and spring for average daily maximum temperature. However, for average daily maximum temperature, the summers of the 1930s and 1950s and the falls of the 1930s were warmer on average. The southeastern United States is one of the few regions in the world that has experienced little overall warming of daily maximum temperatures since 1900. The reasons for this have been the subject of much research, and hypothesized causes include both human and natural influences.[13,14,15,16,17] However, since the early 1960s, the Southeast has been warming at a similar rate as the rest of the United States (Ch.

2: Climate, Figure 2.4). During the 2010s, the number of nights with minimum temperatures greater than 75°F was nearly double the long-term average for 1901–1960 (Figure 19.1), while the length of the freeze-free season was nearly 1.5 weeks greater than any other period in the historical record (Figure 19.2). These increases were widespread across the region and can have important effects on both humans and the natural environment.[18] By contrast, the number of days above 95°F has been lower since 1960 compared to the pre-1960 period, with the highest numbers occurring in the 1930s and 1950s, both periods of severe drought (Figure 19.1). The differing trends in hot days and warm nights reflect the seasonal differences in average daily maximum and average daily minimum temperature trends.

Historical Changes in Hot Days and Warm Nights

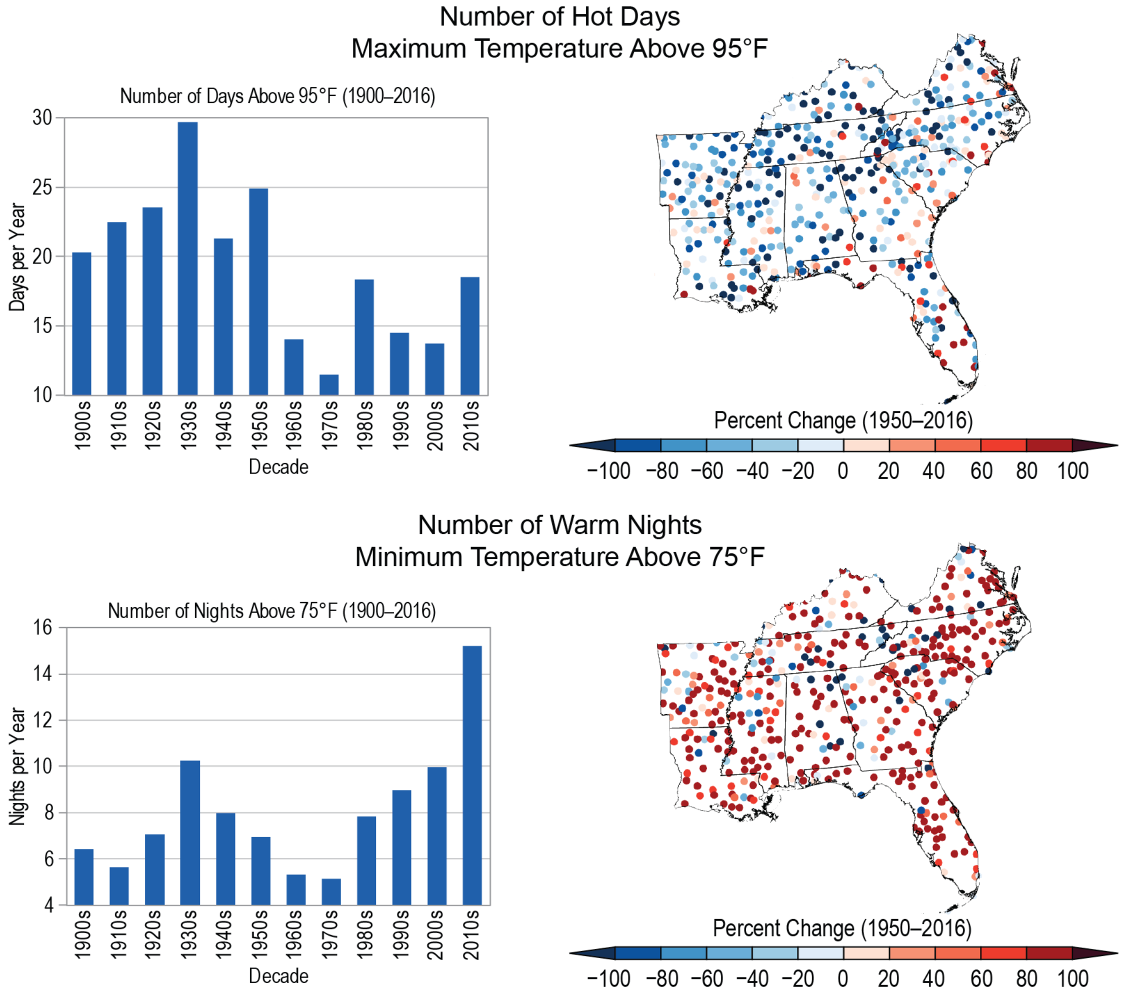


Figure 19.1: Sixty-one percent of major Southeast cities are exhibiting some aspects of worsening heat waves, which is a higher percentage than any other region of the country.[12] Hot days and warm nights together impact human comfort and health and result in the need for increased cooling efforts. Agriculture is also impacted by a lack of nighttime cooling. Variability and change in (top) the annual number of hot days and (bottom) warm nights are shown. The bar charts show averages over the region by decade for 1900–2016, while the maps show the trends for 1950–2016 for individual weather stations. Average summer temperatures during the most recent 10 years have been the warmest on record, with very large increases in nighttime temperatures and more modest increases in daytime temperatures, as indicated by contrasting changes in hot days and warm nights. (top left) The annual number of hot days (maximum temperature above 95°F) has been lower since 1960 than the average during the first half of the 20th century; (top right) trends in hot days since 1950 are generally downward except along the south Atlantic coast and in Florida due to high numbers during the 1950s but have been slightly upward since 1960, following a gradual increase in average daytime maximum temperatures during that time. (bottom left) Conversely, the number of warm nights (minimum temperature above 75°F) has doubled on average compared to the first half of the 20th century and (bottom right) locally has increased at most stations. Sources: NOAA NCEI and CICS-NC.

Historical Change in Freeze-Free Season Length

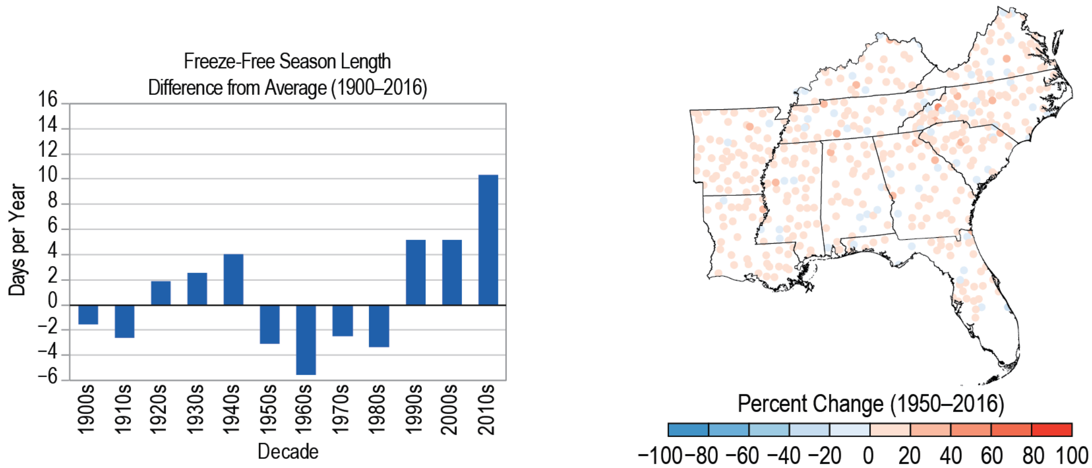


Figure 19.2: The figure shows the variability and change in the length of the freeze-free season. (left) The bar chart shows differences in the length of the freeze-free season by decade (1900–2016) as compared to the long-term average for the Southeast. (right) The map shows trends over 1950–2016 for individual weather stations. The length of the freeze-free season has increased at most stations, particularly since the 1980s. Sources: NOAA NCEI and CICS-NC.

Historical Change in Heavy Precipitation

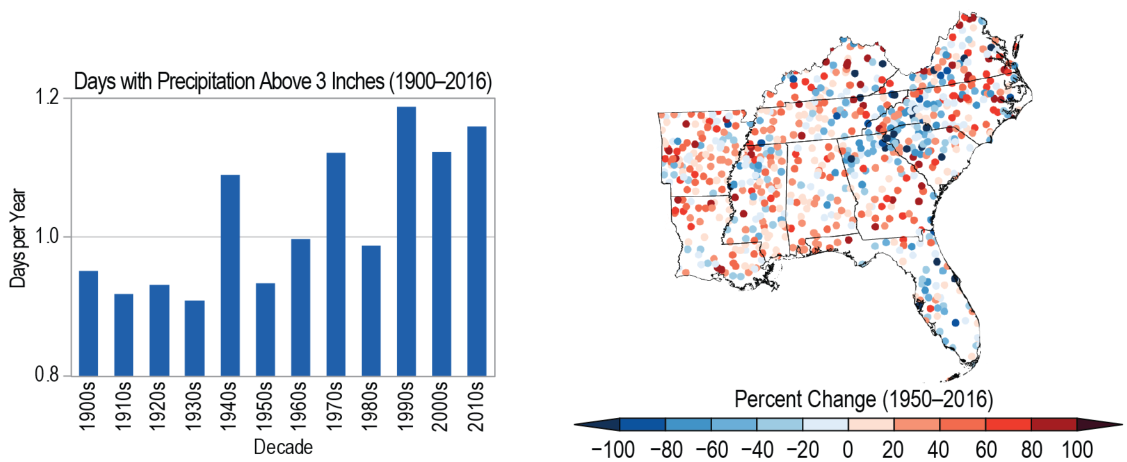


Figure 19.3: The figure shows variability and change in (left) the annual number of days with precipitation greater than 3 inches (1900–2016) averaged over the Southeast by decade and (right) individual station trends (1950–2016). The numbers of days with heavy precipitation has increased at most stations, particularly since the 1980s. Sources: NOAA NCEI and CICS-NC.

The number of extreme rainfall events is increasing. For example, the number of days with 3 or more inches of precipitation has been historically high over the past 25 years, with the 1990s, 2000s, and 2010s ranking as the decades with the 1st, 3rd, and 2nd highest number of events, respectively (Figure 19.3). More than 70% of precipitation recording locations show upward trends since 1950, although there are downward trends at many stations along and southeast of the Appalachian Mountains and in Florida (Figure 19.3).

Climate model simulations of future conditions project increases in temperature and extreme precipitation for both lower and higher scenarios (RCP4.5 and RCP8.5; see Figure 19.5).[13,19] After the middle of the 21st century, however, the projected increases are lower for the lower scenario (RCP4.5). Much larger changes are simulated by the late 21st century under the higher scenario (RCP8.5), which most closely tracks with our current consumption of fossil fuels. Under the higher scenario, nighttime minimum temperatures above 75°F and daytime maximum temperatures above 95°F become the summer norm and nights above 80°F and days above 100°F, now relatively rare occurrences, become commonplace. Cooling degree days (a measure of the need for air conditioning [cooling] based on daily average temperatures rising above a standard temperature—often 65°F) nearly double, while heating degree days (a measure of the need for heating) decrease by over a third (Figure 19.22). The freeze-free season lengthens by more than a month, and the frequency of freezing temperatures decreases substantially.[20,21]

Key Message 1

Urban Infrastructure and Health Risks

Many southeastern cities are particularly vulnerable to climate change compared to cities in other regions, with expected impacts to infrastructure and human health. The vibrancy and viability of these metropolitan areas, including the people and critical regional resources located in them, are increasingly at risk due to heat, flooding, and vector-borne disease brought about by a changing climate. Many of these urban areas are rapidly growing and offer opportunities to adopt effective adaptation efforts to prevent future negative impacts of climate change.

Rapid Population Shifts and Climate Impacts on Urban Areas

While the Southeast is historically known for having a rural nature, a drastic shift toward a more urbanized region is underway. The Southeast contains many of the fastest-growing urban areas in the country, including a dozen of the top 20 fastest-growing metropolitan areas (by percentage) in 2016.[22] Metropolitan Atlanta has been swiftly growing, adding 69,200 residents in just one year.[23] At the same time, many rural counties in the South are losing population.[24] These trends towards a more urbanized and dense Southeast are expected to continue, creating new climate vulnerabilities but also opportunities to adapt as capacity and resources increase in cities (Ch. 17: Complex Systems). In particular, coastal cities in the Southeast face multiple climate risks, and many planning efforts are underway in these cities. Adaptation, mitigation, and planning efforts are emphasizing "co-benefits" (positive benefits related to the reduction of greenhouse gases or implementation of adaptation efforts) to help boost the economy while protecting people and infrastructure.

Increasing Heat

Cities across the Southeast are experiencing more and longer summer heat waves. Nationally, there are only five large cities that have increasing trends exceeding the national average for all aspects of heat waves (timing, frequency, intensity, and duration), and three of these cities are in the Southeast region—Birmingham, New Orleans, and Raleigh. Sixty-one percent of major Southeast cities are exhibiting some aspects of worsening heat waves, which is a higher percentage than any other region of the country.[12] The urban heat island effect (cities that are warmer than surrounding rural areas, especially at night) adds to the impact of heat waves in cities (Ch. 5: Land Changes, KM 1). Southeastern cities including Memphis and Raleigh have a particularly high future heat risk.[25]

The number of days with high minimum temperatures (nighttime temperatures that stay above 75°F) has been increasing across the Southeast (Figure 19.1), and this trend is projected to intensify, with some areas experiencing more than 100 additional warm nights per year by the end of the century (Figures 19.4 and 19.5). Exposure to high nighttime minimum temperatures reduces the ability of some people to recover from high daytime temperatures, resulting in heat-related illness and death.[26] This effect is particularly pronounced in cities, many of which have urban heat islands that already cause elevated nighttime temperatures.[27] Cities are taking steps to prevent negative health impacts from heat. For example, the Louisville, Kentucky, metro government conducted an urban heat management study and installed 145,000 square feet of cool roofs as part of their goal to lessen the risk of climate change impacts.[28]

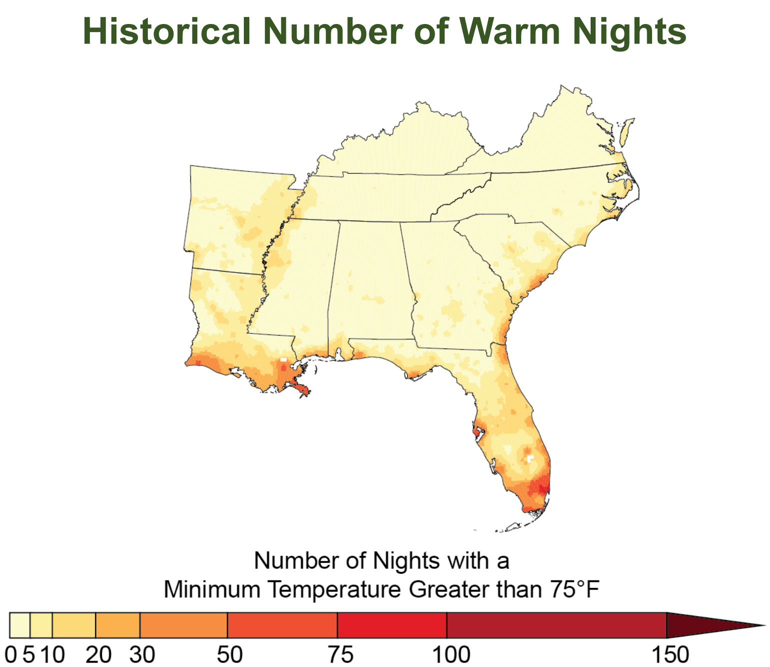


Figure 19.4: The map shows the historical number of warm nights (days with minimum temperatures above 75°F) per year in the Southeast, based on model simulations averaged over the period 1976–2005. Sources: NOAA NCEI and CICS-NC.

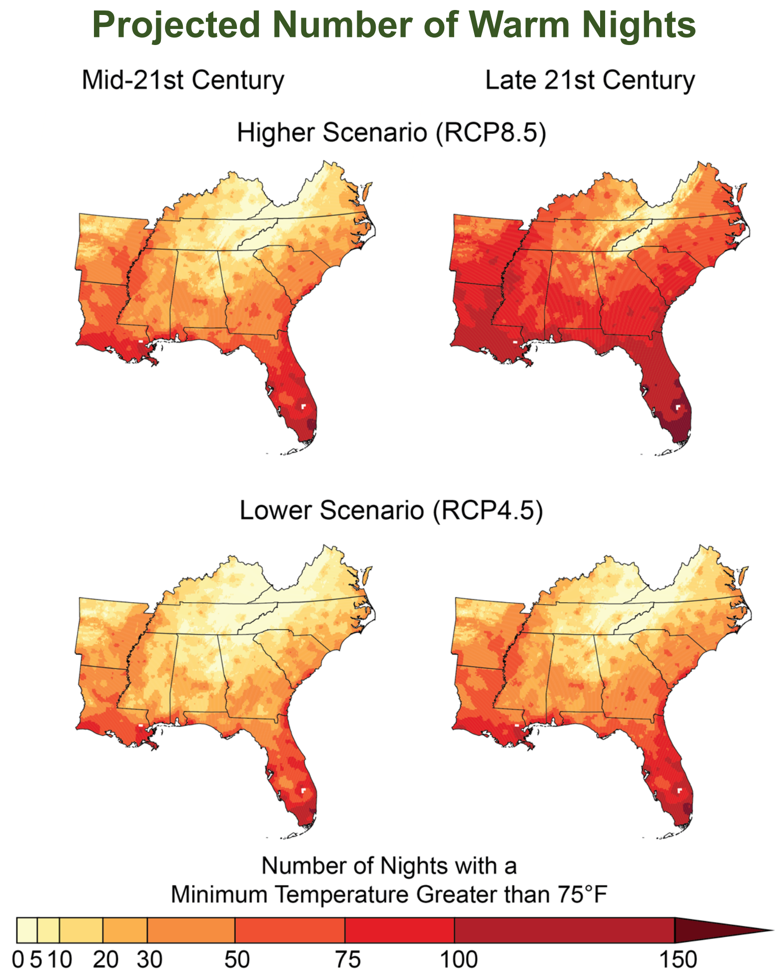


Figure 19.5: The maps show the projected number of warm nights (days with minimum temperatures above 75°F) per year in the Southeast for the mid-21st century (left; 2036–2065) and the late 21st century (right; 2070–2099) under a higher scenario (RCP8.5; top row) and a lower scenario (RCP4.5; bottom row). These warm nights currently occur only a few times per year across most of the region (Figure 19.4) but are expected to become common events across much of the Southeast under a higher scenario. Increases in the number of warm nights adversely affect agriculture and reduce the ability of some people to recover from high daytime temperatures. With more heat waves expected, there will likely be a higher risk for more heat-related illness and deaths. Sources: NOAA NCEI and CICS-NC.

Vector-Borne Disease

The transmission of vector-borne diseases, which are spread by the bite of an animal such as a mosquito or tick, is complex and depends on a number of factors, including weather and climate, vegetation, animal host populations, and human activities (Ch. 14: Human Health, KM 1). Climate change is likely to modify the seasonality, distribution, and prevalence of vector-borne diseases in the Southeast.[29] Vector-borne diseases pose a greater risk in cities than in rural areas because of higher population densities and other human factors (for example, pools of standing water in man-made structures, such as tires or buckets, are breeding grounds for some species of mosquitoes). Climatic conditions are currently suitable for adult mosquitoes of the species *Aedes aegypti*, which can spread dengue, chikungunya, and Zika viruses, across most of the Southeast from July through September (Figure 19.6), and cities in South Florida already have suitable conditions for year-round mosquito activity. The Southeast is the region of the country with the most favorable conditions for this mosquito and thus faces the greatest threat from diseases the mosquito carries.[30] Climate change is expected to make conditions more suitable for transmission of certain vector-borne diseases, including year-round transmission in southern

Florida. Summer increases in dengue cases are expected across every state in the Southeast. Despite warming, low winter temperatures may prevent permanent year-round establishment of the virus across the region.[31] Strategies such as management of urban wetlands have resulted in lower dengue fever risk in Puerto Rico.[32] Similar adaptation strategies have the potential to limit vector-borne disease in southeastern cities, particularly those cities with characteristics similar to Caribbean cities that have already implemented vector control strategies (Ch. 20: U.S. Caribbean).[33,34] The Southeast is also the region with the greatest projected increase in cases of West Nile neuroinvasive disease under both a lower and higher scenario (RCP4.5 and RCP8.5).[35,36]

Air Quality and Human Health

Poor air quality directly impacts human health, resulting in respiratory disease and other ailments. In the Southeast, poor air quality can result from emissions (mostly from vehicles and power plants), wildfires, and allergens such as pollen. The major urban centers in the Southeast are already impacted by poor air quality during warmer months. The Southeast has more days with stagnant air masses than other regions of the country (40% of summer days) and higher levels of fine (small) particulate matter ($PM_{2.5}$), which cause heart and lung disease.[37] There is mixed evidence on the future health impacts of these pollutants. Ozone concentrations would be expected to increase under higher temperatures; however, a variety of factors complicate projections (Ch. 13: Air Quality, KM 1). There are many possible future wind and cloud cover conditions for the Southeast as well as the potential for continued shifts in land-use patterns, demographics and population geography, and vehicle and power plant emissions standards. Increases in precipitation and shifts in wind trajectories may reduce future health impacts of ground level ozone in the Southeast,[35] but warmer and drier autumns are expected to result in a lengthening of the period of ozone exposure.[38] Warmer August temperatures in the Southeast from 1988 to 2011 were associated with increased human sensitivity to ground-level ozone.[39]

Potential Abundance of Disease-Carrying Mosquito

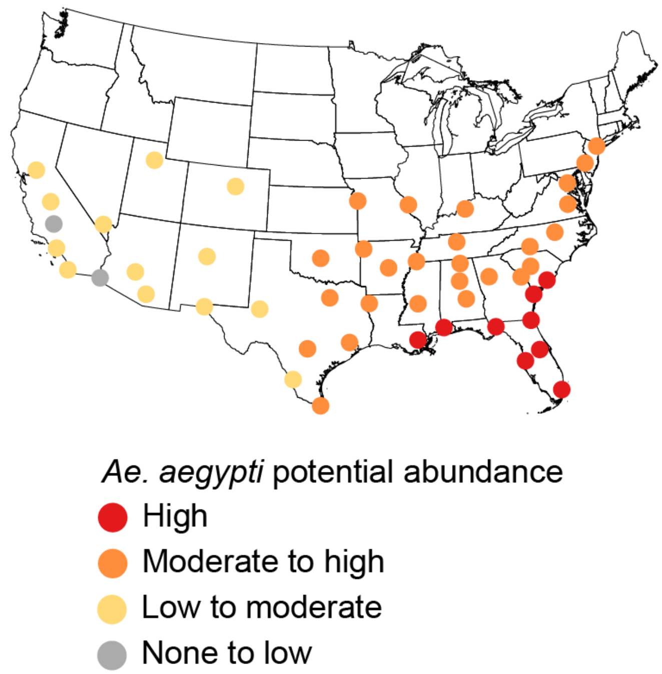


Figure 19.6: The map shows current suitability for the *Aedes aegypti* mosquito in July in 50 different cities. *Aedes aegypti* mosquitoes can spread several important diseases, including dengue fever, chikungunya, and Zika fever. The Southeast is the region of the country with the greatest potential mosquito activity. Warming temperatures have the potential to expand mosquito habitat and disease risk. Source: adapted from Monaghan et al. 2016.[30]

The fast growth rate of urban areas in the Southeast contributes to aeroallergens, which are known to cause and exacerbate respiratory diseases such as asthma. Urban areas have higher concentrations of CO_2, which causes allergenic plants, such as ragweed, to grow faster and produce more pollen than in rural areas.[40] Continued rising temperatures and atmospheric CO_2 levels are projected to further contribute to aeroallergens in cities (Ch. 13: Air Quality, KM 3).

Infrastructure

Infrastructure, particularly roads, bridges, coastal properties, and urban drainage, is vulnerable to climate change and climate-related events (see Key Message 2) (see also Ch. 3: Water, KM 2; Ch. 11: Urban, KM 2; Ch. 12: Transportation, KM 1).[41] By 2050, the Southeast is the region expected to have the most vulnerable bridges.[35] An extreme weather vulnerability assessment conducted by the Tennessee Department of Transportation found that the urban areas of Memphis and Nashville had the most at-risk transportation infrastructure in the state.[42] Increasing precipitation and extreme weather events will likely impact roads, freight rail, and passenger rail, especially in Memphis, which will likely have cascading effects across the region.[43] Transit infrastructure, such as the rail lines of the Metropolitan Atlanta Rapid Transit Authority (MARTA), are also at risk. As a result, MARTA has begun to identify vulnerable assets and prioritize improvements to develop a more resilient system.[44]

Many cities across the Southeast are planning for the impacts sea level rise is likely to have on their infrastructure (see Case Study "Charleston, South Carolina, Begins Planning and Reinvesting" and Key Message 2). Flood events in Charleston, South Carolina, have been increasing, and by 2045 the city is projected to face nearly 180 tidal floods (flooding in coastal areas at high tide) per year, as compared to 11 floods per year in 2014.[45] These floods affect tourism, transportation, and the economy as a whole. The city has responded by making physical modifications, developing a more robust disaster response plan, and improving planning and monitoring prior to flood events.

Infrastructure related to drinking water treatment and wastewater treatment may be compromised by climate-related events (Ch. 3: Water, KM 2). Water utilities across the Southeast are preparing for these impacts. Tampa Bay Water, the largest wholesale water utility in the Southeast, is coordinating with groups including the Florida Water and Climate Alliance to study the impact of climate change on its ability to provide clean water in the future.[46,47] Spartanburg Water, in South Carolina, is reinforcing the ability of the utility to "cope with, and recover from disruption, trends and variability in order to maintain services."[48] Similarly, the Seminole Tribe of Florida, which provides drinking and wastewater services, assessed flooding and sea level rise threats to their water infrastructure and developed potential adaptation measures.[49] The development of "green" water infrastructure (using natural hydrologic features to manage water and provide environmental and community benefits), such as the strategies promoted in the City of Atlanta Climate Action Plan, is one way to adapt to future water management needs. Implementation of these strategies has already resulted in a reduction in water consumption in the city of Atlanta, relieving strain on the water utility and increasing resilience.[50]

There are still gaps in knowledge regarding the potential effects of climate change on cities across the Southeast. Cross-disciplinary groups such as the Georgia Climate Project (http://www.georgiaclimateproject.org) are developing research roadmaps that can help to prioritize research and action with relevance to policymakers, practitioners, and scientists.

Key Message 2

Increasing Flood Risks in Coastal and Low-Lying Regions

The Southeast's coastal plain and inland low-lying regions support a rapidly growing population, a tourism economy, critical industries, and important cultural resources that are highly vulnerable to climate change impacts. The combined effects of changing extreme rainfall events and sea level rise are already increasing flood frequencies, which impacts property values and infrastructure viability, particularly in coastal cities. Without significant adaptation measures, these regions are projected to experience daily high tide flooding by the end of the century.

Sea Level Rise Is Contributing to Increased Coastal Flooding in the Southeast

Average global sea level (or global mean sea level; GMSL) has risen about 8–9 inches since 1880, with about 3 inches of that rise occurring since 1990.[51,52] This recent increase in the rate of rise is projected to accelerate in the future due to continuing temperature increases and additional melting of land ice.[51] This recent global rate increase, combined with the local effects of vertical land motion (sinking) and oceanographic effects such as changing ocean currents, has caused some areas in the Southeast to experience even higher local rates of sea level rise than the global average.[53,54,55,56,57,58,59] Analyses at National Oceanic and Atmospheric Administration (NOAA) tide gauges show as much as 1 to 3 feet of local relative sea level rise in the past 100 years in low-lying areas of the Southeast.[54,59] This recent rise in local relative sea level has caused normal high tides to reach critical levels that result in flooding in many coastal areas in the region.

Monthly and seasonal fluctuations in high tide levels are caused by a combination of astronomical factors (sun and moon gravitational attraction) and non-astronomical factors such as geomorphology (landscape of the area), as well as meteorological (weather) conditions. The highest tides of the year are generally the perigean, or spring, tides, which occur when the moon is full or new and is closest to the Earth. These perigean tides, also known as "king tides," occur twice a year and in many cities are causing what has been called "nuisance" or "recurrent" flooding (referred to herein as high tide flooding). These floods can cause problems ranging from inconvenient to life changing. While the challenges brought on by rising perigean tides are diverse, important examples include increasingly frequent road closures, excessive water in storm water management systems, and deterioration of infrastructure such as roads and rail from saltwater. NOAA's National Weather Service (NWS) issues coastal flood advisories and warnings when water levels at tide gauges are expected to exceed flood thresholds. These thresholds correspond to discrete water levels relative to NOAA tide gauges.

Recent analyses of historical water levels at many NOAA tide gauges has shown an increase in the number of times that these warning thresholds were exceeded compared to the past. Annual occurrences of high tide coastal flooding have increased 5- to 10-fold since the 1960s in several low-lying coastal cities in the Southeast (Figure 19.7).[51,60] In 2015, several Southeast coastal cities experienced all-time records of coastal flooding occurrences, including Wilmington, NC (90 days), Charleston, SC (38 days), Mayport, FL (19 days), Miami, FL (18 days), Key West, FL (14 days), and Fernandina Beach, FL (7 days). These flooding occurrences increased more than 50% in 2015 compared to 2014.[58] In 2016, three all-time records were either tied (14 days at Key West, FL) or broken (50 days at Charleston, SC, and 38 days at Savannah, GA). The Miami area nearly matched the 2015 record of 18 days.[61] This increase in high tide flooding frequency is directly tied to sea level rise. For example, in Norfolk, Virginia, local relative sea level rise has led to a fourfold increase in the probability of exceeding NWS thresholds compared to the 1960s (Figure 19.8). High tide flooding is now posing daily risks to businesses, neighborhoods, infrastructure, transportation, and ecosystems in the Southeast.[1,2]

Global sea level is very likely to rise by 0.3–0.6 feet by 2030, 0.5–1.2 feet by 2050, and 1.0–4.3 feet by 2100 under a range of scenarios from very low (RCP2.6) to high (RCP8.5),[51,52,62] which would result in increases in both the depth and frequency of coastal flooding (Figure 19.7).[51] Under higher emissions scenarios (RCP8.5), global sea level rise exceeding 8 feet (and even higher in the Southeast) by 2100 cannot be ruled out.[51] By 2050, many Southeast cities are projected to experience more than 30 days of high tide flooding regardless of scenario.[63] In addition, more extreme coastal flood events are also projected to increase in frequency and duration.[60] For example, water levels that currently have a 1% chance of occurring each year (known as a 100-year event) will be more frequent with sea level rise. This increase in flood frequency suggests the need to consider revising flood study techniques and standards that are currently used to design and build coastal infrastructure.

Higher sea levels will cause the storm surges from tropical storms to travel farther inland than in the past, impacting more coastal properties. The combined impacts of sea level rise and storm surge in the Southeast have the potential to cost up to $60 billion each year in 2050 and up to $99 billion in 2090 under a higher scenario (RCP8.5).[35] Even under a lower scenario (RCP4.5), projected damages are $56 and $79 billion in 2050 and 2090, respectively (in 2015 dollars, undiscounted).[35] Florida alone is estimated to have a 1-in-20 chance of having more than $346 billion (in 2011 dollars) in property value (8.7%) below average sea level by 2100 under a higher scenario (RCP8.5).[64] An assessment by the Florida Department of Health determined that 590,000 people in South Florida face "extreme" or "high" risk from sea level rise, with 125,000 people living in these areas identified as socially vulnerable and 55,000 classified as medically vulnerable.[65] In addition to causing direct injury, storm surge and related flooding can impact transportation infrastructure by blocking or flooding roads and affecting access to healthcare facilities (Ch. 12: Transportation, KM 1). Marine transportation can be impacted as well. Large ports in the Southeast, such as Charleston, Savannah, and Jacksonville, and the rails and roads that link to them, are particularly vulnerable to both coastal flooding and sea level rise (Ch. 12: Transportation, KM 1; Ch. 8: Coastal, KM 1). The Port of Jacksonville provides raw material for industries, food, clothes, and essential goods to Puerto Rico, thus impacting the U.S. Caribbean region, as well (Ch. 20: U.S. Caribbean, KM 3). It is estimated that with a meter (about 3.3 feet) of sea level rise, the Southeast would lose over 13,000 recorded historic and prehistoric archaeological sites and more than 1,000 locations currently eligible for inclusion on the National Register of Historic Places.[66] This includes many historic buildings and forts in cities like Charleston, Savannah, and St. Augustine.

Annual Number of High Tide Flooding Days

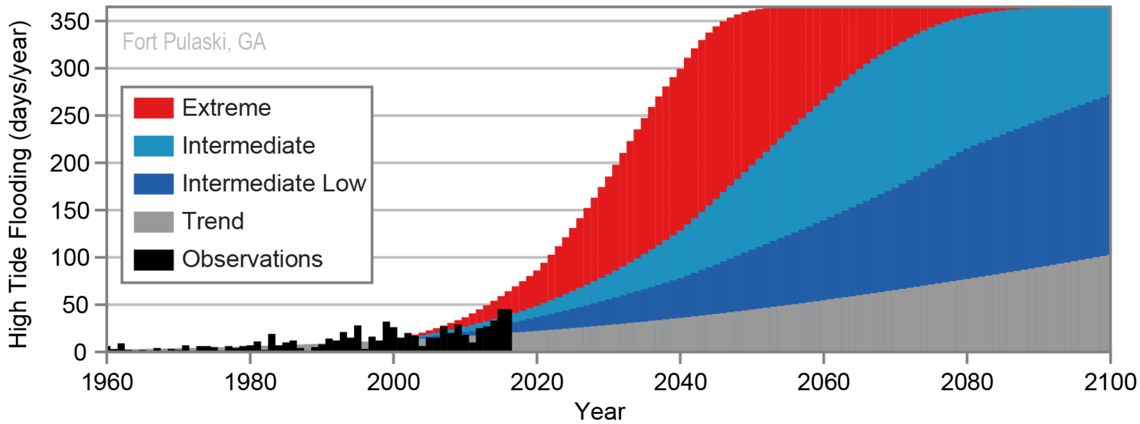


Figure 19.7: The figure shows the annual number of days experiencing high tide floods based on observations for 1960–2016 for Fort Pulaski, near Savannah, Georgia (black), and projected increases in the number of annual flood events based on four future scenarios: a continuation of the current relative sea level trend (gray) and the Intermediate-Low (dark blue), Intermediate (light blue), and Extreme (red) sea level rise scenarios. See Sweet et al. (2017)[51] and Appendix 3: Data & Scenarios for additional information on projection and trend data. Source: adapted from Sweet and Park 2014.[63]

Range of Daily Highest Water Levels in Norfolk, Virginia

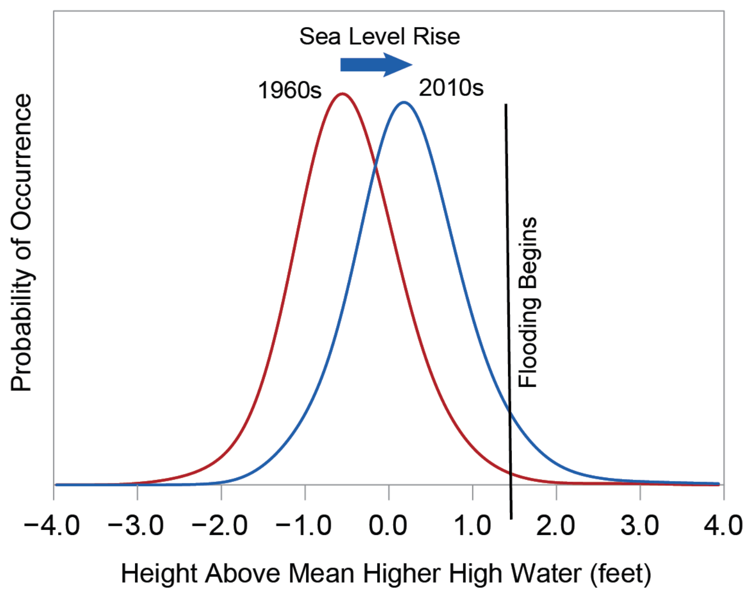


Figure 19.8: The curves in this figure show a range of daily Mean Higher High Water (MHHW) levels in Norfolk, Virginia (Sewells Point), for the 1960s and 2010s. Local sea level rise has shifted the curve closer to the point where high tide flooding begins (based on warning thresholds established by the National Weather Service). This shows why many more high tide flood events occur now than they did in the past (increase of 6 flood days per year). Source: adapted from Sweet et al. 2017.[52] *This figure was revised in June 2019. See Errata for details: https://nca2018.globalchange.gov/downloads*

Case Study: Charleston, South Carolina, Begins Planning and Reinvesting for Sea Level Rise

The main crosstown traffic artery in Charleston, South Carolina (U.S. 17 Septima Clark Parkway–crosstown), has historically been susceptible to flooding events (Figure 19.9). Charleston experienced all-time record high tide flood occurrences in 2015 (38 days) and 2016 (50 days).[52,58] By 2045, Charleston is projected to experience up to 180 high tide flood events a year.[1] The City of Charleston estimated that each flood event that affects the crosstown costs $12.4 million (in 2009 dollars). Over the past 50 years, the resultant gross damage and lost wages have totaled more than $1.53 billion (dollar year not specified). As a result, Charleston has developed a Sea Level Rise Strategy that plans for 50 years out based on moderate sea level rise scenarios (Figure 19.10) and that reinvests in infrastructure, develops a response plan, and increases readiness.[45] As of 2016, the City of Charleston has spent or set aside $235 million (in 2015 dollars) to complete ongoing drainage improvement projects (Figure 19.9) to prevent current and future flooding.

Figure 19.9: (left) U.S. Highway 17 (Septima Clark Parkway—crosstown) in Charleston, South Carolina, during a flood event. Floodwaters can get deep enough to stall vehicles. (right) Market Street drainage tunnel being constructed in Charleston, South Carolina, as part of a drainage improvement project to prevent current and future flooding. This tunnel crosses a portion of downtown Charleston 140 feet underground and is designed to rapidly convey storm water to the nearby Ashley River. Photo credit: City of Charleston 2015.[45]

Projected Sea Level Rise for Charleston, South Carolina

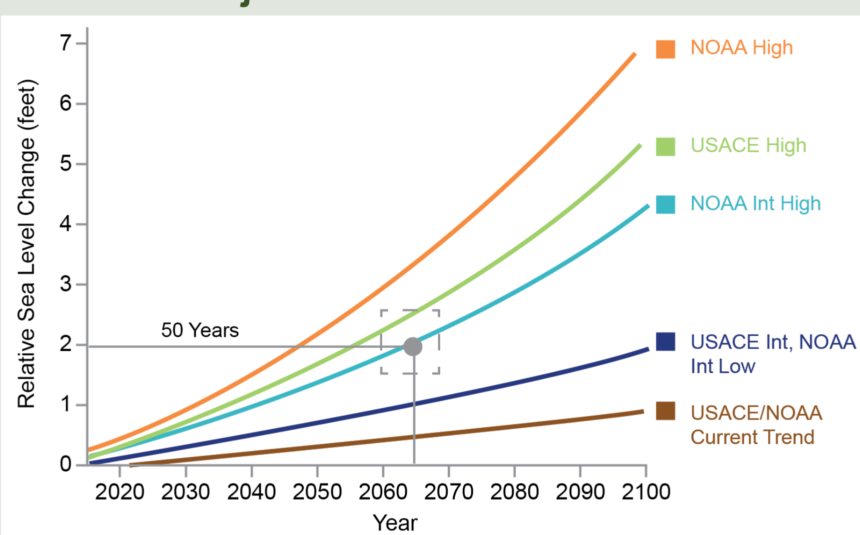


Figure 19.10: The City of Charleston Sea Level Rise Strategy calls for a 50-year outlook, based on existing federal sea level change projections in 2015 (colored curves), and calls for using a range of 1.5–2.5 feet of sea level rise (dashed box). A 1.5-foot increase will be used for short-term, less vulnerable investments, such as a parking lot. A 2.5-foot increase will be used for critical, longer-term investments, such as emergency routes and public buildings. This 1-foot range was chosen to approximate the average of these projections in 2065. Source: City of Charleston 2015.[45]

Many of the older historical coastal cities in the Southeast were built just above the current Mean Higher High Water (MHHW) level (the average height of the higher of the two daily high tides at a given location), with a gravity-driven drainage system designed to drain rainwater into the tidal estuaries. As sea levels have risen locally in the last one hundred years, the storm water systems in these areas are no longer able to perform as designed. When these cities experience high tide coastal flooding due to perigean tides, the tidewater enters the storm water system, which prevents rainwater from entering storm drains and causes increased impacts from flooding. In the future, the gravity-driven nature of many of these systems may cease to function as designed, causing rainwater to flood streets and neighborhoods until the tide lowers and water can drain normally. Cities such as Charleston and Miami have already begun to improve storm water infrastructure and explore natural and nature-based infrastructure design to reduce future flood risk.

Much of the Southeast region's coast is bordered by large expanses of salt marsh and barrier islands. Long causeways with intermittent bridges to connect the mainland to these popular tourism destinations were built decades ago at only a few feet above MHHW. Sea level rise has put these transportation connection points at risk. High tide coastal flooding has started to inundate these low-lying roads, restricting access during certain times of the day and causing public safety concerns. The U.S. East Coast, for example, already has 7,508 miles of roadways, including over 400 miles of interstate roadways, currently threatened by high tide coastal flooding (Ch. 12: Transportation, KM 1 and Figure 12.2).

Sea level rise is already causing an increase in high tide flood events in the Southeast region and is adding to the impact of more extreme coastal flooding events. In the future, this flooding is projected to become more serious, disruptive, and costly as its frequency, depth, and inland extent grow with time (Ch. 12: Transportation, KM 1).[52,63,67,68]

Case Study: A Lesson Learned for Community Resettlement: Isle de Jean Charles Band of Biloxi-Chitimacha-Choctaw Tribe

Coastal communities in the Southeast are already experiencing impacts from higher temperatures, sea level rise, increased flooding, and extreme weather events.[69,70,71,72] Several communities in the United States are already discussing the complexities of relocation; most are tribal and Indigenous communities.[73] Some have chosen to stay in their homelands, while others have few options but to relocate (Ch. 15: Tribes, KM 3).

Isle de Jean Charles is a narrow island in the bayous of South Terrebonne Parish, Louisiana, and home to the Isle de Jean Charles Band of Biloxi-Chitimacha-Choctaw, a tribal community already living the day-to-day impacts of land loss, sea level rise, and coastal flooding. The island has lost 98% of its landmass since 1955 and has only approximately 320 acres (approximately 1/2 square mile) remaining. The population living on the Island has fallen from 400 to 85 people. The decline is due in large part to land loss and flooding driven by climate change, extreme weather, and unsustainable development practices, which stem from oil and gas production, extraction, and water-management practices.[74] This process has resulted in family separation, spreading them across southern Louisiana.[75] In addition, the Tribe continues to lose parts of its livelihood and culture, including sacred places, cultural sites and practices, healing plants, traditional foods, and lifeways.[76]

Case Study: A Lesson Learned for Community Resettlement: Isle de Jean Charles Band of Biloxi-Chitimacha-Choctaw Tribe, *continued*

The Third National Climate Assessment[77] discussed the initial plans for resettlement of the Isle de Jean Charles community. Recently, after nearly 20 years of tribal persistence and two previous efforts, the U.S. Department of Housing and Urban Development (HUD) through the National Disaster Resilience Competition,[78] along with technical assistance from The Rockefeller Foundation, awarded the State of Louisiana $48 million (in 2016 dollars) to implement the Tribe's resettlement plan: a community-driven, culturally appropriate, sustainable development-based plan. It was developed in partnership with the Lowlander Center, a local nongovernmental organization with a long-standing relationship with the Tribe and other scientists, researchers, and planners. The award provides the Tribe with a historic opportunity to reunite a community.[79] While the application to relocate was initiated by the Tribe, the relocation funds now are for all residents of Isle de Jean Charles, according to the Louisiana State Office of Community Development.[75]

Figure 19.11: Chantel Comardelle, Isle de Jean Charles Tribe's Executive Secretary, leads a discussion at a community meeting for the Tribe's resettlement planning process in Pointe-aux-Chenes, Louisiana, on January 18, 2016. The meeting was supported by the Lowlander Center. Photo credit: The Lowlander Center Team.

The resettlement plan is expected to be implemented by 2022 with the inclusion of many facilities in the new location to revitalize the tribal community, including a tribal center and a healthcare facility. The Tribe's experience highlights how success can be achieved when at-risk communities are engaged in the resettlement planning process from the beginning to ensure long-term successful relocation and maintain community integrity.[80] It also highlights an opportunity for institutions to evolve in more flexible ways to accommodate the growing number of communities that may need to relocate.

Extreme Rainfall Events Are Contributing to Increased Inland and Coastal Flooding

Extreme rainfall events have increased in frequency and intensity in the Southeast, and there is *high confidence* they will continue to increase in the future (Figure 19.3).[19] The region, as a whole, has experienced increases in the number of days with more than 3 inches of precipitation (Figure 19.3) and a 16% increase in observed 5-year maximum daily precipitation (the amount falling in an event expected to occur only once every 5 years).[19] Both the frequency and severity of extreme precipitation events are projected to continue increasing in the region under both lower and higher scenarios (RCP4.5 and RCP8.5). By the end of the century under a higher scenario (RCP8.5), projections indicate approximately double the number of heavy rainfall events (2-day precipitation events with a 5-year return period) and a 21% increase in the amount of rain falling on the heaviest precipitation days (days with a 20-year return period).[19,81] These projected increases would directly affect the vulnerability of the Southeast's coastal and low-lying areas. Natural resources (see Key Message 3), industry, the local economy, and the population of the region are at increasing risk to these extreme events.

Across the Southeast since 2014, there have been numerous examples of intense rainfall events—many approaching levels that would be expected to occur only once every 500 years[82,83]—that have made state or national news due to the devastating impact they had on inland communities. Of these events, four major inland flood events have occurred in just three years (2014–2016) in the Southeast, causing billions of dollars in damages and loss of life (see Table 19.1 and Case Study "Coastal and Inland Impacts of Extreme Rainfall").[84]

A closer look at the August 2016 event in Louisiana provides an example of how vulnerable inland communities in the Southeast region are to these extreme rainfall events. Between August 11–15 2016, nearly half of southern Louisiana received at least 12–14 inches of rainfall. While urban areas such as Baton Rouge and Lafayette were hit the hardest, receiving upwards of 30 inches in a few days, coastal locations were also inundated with up to 20 inches of rain. Rainfall totals across the region exceeded amounts that would be expected to occur once every 1,000 years (or a less than 0.1% annual probability of occurrence), causing the Amite and Comite Rivers to surge past their banks and resulting in some 50,000 homes across the region filling with more than 18 inches of water.[85] Nearly 10 times the number of homes received major flooding (18 inches or more) during this event compared to a historic 1983 flood in Baton Rouge, and the damage resulted in more than 2 million cubic yards of curbside debris from cleaning up homes (enough to fill over 600 Olympic-sized pools).[86] A preceding event in northern Louisiana on March 8–12, 2016, caused $2.4 billion in damages (in 2017 dollars; $2.3 billion in 2015 dollars) and five casualties,[84] illustrating that inland low-lying areas in the Southeast region are also vulnerable to flooding impacts. Events of such magnitudes are projected to become more likely in the future due to a changing climate,[19,87] putting more people in peril from future floods. Existing flood map boundaries do not account for future flood risk due to the increasing frequency of more intense precipitation events, as well as new development that would reduce the floodplain's ability to manage storm water. As building and rebuilding in flood-prone areas continue, the risks of the kinds of major losses seen in these events will continue to grow.

The growing number of extreme rainfall events is stressing the deteriorating infrastructure in the Southeast. Many transportation and storm water systems have not been designed to withstand these events. The combined effects of rising numbers of high tide flooding and extreme rainfall events, along with deteriorating storm water infrastructure, are increasing the frequency and magnitude of coastal and lowland flood events.[45,88,89,90]

Billion-Dollar Flood Events in the Southeast, 2014–2016

Event	Date	Damages	Casualties
Southeast tornadoes and flooding (FL, AL, AR)	April 27–28, 2014	$1.8 Billion	33
South Carolina record flooding	October 1–5, 2015	$2.1 Billion	25
Hurricane Matthew	October 7–9, 2016	$10.1 Billion	49
Louisiana flooding (Baton Rouge)	August 11–15, 2016	$10.1 Billion	13

Table 19.1: Values are Consumer Price Index adjusted and are in 2017 dollars. Source: NOAA NCEI 2017.[84]

The recent increases in flood risk have led many cities and counties to take adaptive actions to reduce these effects. Four counties in Southeast Florida formed a climate compact in 2010 to address climate change impacts, including sea level rise and high tide flooding.[91] Recently updated in 2017, their climate action plan was one of the first intergovernmental collaborations to address climate change, adaptation, and mitigation in the country. Since then, cities like Charleston, South Carolina, have started to invest in flood management activities (see Case Study "Charleston, South Carolina, Begins Planning and Reinvesting"). Other examples include Miami Beach, Florida, which has a multiyear, $500-million program to raise public roads and seawalls and improve storm water drainage.[92] Norfolk, Virginia, has begun comprehensive planning to fix its high tide flooding issues.[93] Biloxi, Mississippi, has put in place several adaptation strategies to lessen the future impacts, including enacting a new building code that requires elevating structures an additional one foot above the base flood elevation.[94] Tybee Island, Georgia, has developed a sea level rise adaptation plan with recommendations to flood-proof a 5.5-mile stretch of their sole access causeway, replace two vulnerable bridges, and retrofit their existing storm water infrastructure to improve drainage.[95] In response to the 2016 flooding, eight parishes in the Acadiana region of Louisiana came together to collaborate at a watershed level, pooling their federal hazard mitigation grant funding to support projects across the Teche-Vermilion watershed. This is the only watershed-level hazard mitigation collaboration of this kind happening in the state and has the support of the Federal Emergency Management Agency (FEMA), the Governor's Office of Homeland Security and Emergency Preparedness, and the Louisiana Office of Community Development.[96]

Many communities in the Southeast also participate in FEMA's Community Rating System (CRS) program, which provides reduced flood insurance premiums to communities that go above and beyond the minimum National Flood Insurance Program regulation standards.[97] Many communities require a safety factor, also known as freeboard, expressed as feet above the base flood elevation, for construction in special flood hazard areas. Several Southeast communities—such as Hillsborough and Pinellas Counties, Florida; Biloxi, Mississippi; Chatham County, Georgia; and Myrtle Beach, South Carolina—have earned low CRS classes (5 on a scale of 1–10, with 1 being the best or most insurance premium discount) by implementing freeboard and other regulations that exceed the minimum standards.[97]

Case Study: Coastal and Inland Impacts of Extreme Rainfall

In October 2015, an extreme rainfall event impacted both inland and coastal South Carolina, leading to the largest flood-related disaster in the state since Hurricane Hugo struck in 1989. The October 2015 event is among a series of devastating precipitation events that have occurred across the Southeast in recent years. From October 1–5, 2015, deep tropical moisture combined with a slow-moving (stalled) upper-level low pressure system to pump moisture into South Carolina's coastal and interior regions. Much of the affected region received between 10 and 26 inches of rain over the 4-day event, breaking many all-time precipitation records (Figure 19.12). Mount Pleasant, located on South Carolina's coast, received 26.88 inches of rain, which is an extremely rare event. The rainfall sparked inland flooding that led to three dam breaches and the destruction of countless roads and homes (see Figure 19.13 showing flash flooding impacts to inland roads). Roughly 52,000 residents applied for disaster relief, and 160,000 homes sustained some type of damage. At the coast, a combination of high tide and heavy rain caused significant flooding in downtown Charleston. A high tide of 2.38 feet above Mean Higher High Water (MHHW) occurred in the afternoon of October 3. This was the seventh highest tide ever recorded in Charleston Harbor and the highest since Hurricane Hugo in 1989. Under future climate scenarios, the combination of extreme precipitation and higher tides due to local sea level rise will likely cause more frequent events of this intensity and magnitude.[98]

Case Study: Coastal and Inland Impacts of Extreme Rainfall, *continued*

October 2015 Extreme Rainfall Event

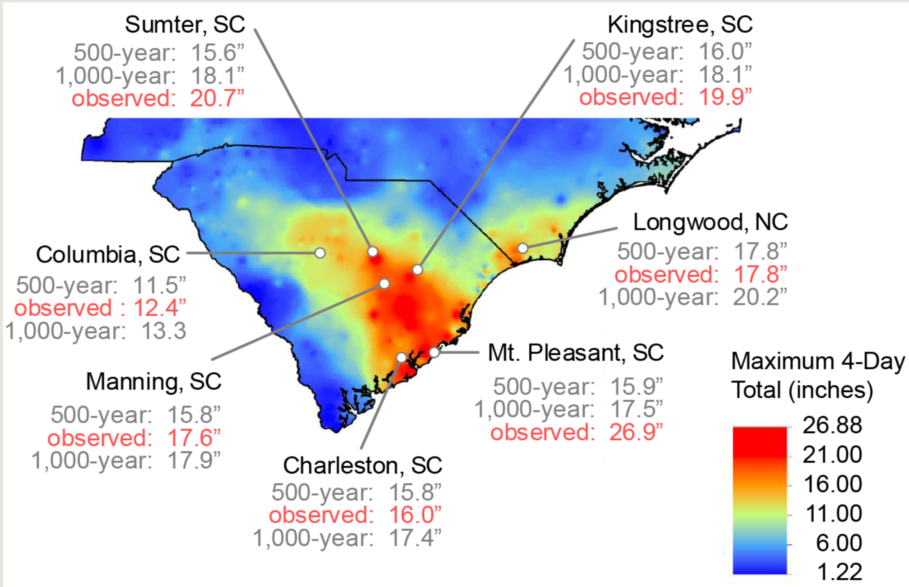


Figure 19.12: The map shows rainfall totals from the October 2015 South Carolina flood event. Red colors in the map indicate areas that received excessive rainfall totals that broke all-time records. Some of these totals exceeded the 500-year and 1,000-year return period amounts (rainfall amounts that would be expected to have only a 0.2% or 0.1% chance of occurring in a given year). Extreme precipitation events will likely increase in frequency in the Southeast. Source: CISA 2015.[98]

Figure 19.13: Many roads became impassable in the inland areas of South Carolina as a result of the October 2015 extreme rainfall event. This photo shows a neighborhood in North Charleston after the event with knee-deep flooding. Photo credit: Ryan Johnson (CC BY-SA 2.0).

Increases in extreme rainfall events and high tide coastal floods due to future climate change could impact the quality of life of permanent residents as well as tourists visiting the low-lying and coastal regions of the Southeast. Recent social science studies have indicated that people may migrate from many coastal communities that are vulnerable to the impacts of sea level rise, high tide flooding, saltwater intrusion, and storm surge.[71] Even though many communities are starting to develop adaptation strategies to address current flooding issues, many adaptation strategies are not being designed for longer time horizons and more extreme worst-case climate scenarios.[1,67]

The 2017 Hurricane Season

For the United States, 2017 was a historic year for weather and climate disasters, with widespread impacts and lingering costs. While 2017 tied the previous record year of 2011 for the total number of billion-dollar weather and climate disasters—16—the year broke the all-time previous record high costs by reaching $306.2 billion in damages (in 2017 dollars; $297 billion in 2015 dollars). The previous record year was 2005 with a total of $214.8 billion (in 2017 dollars; $208.4 billion in 2015 dollars), which included the impacts of Hurricanes Dennis, Katrina, Rita, and Wilma.[99]

In 2017, Hurricane Irma was one of three major hurricanes to make landfall in the United States and territories, with the most significant impacts occurring in the Southeast region. Irma was a Category 4 storm with 130 mph wind speeds when it made landfall at Cudjoe Key, Florida (20 miles north of Key West). Storm surge inundations at Cudjoe and the surrounding Keys were between 5 and 8 feet.[100] Prior to landfall in Florida, Irma caused significant damage in the U.S. Virgin Islands and parts of Puerto Rico as a Category 5 hurricane with 185 mph wind speeds (see Ch. 20: U.S. Caribbean, Box 20.1 and KM 5).[84]

Irma's intensity was impressive by any measure. According to the National Weather Service, Hurricane Irma was only the fifth hurricane with winds of 185 mph or higher in the whole of the Atlantic Basin since reliable record keeping began, and it was the strongest observed hurricane in the open Atlantic Ocean.[101] For three days, the storm maintained maximum sustained winds of 185 miles per hour, the longest observed duration in the satellite era.[101,102] Not only was Irma extremely strong, it was also very large with tropical storm force winds reaching as far away as 400 miles from the hurricane's center and driving hurricane force winds up to 80 miles away.[101] Two factors supported Irma's strength: the very warm waters it passed over, which exceeded 86°F,[102] and the light winds Irma encountered in the upper atmosphere (Figure 19.14).[101] High-intensity hurricanes such as Irma are expected to become more common in the future due to climate change.[103] Rapid intensification of storms is also more likely as the climate warms,[104] even though there is also some historical evidence that the same conditions that lead to this intensification also act to weaken hurricane intensity near the U.S. coast, but it is unclear whether this relationship will continue as the climate warms further (see Kossin et al. 2017,[103] Box 9.1).

The storm tracked up the west coast of Florida, impacting both coasts of the Florida peninsula with 3–5 feet of inundation from Cape Canaveral north to the Florida–Georgia border and even further, impacting coastal areas of Georgia and South Carolina with high tides and storm surge that reached 3–5 feet. Inland areas were also impacted by winds and heavy rains with river gauges and high-water marks showing upwards of 2–6 feet above ground level.[100] The winds eventually fell below tropical storm strength near Columbus, Georgia. Even though the wind speed fell below tropical storm strength, many communities along the coasts of Florida, Georgia, North and South Carolina, and Virginia experienced severe wind and storm surge damage with some near-historic levels of coastal flooding. A state of emergency was declared in four states from Florida north to Virginia and in Puerto Rico and the U.S. Virgin Islands, and, for the first time ever, Atlanta was placed under a tropical storm warning.[105,106,107,108] In Florida, a record 6.8 million people were ordered to evacuate, as were 540,000 coastal residents in Georgia and untold numbers in other coastal locations.[102,109,110] Nearly 192,000 evacuees were housed in approximately 700 emergency shelters in Florida alone.[109] According to NOAA's National Centers for Environmental Information (NCEI),[84] Irma significantly damaged 65% of the buildings in the Keys and destroyed 25% of them.

Warm Waters Contribute to the Formation of Hurricane Irma

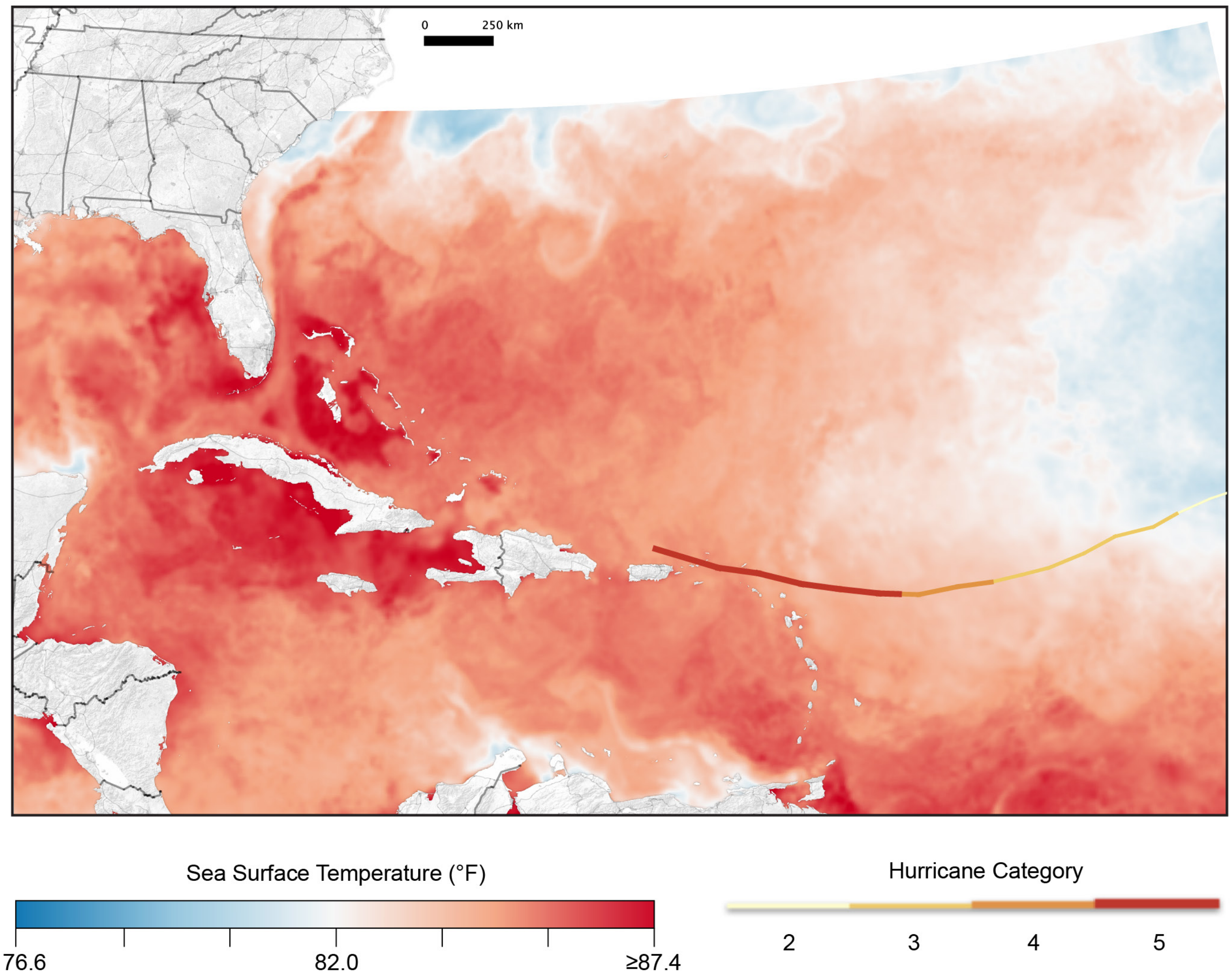


Figure 19.14: Two factors supported Hurricane Irma's strength as it reached the Southeast region: the very warm waters it passed over, depicted in this figure, and the light winds Irma encountered in the upper atmosphere.[101] High-intensity hurricanes such as Irma are expected to become more common in the future due to climate change.[103] Source: NASA 2017.[102]

High rainfall totals were experienced in many impacted areas, with Fort Pierce, Florida, receiving the highest rainfall of more than 21.5 inches[100] and the Florida Keys receiving 12 inches of rain.[84,102] Flooding occurred on most rivers in northern Florida and in many rivers in both Georgia and South Carolina to the point that rescues were required. In Jacksonville, Florida, heavy rains were the major issue causing rivers to reach major or record flood stage and flooded some city streets up to 5 feet deep in water. The heavy rainfall was noted even in Alabama, at 5 inches, and near 6 inches in the mountains of western North Carolina.[100] Twenty-five tornadoes were confirmed from Hurricane Irma, and many of them occurred along the east coast of central and northern Florida.[100] Even as Irma headed north, continuing to lose force, there were still 6.7 million people without electricity.[109]

According to NCEI,[84] the U.S. direct cost from Hurricane Irma is approximately $50 billion (in 2017 dollars), and the non-U.S. territory Caribbean Islands could add another $10–$15 billion to that total. Of the $50 billion, approximately $30–$35 billion accounts for wind and flood damage to a combination of residential and commercial properties, automobiles, and boats—with 80%–90% of this cost felt in Florida. The remainder of the costs include $5 billion for infrastructure repairs and $1.5–$2.0 billion for damage to the agricultural sector, also mainly in Florida. The remaining costs would address losses in the U.S. Virgin Islands and Puerto Rico.[84] The losses could have been worse except for the fact that Florida has implemented one of the strictest building codes in the country after the destruction caused by Hurricane Andrew in 1992.[111] Recent estimates using insured loss data show that implementing the Florida Building Code resulted in a 72% reduction of windstorm losses, and for every $1 in added cost to implement the building code, there is a savings of $6 in reduced losses, with the return or payback period being roughly 8 years (in 2010 dollars).[111]

Indirect impacts and costs are difficult to calculate and would add to the totals. In Central and South Florida, such things would include the closing of schools, colleges, and universities; the closing of tourist attractions and the cancellation of thousands of flights into and out of region; and the closing or restricting of the use of seaports including Canaveral, Key West, Miami, and Jacksonville, among others.[109,112] The Select Committee on Hurricane Response and Preparedness: Final Report[109] estimates that there were 84 U.S. deaths attributable to Hurricane Irma and other untold damage and human suffering. While the hurricane directly damaged portions of the Southeast, the impacts could be felt around the country in the form of business interruptions (such as tourism), transportation and infrastructure damages (such as ports, roadways, and airports), increases in fuel costs, and $2.5 billion (in 2018 dollars) in total estimated crop losses,[109] which had the potential to impact the cost of food and other products for all Americans.

Key Message 3

Natural Ecosystems Will Be Transformed

The Southeast's diverse natural systems, which provide many benefits to society, will be transformed by climate change. Changing winter temperature extremes, wildfire patterns, sea levels, hurricanes, floods, droughts, and warming ocean temperatures are expected to redistribute species and greatly modify ecosystems. As a result, the ecological resources that people depend on for livelihood, protection, and well-being are increasingly at risk, and future generations can expect to experience and interact with natural systems that are much different than those that we see today.

Ecosystems in the Southeast span the transition zone between tropical and temperate climates. The region's more temperate ecosystems include hardwood forests, spruce-fir forests, pine-dominated forests, and salt marshes. The region's more tropical ecosystems include mangrove forests, coral reefs, pine savannas, and the tropical freshwater wetlands of the Everglades. Ecological diversity in the Southeast is high,[113,114,115,116,117] and southeastern ecosystems and landscapes provide many benefits to society. In addition to providing habitat for fish and wildlife species, ecosystems in the Southeast provide recreational opportunities, improve water quality, provide seafood, reduce erosion, provide timber, support food webs, minimize flooding impacts, and support high rates of carbon sequestration (or storage).[118,119,120] These ecological resources that people depend on for livelihoods, protection, and well-being are increasingly at risk from the impacts of climate change.

Climate greatly influences the structure and functioning of all natural systems (Ch. 7: Ecosystems). An analysis of ecological changes that have occurred in the past can help provide some context for anticipating and preparing for future ecological changes. In response to past climatic changes, many ecosystems in the Southeast were much different than those present today. For example, since the end of the last glacial maximum (about 19,000 years ago—the most recent period of maximum ice extent),[121] forests in the region have been transformed by warming temperatures, sea level rise, and glacial retreat.[122,123] Spruce species that were once present in the region's forests have moved northward and have been replaced by oaks and other less cold-tolerant tree species that have expanded from the south.[124] And along the coast, freeze-sensitive mangrove forests and other tropical coastal species have been expanding northward and upslope since the last glacial maximum.[125,126,127,128,129]

In the coming decades and centuries, climate change will continue to transform many ecosystems throughout the Southeast,[6,130,131,132,133,134,135] which would affect many of the societal benefits these ecosystems provide. As a result, future generations can expect to experience, interact with, and potentially benefit from natural systems that are much different than those that we see today (Ch. 7: Ecosystems).[136,137]

Warming Winter Temperature Extremes

Changes in winter air temperature patterns are one aspect of climate change that will play an especially important role in the Southeast. By the late 21st century under the higher scenario (RCP8.5), the freeze-free season is expected to lengthen by more than a month. Winter air temperature extremes (for example, freezing and chilling events) constrain the northern limit of many tropical and subtropical species.[138,139,140,141,142,143,144] Certain ecosystems in the region are located near thresholds where small changes in winter air temperature regimes can trigger comparatively large and abrupt landscape-scale ecological changes (in other words, ecological regime shifts).[135,145] Reductions in the frequency and intensity of cold winter air temperature extremes can allow tropical and subtropical species to move northward and replace more temperate species. Where climatic thresholds are crossed, certain ecosystem and landscapes will be transformed by changing winter air temperatures.

Plant hardiness zone maps help convey the importance of winter air temperature extremes for species and natural systems in the Southeast. To help gardeners and farmers, the U.S. Department of Agriculture has produced plant hardiness zone maps that can be used to determine which species are most likely to survive and thrive in a given location. The plant hardiness zones are reflective of the frequency and intensity of winter air temperature extremes in a specific region. Already, in response to climate change, plant hardiness zones in certain areas are moving northward and are expected to continue their northward and upslope progression.[139,142,146,147] Continued reductions in the frequency and intensity of winter air temperature extremes are expected to change which species are able to survive and thrive in a given location (Figure 19.15). For example, citrus species are sensitive to freezing and chilling temperatures.[148] However, in the future, climate change is expected to enable the survival of citrus in areas that are north of the current tolerance zone.[142]

The effects of changing winters reach far beyond just agricultural and garden plants. Along the coast, for example, warmer winter temperatures are expected to allow mangrove forests to move northward and replace salt marshes (Figures 19.16 and 19.17).[135,149,150,151,152]

Coastal wetlands, like mangrove forests and salt marshes, are abundant in the Southeast.[153,154] The societal benefits provided by coastal wetlands are numerous.[119] Hence, where coastal wetlands are abundant (for example, the Mississippi River Delta), their cumulative value can be worth billions of dollars each year and trillions of dollars over a 100-year period.[155] Coastal wetlands provide seafood, improve water quality, provide recreational opportunities, reduce erosion, support food webs, minimize flooding impacts, and support high rates of carbon sequestration.[118] Foundation species are species that create habitat and support entire ecological communities.[156,157] In coastal wetlands and many other ecosystems, foundation plant species play an especially important role. Hence, the loss and/or replacement of foundation plant species, like salt marsh grasses, will have ecological and societal consequences in certain areas.[135,145,157,158,159,160,161,162,163,164]

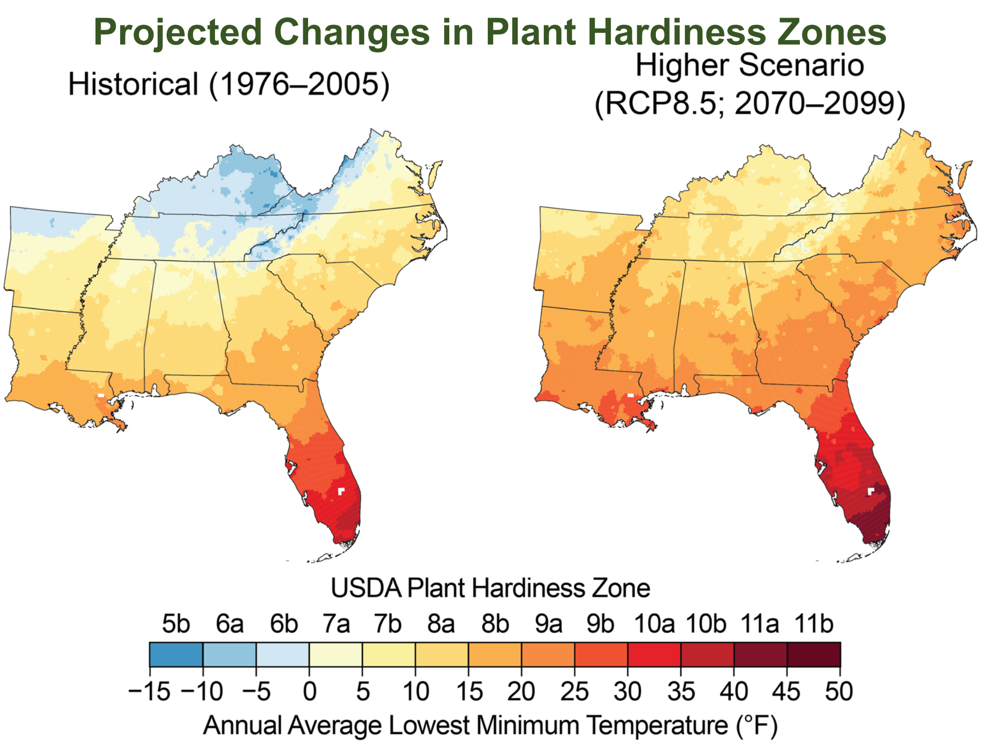


Figure 19.15: Increasing winter temperatures are expected to result in a northward shift of the zones conducive to growing various types of plants, known as plant hardiness zones. These maps show the mean projected changes in the plant hardiness zones, as defined by the U.S. Department of Agriculture (USDA), by the late 21st century (2070–2099) under a higher scenario (RCP8.5). The USDA plant hardiness zones are based on the average lowest minimum temperature for the year, divided into increments of 5°F. Based on these projected changes, freeze-sensitive plants, like oranges, papayas, and mangoes, would be able to survive in new areas.[142] Note that large changes are projected across the region, but especially in Kentucky, Tennessee, and northern Arkansas. Sources: NOAA NCEI and CICS-NC.

While salt marsh and mangrove wetlands both contain valuable foundation species, some of the habitat and societal benefits provided by existing salt marsh habitats will be affected by the northward expansion of mangrove forests.[145,158,160,161,164,165]

Salt Marsh Conversion to Mangrove Forest

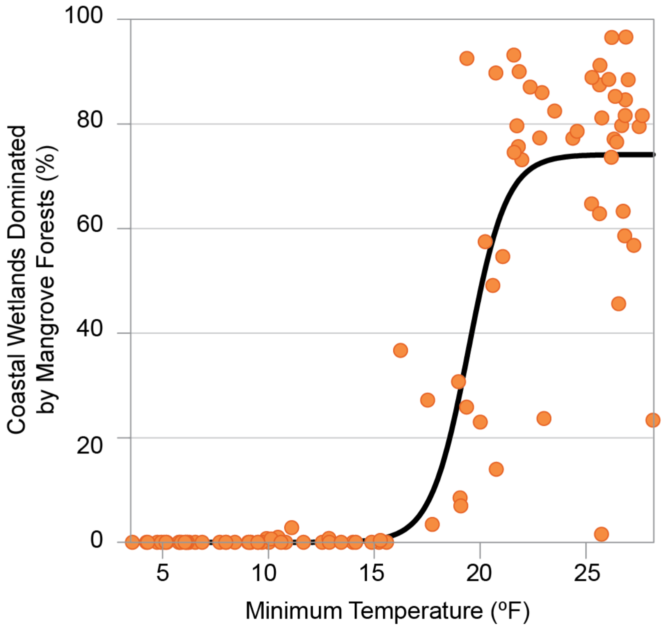


Figure 19.16: Where tropical and temperate ecosystems meet, warmer winter temperatures can lead to large ecological changes such as mangrove forest replacement of salt marshes along the Gulf and Atlantic Coasts. Mangrove forests are sensitive to freezing temperatures and are expected to expand northward at the expense of salt marshes. The figure shows the relationship between temperature and the percentage area dominated by mangrove forests. Mangrove expansion would entail a grassland-to-forest conversion, which would affect fish and wildlife habitat and many societal benefits. Source: adapted from Osland et al. 2013.[135] ©2012 Blackwell Publishing Ltd.

Transitioning Coastal Ecosystems

Figure 19.17: In Louisiana and parts of northern Florida, future coastal wetlands are expected to look and function more like the mangrove-dominated systems currently present in South Florida and the Caribbean. Like salt marshes (left), mangrove forests (right) provide coastal protection against wind and waves (Ch. 20: U.S. Caribbean, KM 2). Photo credit: Michael Osland.

In addition to plants, warmer winter air temperatures will also affect the movement and interactions between many different kinds of organisms. For example, certain insect species, including mosquitoes and tree-damaging beetles, are expected to move northward in response to climate change, which could affect human health and timber supplies.[30,144,166,167,168,169,170,171,172] And some bird species, including certain ducks, are not expected to migrate as far south in response to milder winters,[173] which could affect birding and hunting recreational opportunities. Many recreational fishery populations in tropical coastal areas are freeze-sensitive[138,174,175,176,177,178] and are, therefore, expected to move northward in response to warmer water and air temperatures. Although the appearance of tropical recreational fish, like snook for example, may be favorable for some anglers, the movement of tropical marine species is expected to greatly modify existing food webs and ecosystems (Ch. 7: Ecosystems, Figure 7.4).[179] Some problematic invasive species are expected to be favored by changing winters. For example, in South Florida, the Burmese python and the Brazilian pepper tree are two freeze-sensitive, nonnative species that have, respectively, decimated mammal populations and transformed native plant communities within Everglades National Park.[180,181,182,183,184,185,186,187,188] In the future, warmer winter temperatures are expected to facilitate the northward movement of these problematic invasive species, which would transform natural systems north of their current distribution.

Warm Winters Favor Invasive Species

Figure 19.18: Burmese pythons are apex predators (not preyed upon by other animals) that are sensitive to cold temperatures and are expected to be favored by warming winters. This photo is from Everglades National Park, where unintentionally introduced pythons have expanded and reduced native mammal populations. Photo credit: U.S. Geological Survey.

Changing Patterns of Fire

In the Southeast region, changing fire regimes (defined by factors including frequency, intensity, size, pattern, season, and severity) are expected to have a large impact on natural systems. Fire has historically played an important role in the region, and ecological diversity in many southeastern natural systems is dependent upon fire.[115,116,134,189] Although the total area burned by wildfire is greatest in the western United States, the Southeast has the largest area burned by prescribed fire (see Case Study "Prescribed Fire") and the highest number of wildfires.[134,190] In the future, rising temperatures and increases in the duration and intensity of drought are expected to increase wildfire occurrence and also reduce the effectiveness of prescribed fire.[3,4,5,6] Moreover, rapid urban expansion near managed forests has the potential to reduce opportunities to use prescribed fire, which could lead to native species declines, increased wildfire occurrence, and economic and health impacts.[134,191]

A recent example of the importance of fire lies in the forests of the southern Appalachians. Over the last century, invasive insects, logging, and pathogens have transformed forests in the region.[192] Warmer temperatures and insects have led to the loss of cold-adapted boreal communities, and flammable, fire-adapted tree species have been replaced by less flammable, fire-sensitive species—a process known as mesophication.[193,194] However, intense fires, like those observed in 2016, can halt the mesophication process. High temperatures, increases in accumulated plant material on the forest floor, and a four-month seasonal drought in the fall of 2016 collectively produced the worst wildfires the region has seen in a century. Intra-annual droughts, like the one in 2016, are expected to become more frequent in the future.[6] Thus, drought and greater fire activity[134] are expected to continue to transform forest ecosystems in the region (see Ch. 6: Forests, KM 1).

Case Study: Prescribed Fire

With wildfire projected to increase in the Southeast,[6,191] prescribed fire (the purposeful ignition of low-intensity fires in a controlled setting), remains the most effective tool for reducing wildfire risk.[4,195] Department of Defense (DoD) lands represent the largest reservoirs of biodiversity and native ecosystems in the region.[117] Military activities are a frequent source of wildfires, but increases in prescribed fire acres (Figure 19.19) show a corresponding decrease in wildfire ignitions for DoD.[4] Climate resilience by DoD is further achieved through restoration of native longleaf pine forests that occupy a wide range of site types, including wetland and well-drained soils—the latter leading many to characterize this forest as being drought resistant.[196,197,198,199] In addition to proactive adaptation through prescribed fire, DoD has been a leader in climate strategies that include regional conservation planning, ecosystem management, endangered species recovery, and research funding.

Wildlife and Prescribed Fire

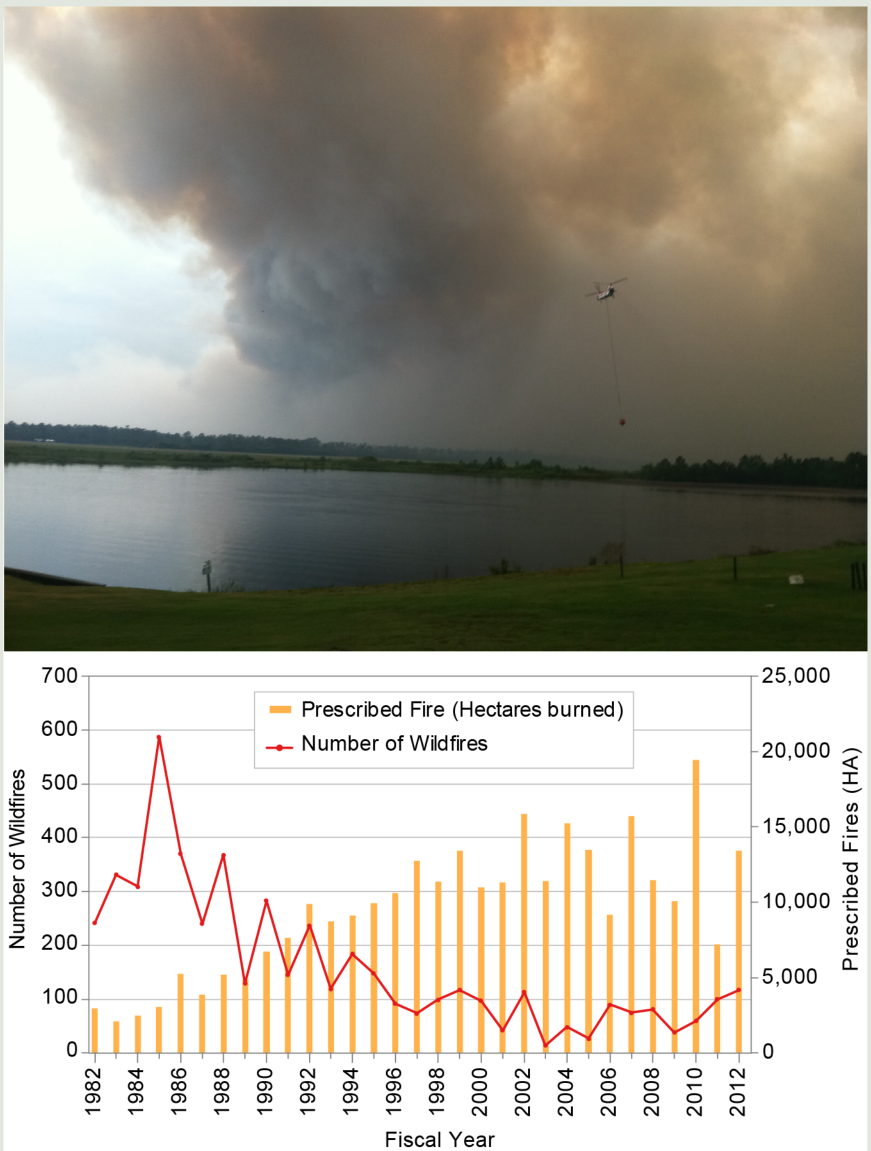


Figure 19.19: (top) A helicopter drops water on a 1,500-hectare wildfire on Hurlburt Field (Eglin Air Force Base) in Florida in June of 2012. (bottom) The increased use of prescribed fire at Ft. Benning, Georgia, led to a decrease in wildfire occurrence from 1982 to 2012. Photo credit: Kevin Hiers, Tall Timbers. Figure source: adapted from Addington et al. 2015.[4] Reprinted by permission of CSIRO Australia, ©CSIRO.

Rising Sea Levels and Hurricanes

Rising sea levels and potential changes in hurricane intensity are aspects of climate change that are expected to have a tremendous effect on coastal ecosystems in the Southeast (Ch. 8: Coastal, KM 2; Ch. 9: Oceans, KM 1). Since coastal terrestrial and freshwater ecosystems are highly sensitive to increases in inundation and salinity, sea level rise will result in the rapid conversion of these systems to tidal saline habitats. Historically, coastal ecosystems in the region have adjusted to sea level rise by vertical and horizontal movement across the landscape.[125,129,200,201] As sea levels rise in the future, some coastal ecosystems will be submerged and converted to open water, and saltwater intrusion will allow salt-tolerant coastal ecosystems to move inland at the expense of upslope and upriver ecosystems.[128,202,203,204,205,206,207,208] Where barriers are present (for example, levees and other coastal infrastructure), the potential for landward migration of natural systems will be reduced and certain coastal habitats will be lost (Ch. 20: U.S. Caribbean, KM 3).[204] With higher sea levels and increasing saltwater intrusion, the high winds, high precipitation rates, storm surges, and salts that accompany hurricanes will have large ecological impacts to terrestrial and freshwater ecosystems.[209,210]

An example of the effects of rising sea levels can be found in Louisiana, which faces some of the highest land loss rates in the world. The ecosystems of the Mississippi River Delta provide at least $12–$47 billion (in 2017 dollars) in benefits to people each year.[155] These benefits include hurricane storm protection, water supply, furs, habitat, climate stability, and waste treatment. However, between 1932 and 2016, Louisiana lost 2,006 square miles of land area (see Case Study "A Lesson Learned for Community Resettlement"),[211] due in part to high rates of relative sea level rise.[212,213,214,215] The rate of wetland loss during this period equates to Louisiana losing an area the size of one football field every 34 to 100 minutes.[211] To protect and restore the Louisiana coast, the Louisiana Coastal Protection and Restoration Authority (CPRA) has worked with local, state, and federal partners to iteratively develop a 2017 Coastal Master Plan that identifies investments that can provide direct restoration and risk reduction benefits.[216] The aim of the 50-year, $50-billion strategy is to sustain Louisiana's coastal ecosystems, safeguard coastal populations, and protect vital economic and cultural resources.[216]

Drought and Extreme Rainfall

Climate change is expected to intensify the hydrologic cycle and increase the frequency and severity of extreme events like drought and heavy rainfall. Drought and extreme heat can result in tree mortality and transform the region's forested ecosystems (Ch. 6: Forests, KM 1).[217,218,219,220,221,222,223] Drought can also affect aquatic and wetland ecosystems,[224] for example by contributing to mortality and ecological transformations in salt marshes,[225,226] mangrove forests,[227,228,229,230,231] and tidal freshwater forests.[232] In addition to drought, extreme rainfall events are also expected to become more frequent and severe in the future. The prolonged inundation and lack of oxygen that results from extreme rainfall can also result in mortality, such as the dieback of critical foundation plant species, and other large impacts to natural systems.[233] In combination, future increases in the frequency and severity of both extreme drought and extreme rainfall are expected to transform many ecosystems in the Southeast region. Natural systems in the region will have to become resistant and resilient to both too little water and too much water. The ecological transformations induced by these extreme events will affect many of the benefits that natural systems provide to society.

Warming Ocean Temperatures

Warming ocean temperatures due to climate change are expected to have a large effect on marine and coastal ecosystems (Ch. 9: Oceans, KM 3).[234,235,236] Many species are sensitive to small changes in ocean temperature; hence, the distribution and abundance of marine organisms are expected to be greatly altered by increasing ocean temperatures. For example, the distribution of tropical herbivorous fish has been expanding in response to warmer waters, which has resulted in the tropicalization of some temperate marine ecosystems and decreases in the cover of valuable macroalgal plant communities.[179] A decrease in the growth of sea turtles in the West Atlantic has been linked to higher ocean temperatures.[237] Due to climate change, warming ocean temperatures in the coming decades are expected to transform many marine and coastal ecosystems across the Southeast. However, the impacts to coral reef ecosystems in the region have been and are expected to be particularly dire. Coral reefs are biologically diverse ecosystems that provide many societal benefits, including coastal protection from waves, habitat for fish, and recreational and tourism opportunities.[238,239] However, coral reef mortality in the Florida Keys and across the globe has been very high in recent decades, due in part to warming ocean temperatures, nutrient enrichment, overfishing, and coastal development.[240,241,242,243,244] Small increases in ocean temperature can cause corals to expel the symbiotic algae upon which they depend for nourishment. When this happens, corals lose their color and die in a process known as coral bleaching (Ch. 9: Oceans, KM 1). Coral elevation and volume in the Florida Keys have been declining in recent decades,[245] and present-day temperatures in the region are already close to bleaching thresholds; hence, it is likely that many of the remaining coral reefs in the Southeast region will be lost in the coming decades.[246,247] In addition to warming temperatures, accelerated ocean acidification is also expected to contribute to coral reef mortality and decline.[248,249] When coral reefs are lost, coastal communities lose the many benefits provided by these valuable ecosystems, including lost tourism opportunities, a decline in fisheries, and a decrease in wave protection.[246,247]

Key Message 4

Economic and Health Risks for Rural Communities

Rural communities are integral to the Southeast's cultural heritage and to the strong agricultural and forest products industries across the region. More frequent extreme heat episodes and changing seasonal climates are projected to increase exposure-linked health impacts and economic vulnerabilities in the agricultural, timber, and manufacturing sectors. By the end of the century, over one-half billion labor hours could be lost from extreme heat-related impacts. Such changes would negatively impact the region's labor-intensive agricultural industry and compound existing social stresses in rural areas related to limited local community capabilities and associated with rural demography, occupations, earnings, literacy, and poverty incidence. Reduction of existing stresses can increase resilience.

In the Southeast, over 56% of land remains rural (nonmetropolitan) and home to approximately 16 million people, or about 17% percent of the region's population.[250] These rural areas are important to the social and economic well-being of the Southeast. Many in rural communities are maintaining connections to traditional livelihoods and relying on natural resources that are inherently vulnerable to climate change. The Southeast has the second highest number of farmworkers hired per year compared to other National Climate Assessment (NCA) regions.[251] Climate trends and possible climate futures show patterns that are already impacting—and are expected to further impact—rural sectors, from agriculture and forestry to human health and labor productivity (Ch. 10: Ag & Rural, KM 3). For example, shrimping, oystering, and fishing along the coast are long-standing traditions in the coastal economy that are expected to face substantial challenges. For example, by the end of the century, annual oyster harvests in the Southeast are projected to decline between 20% (19%–22%) under a lower scenario (RCP4.5) and 46% (44%–48%) under a higher scenario (RCP8.5), leading to projected price increases of 48% (RCP4.5) to 140% (RCP8.5).[35] Projected warming ocean temperatures, sea level rise, and ocean and coastal acidification are raising concern over future harvests (Ch. 9: Oceans, KM 2).[35,252] While adaptation and resilience can moderate climate change impacts, rural areas generally face other stressors, such as poverty and limited access to healthcare, which will make coping to these climate-related challenges more difficult.

Heat-related stresses are presently a major concern in the Southeast. Future temperature increases are projected to pose challenges for human health. While recent regional temperature trends have not shown the same consistent rate of daytime maximum temperature increase as observed in other parts of the United States, climate model simulations strongly suggest that daytime maximum temperatures are likely to increase as humans continue to emit greenhouse gases into the atmosphere.[13] The resulting temperature increases are expected to add to the heat health burden in rural, as well as urban, areas.[35] Projected temperature increases also pose challenges for crop production dependent on periods of lower temperatures to reach full productivity. Drought has been a recurrent issue in the Southeast affecting agriculture, forestry, and water resources.[253] With rapid growth in population and overall demand, drought is increasingly a concern for water resource management sectors such as cities, ecosystems, and energy production.

Diverse Rural Regions

Urban and rural areas exist along a continuum from major metro areas to suburbs, small towns, and lightly populated places. These areas are linked through many processes, commuting patterns, and shared central services, such as airports and hospitals, that connect the risks. Rapid population growth with associated urbanization and suburbanization over the last several decades has resulted in a more fine-grained forest landscape with smaller and more numerous forest patches.[254] Agriculture, manufacturing, tourism, and other major economic sectors are spread across the Southeast region. Rural counties in the region generally have a diversified economy with a relatively low percentage being heavily dependent on one sector. While well known for agriculture and forestry, rural areas also support manufacturing and tourism.[250]

In 2013, approximately 34% of the U.S. manufacturing output, or about $700 billion (dollar year not reported), came from the Southeast and Texas, including rural areas.[255] While manufacturing growth has been particularly strong in the Southeast in recent years, future climate changes would pose challenges for economic competitiveness. For companies involved in food processing, there are additional secondary economic risks associated with climate impacts on crops and livestock that could alter price or availability.[64,255] Facilities that are energy- or water-intensive are more likely to face increases in the costs and decreases in the availability of these resources, with potential impacts to their economic competitiveness.[246,255]

Energy production, and its dependence on water availability, is a key concern in the Southeast, given the region's growing population and large, diversified economy. An increasing number of high heat and dry days as the climate warms poses a risk to efficient power generation, particularly under conditions where the mode of primary generation moves towards natural gas and water-intensive nuclear power.[256]

Risks to Agriculture and Forestry

Agriculture, livestock rearing, and forestry activities are widespread and varied through the Southeast region.[7] Climate change is expected to have an overall negative impact on agricultural productivity in the United States,[35] although some crops could also become newly viable alternatives (Key Message 3, Figure 19.15). Increases in temperatures, water stress, freeze-free days, drought, and wildfire risks, together with changing conditions for invasive species and the movement of diseases, create a number of potential risks for existing agricultural systems (Ch. 10: Ag & Rural, KM 1).[7] In particular, precipitation trends for the Southeast region show an inclination towards slightly drier summers, which could reduce productivity, and wetter fall seasons, which can make it difficult to harvest the full crop. Multimodel averages of climate model simulations (CMIP3 [SRES A2] and CMIP5 [RCP8.5] higher scenarios) show that there is a greater risk of drier summers by the middle of the century in the western portion of the Southeast and in southern Florida, while wetter fall seasons are more likely in the eastern portion of the region.[257]

The conditions for raising and harvesting crops and livestock are projected to change. Higher temperatures can result in decreasing productivity of some cultivated crops, including cotton, corn, soybeans, and rice.[7] Livestock, which includes hogs and pigs, horses, ponies, mules, burros, and donkeys as well as poultry and processed poultry for consumption (for example, chicken nuggets), is a large component of the agricultural sector for these states and the Nation.[258] Livestock are all vulnerable to heat stress, and their care under projected future conditions would require new or enhanced adaptive strategies (Ch. 10: Ag & Rural, KM 3).

Recent changes in seasonal temperatures that are critical for plant development will continue to impact regionally important crops. Plants collected from the wild may become less available as the ideal conditions for their growth shift to other areas (see Case Study "Mountain Ramps"). Peaches—an important crop in the Southeast—require an adequate period of cool temperatures, called the chill period, to produce yields that are economically viable. Peaches also require warm temperatures at specific times during their development.[259] If the warm temperatures come too early, the chill periods could be too short or the peach blossoms can flower too soon and be in danger of late freeze impacts. A late freeze in March 2017 caused over a billion dollars of damages to peaches and other fruit crops.[84] To assist peach growers in adapting to such changes, researchers are working to develop peach varieties that can produce quality fruits in warmer winters and are developing winter chill models that can assist in adaptation planning efforts.[260,261]

Forests, both natural and plantation, in the Southeast are vulnerable to climate variability and change. Southeastern forests represent almost 27% of the U.S. total[262] and are the highest-valued crop in the region.[7] The vast majority of forest is held in private hands, primarily corporate. Forest cover ranges from almost 50% to 80% in these states, creating large areas of interface between populations and forests.[262] Jobs in timber, logging, and support for agriculture and forestry totaled approximately 458,000.[263] (See Ch. 6: Forests, KM 3 for additional discussion on forest change impacts on rural landscapes.)

The Southeast is one of the most dynamic regions for forest change on the globe,[269] though much of the change owes to intensive rotations of pine production and economic forces that drive frequent conversion between forest and agricultural uses in rural areas.[270,271] Climate is expected to have an impact on the region's forests primarily through changes in moisture regimes.[272] Species migration westward across the eastern United States in response to changing precipitation patterns has already been noted.[273] Drought is likely to alter fire regimes and further interact with species distributions (see Key Message 3). The interactions of altered precipitation and natural disturbances will be important in understanding impacts to the forests not dominated by industrial forestry (Ch. 6: Forests, KM 1 and KM 3).[274]

Wildfire is a well-known risk in the Southeast region, where it occurs with greater frequency than any other U.S. region.[275] However, mitigation strategies, particularly the use of prescribed fire, can significantly reduce wildfire risk and have been widely adopted across rural communities in the Southeast.[190] A doubling of prescribed fire at the landscape scale has been found to reduce wildfire ignitions by a factor of four,[4] while it is well documented that prescribed fire reduces the potential for crown fire in treated forest stands.[276] With greater projected fire risks,[191,277] more attention on how to foster fire-adapted communities offers opportunities for risk reduction (see Case Study "Prescribed Fire" and Key Message 3).[278,279]

Case Study: Mountain Ramps

The Cherokee have been harvesting ramps, a wild onion (*Allium tricoccum*), in the southern Appalachians, their ancestral homelands, for thousands of years.[264,265] Collecting ramps for food sustenance is only one aspect of this cultural tradition. The family-bound harvesting techniques are equally as important and make up part of the deeply held tribal lifeways (Ch. 15: Tribes, KM 2). Ramps emerge in springtime and provide important nutrients after a long winter with a dearth of fresh vegetables. These plants grow in moist forest understory areas that are sensitive to temperature and soil moisture.[266]

Figure 19.20: This up-close image of a ramp (*Allium tricoccum*), harvested from the wild, shows leaves and the bulb/corm of the plant. Photo credit: Gary Kaufman, USDA Forest Service Southern Research Station.

In the southern Appalachians, ramps are threatened by two major processes: overharvesting pressures and a changing climate that could expose these plants to higher temperatures and lower soil moisture conditions during sensitive growth periods (Ch. 10: Ag & Rural, KM 1).[267,268] Although ramps are found all along the Appalachian mountain range, on Cherokee ancestral lands, they are already in their southernmost range. Climate change thus acts to increase the vulnerability of this plant to the existing stressors.

Heat, Health, and Livelihoods

Heat-related health threats are already a risk in outdoor jobs and activities. While heat illness is more often associated with urban settings, rural populations are also at risk. For example, higher rates of heat-related illness have been reported in rural North Carolina compared to urban locations.[280] However, strategies to reduce health impacts on hot days, such as staying indoors or altering times outdoors, are already contributing to reducing heat-related illness in the Southeast.[281]

Workers in the agriculture, forestry, hunting, and fishing sectors together with construction and support, waste, and remediation services work are the most highly vulnerable to heat-related deaths in the United States, representing almost 68% of heat-related deaths nationally.[282] Six of the ten states with the highest occupational heat-related deaths in these sectors are in the Southeast region, accounting for 28.6% of occupational heat-related deaths between 2000 and 2010.[282] By 2090, under a higher scenario (RCP8.5), the Southeast is projected to have the largest heat-related impacts on labor productivity in the country, resulting in average annual losses of 570 million labor hours, or $47 billion (in 2015 dollars, undiscounted), a cost representing a third of total national projected losses, although these figures do not include adaptations by workers or industries (Figure 19.21).[35]

Investing in increased cooling is one likely form of adaptation. Among U.S. regions, the Southeast is projected to experience the highest costs associated with meeting increased electricity demands in a warmer world.[35]

Compounding Stresses and Constraints to Adaptation

The people of the rural Southeast confront a number of social stresses likely to add to the challenges posed by increases in climate stresses.[283] Rural communities tend to be more vulnerable due to factors such as demography, occupations, earnings, literacy, poverty incidence, and community capacities (Ch. 10: Ag & Rural, KM 4).[8,9,10] Reducing stress associated with these factors can increase household and community resilience.[9,284]

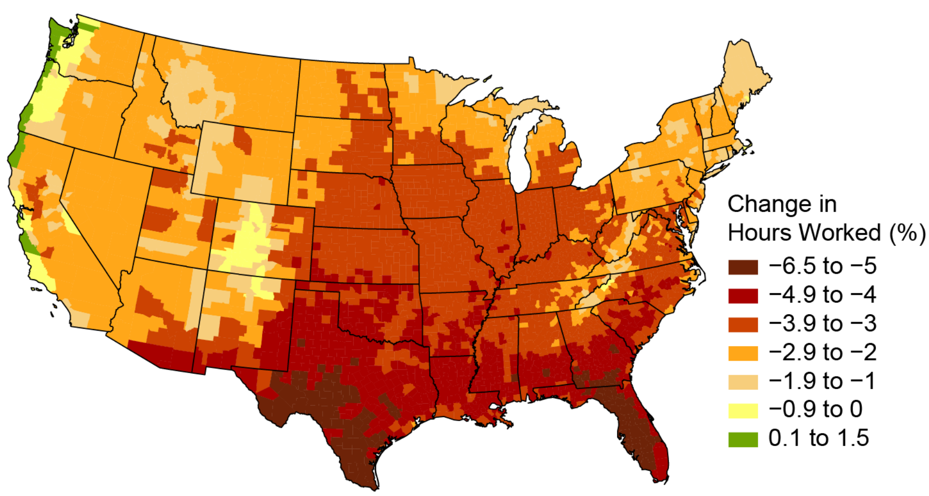


Figure 19.21: This map shows the estimated percent change in hours worked in 2090 under a higher scenario (RCP8.5). Projections indicate an annual average of 570 million labor hours lost per year in the Southeast by 2090 (with models ranging from 340 million to 820 million labor hours).[35] Estimates represent a change in hours worked as compared to a 2003–2007 average baseline for high-risk industries only. These industries are defined as agriculture, forestry, and fishing; hunting, mining, and construction; manufacturing, transportation, and utilities. Source: adapted from EPA 2017.[35]

Persistent rural poverty stands out in the Southeast (Figure 19.22). The rural counties in the region are experiencing higher levels of population loss (13% of rural counties lost population) and low educational attainment (38% of rural counties), with 35% of rural counties experiencing poverty rates of more than 20% persisting over approximately 30 years.[10] The Southeast is expected to experience the highest costs associated with meeting increased energy demands; an estimated $3.3 billion each year under a higher scenario (RCP8.5) and $1.2 billion annually under a lower scenario (RCP4.5) by the end of the century.[35] Energy poverty is a situation "where individuals or households are not able to adequately heat or provide other required energy services in their homes at affordable cost."[285] A case study from rural eastern North Carolina further explains energy poverty as a function of the energy efficiency of the home, energy provision infrastructure, physical health, low incomes, and support of social networks, which collectively influence households' choices about the amount of heating and cooling they can afford.[286] The National Weather Service (NWS) calculates degree days,[287] a way of tracking energy use. NWS starts with the assumption that when the average outside temperature is 65°F, heating or cooling is not needed in order to be comfortable. The difference between the average daily temperature and 65°F is the number of cooling or heating degrees for that day. These days can be added up over time—a month or a year—to give a combined estimate of energy needed for heating or cooling. Although heating costs are expected to decrease as the climate warms in the Southeast, the number of cooling degree days is expected to increase and the length of the cooling season expected to expand, increasing energy demand and exacerbating rural energy poverty (Figure 19.22).

The ability to cope with current and potential impacts, such as flooding, is further reduced by limited county resources. A study of hazard management plans (2004–2008) in 84 selected rural southeastern counties found these plans scored low across various criteria.[288] The rural, geographically remote locations contributed to more difficult logistics in reaching people. Interviewees also identified low-income and minority communities, substandard housing, lack of access to vehicles for evacuation, limited modes of communication, and limited local government capacity as contributing factors to difficulties in emergency planning.[288]

The healthcare system in the Southeast is already overburdened and may be further stressed by climate change. Between 2010 and 2016, more rural hospitals closed in the Southeast than any other region, with Alabama, Georgia, Mississippi, and Tennessee being among the top five states for hospital closures.[289] This strain, when combined with negative health impacts from climate change stressors (such as additional patient demand due to extreme heat and vector-borne diseases and greater flood risk from extreme precipitation events), increases the potential for disruptions of health services in the future. The Green River District Health Department recently did an assessment of ways to reduce vulnerability to negative health impacts of climate change in a mostly rural region of western Kentucky.[290] As a result, the local health department plans to enhance existing epidemiology, public health preparedness, and community health assessment services.[290]

Projected Changes in Cooling Degree Days

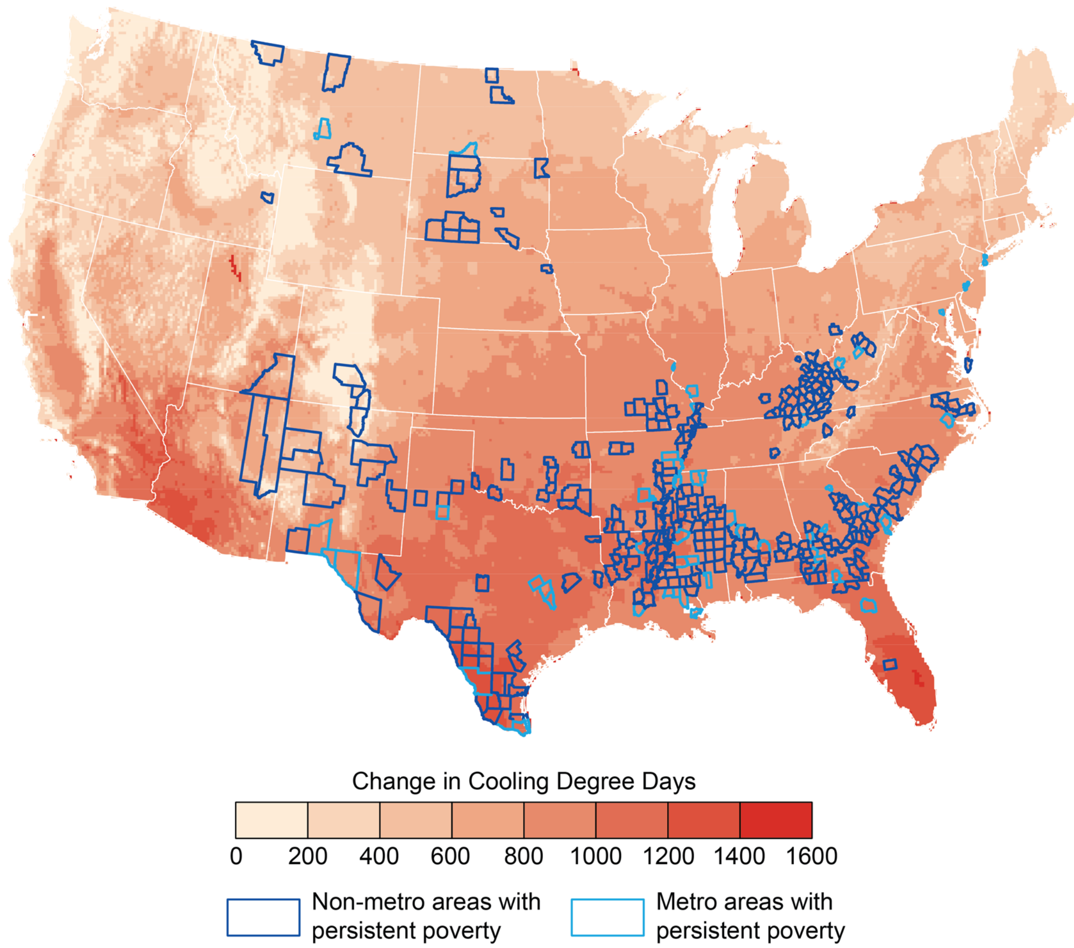


Figure 19.22: The map shows projected changes in cooling degree days by the mid-21st century (2036–2065) under the higher scenario (RCP8.5) based on model simulations. Rural counties experiencing persistent poverty are concentrated in the Southeast, where the need for additional cooling is expected to increase at higher rates than other areas of the country by mid-century. Sources: NOAA NCEI, CICS-NC, and ERT, Inc.

Acknowledgments

Technical Contributors

Vincent Brown
Louisiana State University

Barry Keim
Louisiana State University

Julie K. Maldonado
Livelihoods Knowledge Exchange Network

Colin Polsky
Florida Atlantic University

April Taylor
Chickasaw Nation

USGCRP Coordinators

Allyza Lustig
Program Coordinator

Matthew Dzaugis
Program Coordinator

Natalie Bennett
Adaptation and Assessment Analyst

Opening Image Credit

Red mangrove: © Katja Schulz/Flickr (CC BY 2.0). Adaptation: cropped top and bottom to conform to the size needed for publication.

Traceable Accounts

Process Description

Prior to identifying critical issues for the Southeast assessment focuses for the Fourth National Climate Assessment (NCA4), the Chapter Lead (CL) contacted numerous professional colleagues representing various geographic areas (e.g., Florida, Louisiana, and South Carolina) for expert opinions on critical climate change related issues impacting the region, with a particular emphasis on emerging issues since the Third National Climate Assessment (NCA3) effort.[77] Following those interviews, the CL concluded that the most pressing climate change issues to focus on for the NCA4 effort were extreme events, flooding (both from rainfall and sea level rise), wildfire, health issues, ecosystems, and adaptation actions. Authors with specific expertise in each of these areas were sought, and a draft outline built around these issues was developed. Further refinement of these focal areas occurred in conjunction with the public Regional Engagement Workshop, held on the campus of North Carolina State University in March 2017 and in six satellite locations across the Southeast region. The participants agreed that the identified issues were important and suggested the inclusion of several other topics, including impacts on coastal and rural areas and people, forests, and agriculture. Based on the subsequent authors' meeting and input from NCA staff, the chapter outline and Key Messages were updated to reflect a risk-based framing in the context of a new set of Key Messages. The depth of discussion for any particular topic and Key Message is dependent on the availability of supporting literature and chapter length limitations.

Key Message 1

Urban Infrastructure and Health Risks

Many southeastern cities are particularly vulnerable to climate change compared to cities in other regions, with expected impacts to infrastructure and human health (*very likely, very high confidence*). The vibrancy and viability of these metropolitan areas, including the people and critical regional resources located in them, are increasingly at risk due to heat, flooding, and vector-borne disease brought about by a changing climate (*likely, high confidence*). Many of these urban areas are rapidly growing and offer opportunities to adopt effective adaptation efforts to prevent future negative impacts of climate change (*very likely, high confidence*).

Description of evidence base

Multiple studies have projected that urban areas, including those in the Southeast, will be adversely affected by climate change in a variety of ways. This includes impacts on infrastructure[41,42,43,291,292,293] and human health.[30,31,38,294] Increases in climate-related impacts have already been observed in some Southeast metropolitan areas (e.g., Habeeb et al. 2015, Tzung-May Fu et al. 2015[12,39]).

Southeastern cities may be more vulnerable than cities in other regions of the United States due to the climate being more conducive to some vector-borne diseases, the presence of multiple large coastal cities at low elevation that are vulnerable to flooding and storms, and a rapidly growing urban and coastal population.[22,295,296]

Many city and county governments, utilities, and other government and service organizations have already begun to plan and prepare for the impacts of climate change (e.g., Gregg et al. 2017; FTA 2013; City of Fayetteville 2017; City of Charleston 2015; City of New Orleans 2015; Tampa Bay Water 2014; EPA 2015; City of Atlanta 2015, 2017; Southeast Florida Regional Climate Change Compact 2017[44,45,46,50,91,246,297,298,299]). A wide variety of adaptation options are available, offering opportunities to improve the climate resilience, quality of life, and economy of urban areas.[77,300,301,302,303,304]

Major uncertainties

Population projections are inherently uncertain over long time periods, and shifts in immigration or migration rates and shifting demographics will influence urban vulnerabilities to climate change. The precise impacts on cities are difficult to project. The scope and scale of adaptation efforts, which are already underway, will affect future vulnerability and risk. Technological developments (such as a potential shift in transportation modes) will also affect the scope and location of risk within cities. Newly emerging pathogens could increase risk of disease in the future, while successful adaptations could reduce public health risk.

Description of confidence and likelihood

There is *very high confidence* that southeastern cities will *likely* be impacted by climate change, especially in the areas of infrastructure and human health.

Key Message 2

Increasing Flood Risks in Coastal and Low-Lying Regions

The Southeast's coastal plain and inland low-lying regions support a rapidly growing population, a tourism economy, critical industries, and important cultural resources that are highly vulnerable to climate change impacts (*very likely, very high confidence*). The combined effects of changing extreme rainfall events and sea level rise are already increasing flood frequencies, which impacts property values and infrastructure viability, particularly in coastal cities. Without significant adaptation measures, these regions are projected to experience daily high tide flooding by the end of the century (*likely, high confidence*).

Description of evidence base

Multiple lines of research have shown that global sea levels have increased in the past and are projected to continue to accelerate in the future due to increased global temperature and that higher local sea level rise rates in the Mid-Atlantic and Gulf Coasts have occurred.[51,52,53,54,55,56,57,59,61,62]

Annual occurrences of high tide flooding have increased, causing several Southeast coastal cities to experience all-time records of occurrences that are posing daily risks.[1,52,58,60,61,63,67,68]

There is scientific consensus that sea level rise will continue to cause increases in high tide flooding in the Southeast as well as impact the frequency and duration of extreme water level events, causing an increase in the vulnerability of coastal populations and property.[1,60,63,67,68]

In the future, coastal flooding is projected to become more serious, disruptive, and costly as the frequency, depth, and inland extent grow with time.[1,2,35,64,65,67,68]

Many analyses have determined that extreme rainfall events have increased in the Southeast, and under higher scenarios, the frequency and intensity of these events are projected to increase.[19,21,88]

Rainfall records have shown that since NCA3, many intense rainfall events (approaching 500-year events) have occurred in the Southeast, with some causing billions of dollars in damage and many deaths.[68,82,84]

The flood events in Baton Rouge, Louisiana, in 2016 and in South Carolina in 2015 provide real examples of how vulnerable inland and coastal communities are to extreme rainfall events.[81,85,86]

The socioeconomic impacts of climate change on the Southeast is a developing research field.[65,71]

Major uncertainties

The amount of confidence associated with the historical rate of global sea level rise is impacted by the sparsity of tide gauge records and historical proxies as well as different statistical approaches for estimating sea level change. The amount of unpredictability in future projected rates of sea level rise is likely caused by a range of future climate scenarios projections and rate of ice sheet mass changes. Flooding events are highly variable in both space and time. Detection and attribution of flood events are difficult due to multiple variables that cause flooding.

Description of confidence and likelihood

There is *high confidence* that flood risks will *very likely* increase in coastal and low-lying regions of the Southeast due to rising sea level and an increase in extreme rainfall events. There is *high confidence* that Southeast coastal cities are already experiencing record numbers of high tide flooding events, and without significant adaptation measures, it is *likely* they will be impacted by daily high tide flooding.

Key Message 3

Natural Ecosystems Will Be Transformed

The Southeast's diverse natural systems, which provide many benefits to society, will be transformed by climate change (*very likely, high confidence*). Changing winter temperature extremes, wildfire patterns, sea levels, hurricanes, floods, droughts, and warming ocean temperatures are expected to redistribute species and greatly modify ecosystems (*very likely, high confidence*). As a result, the ecological resources that people depend on for livelihood, protection, and well-being are increasingly at risk, and future generations can expect to experience and interact with natural systems that are much different than those that we see today (*very likely, high confidence*).

Description of evidence base

Winter temperature extremes, fire regimes, sea levels, hurricanes, rainfall extremes, drought extremes, and warming ocean temperatures greatly influence the distribution, abundance, and performance of species and ecosystems.

Winter air temperature extremes (for example, freezing and chilling events) constrain the northern limit of many tropical and subtropical species.[30,48,127,132,135,138,139,140,141,142,143,144,145,148,149,150,152,166,167,168,169,170,172,173,174,175,176,177,178] In the future, warmer winter temperatures are expected to facilitate the northward movement of cold-sensitive species, often at the expense of cold-tolerant species.[132,135,142,145,149,150,152,166,169,173,179] Certain ecosystems are located near thresholds where small changes in winter air temperature regimes can trigger comparatively large and abrupt landscape-scale ecological changes (i.e., ecological regime shifts).[135,145,152]

Changing fire regimes are expected to have a large impact on natural systems. Fire has historically played an important role in the region, and ecological diversity in many southeastern natural systems is dependent upon fire.[115,116,134,189] In the future, rising temperatures and increases in the duration and intensity of drought are expected to increase wildfire occurrence and also reduce the effectiveness of prescribed fire.[3,4,5,6]

Hurricanes and rising sea levels are aspects of climate change that will have a tremendous effect on coastal ecosystems in the Southeast. Historically, coastal ecosystems in the region have adjusted to sea level rise via vertical and/or horizontal movement across the landscape.[125,129,200,201] As sea levels rise in the future, some coastal ecosystems will be submerged and converted to open water, and some coastal ecosystems will move inland at the expense of upslope and upriver ecosystems.[203,204] Since coastal terrestrial and freshwater ecosystems are highly sensitive to increases in inundation and/or salinity, sea level rise will result in the comparatively rapid conversion of these systems to tidal saline habitats. In addition to sea level rise, climate change is expected to increase the impacts of hurricanes; the high winds, storm surges, inundation, and salts that accompany hurricanes will have large ecological impacts to terrestrial and freshwater ecosystems.[209,210]

Climate change is expected to intensify the hydrologic cycle and increase the frequency and severity of extreme events. Extreme drought events are expected to become more frequent and severe. Drought and extreme heat can result in tree mortality and transform southeastern forested ecosystems.[217,218,219,220,221,222,223] Drought can also affect aquatic and wetland ecosystems.[224,225,226,227,228,229,232] Extreme rainfall events are also expected to become more frequent and severe in the future. The prolonged inundation and lack of oxygen that result from extreme rainfall events can also result in mortality and large impacts to natural systems.[233] In combination, future increases in both extreme drought and extreme rainfall are expected to transform many southeastern ecosystems.

Warming ocean temperatures due to climate change are expected to have a large effect on marine and coastal ecosystems.[234,235,236] Many species are sensitive to small changes in ocean temperature; hence, the distribution and abundance of marine organisms are expected to be greatly altered by increasing ocean temperatures. For example, the distribution of tropical herbivorous fish has been expanding in response to warmer waters, which has resulted in the tropicalization of some temperate marine ecosystems and decreases in the cover of valuable macroalgal plant communities.[179] A decrease in the growth of sea turtles in the West Atlantic has been linked to higher ocean temperatures.[237] The impacts to coral reef ecosystems have been and are expected to be particularly dire. Coral reef mortality in the Florida Keys and across the globe has been very high in recent decades, due in part to warming ocean temperatures, nutrient enrichment, overfishing, and coastal development.[240,241,242,243,244] Coral elevation and volume in the Florida Keys have been declining in recent decades,[245] and present-day temperatures in the region are already close to bleaching thresholds; hence, it is likely that many of the remaining coral reefs in the Southeast will be lost in the coming decades.[246,247] In addition to warming temperatures, accelerated ocean acidification is also expected to contribute to coral reef mortality and decline.[248,249]

Major uncertainties

In the Southeast, winter temperature extremes, fire regimes, sea level fluctuations, hurricanes, extreme rainfall, and extreme drought all play critical roles and greatly influence the distribution, structure, and function of species and ecosystems. Changing climatic conditions (particularly, changes in the frequency and severity of climate extremes) are, however, difficult to replicate via experimental manipulations; hence, ecological responses to future climate regimes have not been fully quantified for all species and ecosystems. Natural ecosystems are complex and governed by many interacting biotic and abiotic processes. Although it is possible to make general predictions of climate change effects, specific future ecological transformations can be difficult to predict, especially given the number of interacting and changing biotic and abiotic factors in any specific location. Uncertainties in the range of potential future changes in multiple and concurrent facets of climate and land-use change also affect our ability to predict changes to natural systems.

Description of confidence and likelihood

There is *high confidence* that climate change (e.g., changing winter temperatures extremes, changing fire regimes, rising sea levels and hurricanes, warming ocean temperatures, and more extreme rainfall and drought) will *very likely* affect natural systems in the Southeast region. These climatic drivers play critical roles and greatly influence the distribution, structure, and functioning of ecosystems; hence, changes in these climatic drivers will transform ecosystems in the region and greatly alter the distribution and abundance of species.

Key Message 4

Economic and Health Risks for Rural Communities

Rural communities are integral to the Southeast's cultural heritage and to the strong agricultural and forest products industries across the region. More frequent extreme heat episodes and changing seasonal climates are projected to increase exposure-linked health impacts and economic vulnerabilities in the agricultural, timber, and manufacturing sectors (*very likely, high confidence*). By the end of the century, over one-half billion labor hours could be lost from extreme heat-related impacts (*likely, medium confidence*). Such changes would negatively impact the region's labor-intensive agricultural industry and compound existing social stresses in rural areas related to limited local community capabilities and associated with rural demography, occupations, earnings, literacy, and poverty incidence (*very likely, high confidence*). Reduction of existing stresses can increase resilience (*very likely, high confidence*).

Description of evidence base

Analysis of the sensitivity of some manufacturing sectors to climate changes anticipates secondary risks associated with crop and livestock productivity.[64,255]

Multiple analyses anticipate that energy- or water-intensive industries could face water stress and increased energy costs.[8,64,255,256]

A large body of evidence addresses the sensitivity of many crops grown in the Southeast to changing climate conditions including increased temperatures, decreased summer rainfall, drought, and change in the timing and duration of chill periods.[7,35] Extensive research documents livestock sensitivity to heat stress.[7]

Multiple lines of evidence indicate that forests are likely to be impacted by changing climate, particularly moisture regimes and potential changes in wildfire activity.[191,195,272,274] There is extensive research on heat-related illness and mortality among those living and working in the Southeast. While there is more evidence focused on urban areas, limited research has identified higher levels of heat-related illness in rural areas.[280,281] Research on occupational heat-related mortality identifies some of the Nation's highest levels in southeastern states.[282] Computer model simulations of heat-related reductions in labor productivity anticipate the greatest losses will occur in the Southeast. However, these models do not account for adaptations that may reduce estimated losses.[35,64] By the end of the century, mean annual electricity costs are estimated at $3.3 billion each year under RCP8.5 (model range: $2.4 to $4.2 billion; in 2015 dollars, undiscounted) and mean $1.2 billion each year under RCP4.5 (model range $0.9 to $1.9 billion; in 2015 dollars, undiscounted).[35]

Rural communities tend to be vulnerable due to factors such as demography, occupations, earnings, literacy, and poverty incidence.[8,9,10,250,283,284,305] Reducing the stress created by such factors can improve resilience.[9,284] The availability and accessibility of planning and health services to support coping with climate-related stresses are limited in the rural Southeast.[288,289]

Major uncertainties

There are limited studies documenting direct connections between climate changes and economic impacts. Models are limited in their ability to incorporate adaptation that may reduce losses. These factors restrict the potential to strongly associate declines in agricultural and forest productivity with the level of potential economic impact.

Projections of potential change in the frequency and extent of wildfires depend in part on models of future population growth and human behavior, which are limited, adding to the uncertainty associated with climate and forest modeling.

Many indicators of vulnerability are dynamic, so that adaptation and other changes can affect the patterns of vulnerability to heat and other climate stressors over time. Limited studies indicate concerns over the planning and preparedness of capacity at local levels; however, information is limited.

Projected labor hours lost vary by global climate model, time frame, and scenario, with a mean of 0.57 and a model range of 0.34–0.82 billion labor hours lost each year for RCP8.5 by 2090. The annual mean projected losses are roughly halved (0.28 billion labor hours) and with a model range from 0.19 to 0.43 billion labor hours lost under RCP4.5 by 2090.[35]

Description of confidence and likelihood

There is *high confidence* that climate change (e.g., rising temperatures, changing fire regimes, rising sea levels, and more extreme rainfall and drought) will *very likely* affect agricultural and forest products industries, potentially resulting in economic impacts. There is *high confidence* that increases in temperature are *very likely* to increase heat-related illness, deaths, and loss of labor productivity without greater adaptation efforts.

References

1. Spanger-Siegfried, E., M. Fitzpatrick, and K. Dahl, 2014: Encroaching Tides: How Sea Level Rise and Tidal Flooding Threaten U.S. East and Gulf Coast Communities over the Next 30 Year. Union of Concerned Scientists, Cambridge, MA, 64 pp. http://www.ucsusa.org/global_warming/impacts/effects-of-tidal-flooding-and-sea-level-rise-east-coast-gulf-of-mexico

2. McNeill, R., D.J. Nelson, and D. Wilson, 2014: Water's Edge: The Crisis of Rising Sea Levels. Reuters Investigates. Thomson Reuters. https://www.reuters.com/investigates/special-report/waters-edge-the-crisis-of-rising-sea-levels/

3. Abatzoglou, J.T. and A.P. Williams, 2016: Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences of the United States of America*, **113** (42), 11770-11775. http://dx.doi.org/10.1073/pnas.1607171113

4. Addington, R.N., S.J. Hudson, J.K. Hiers, M.D. Hurteau, T.F. Hutcherson, G. Matusick, and J.M. Parker, 2015: Relationships among wildfire, prescribed fire, and drought in a fire-prone landscape in the south-eastern United States. *International Journal of Wildland Fire*, **24** (6), 778-783. http://dx.doi.org/10.1071/WF14187

5. Littell, J.S., D.L. Peterson, K.L. Riley, Y. Liu, and C.H. Luce, 2016: A review of the relationships between drought and forest fire in the United States. *Global Change Biology*, **22** (7), 2353-2369. http://dx.doi.org/10.1111/gcb.13275

6. Liu, Y., J. Stanturf, and S. Goodrick, 2010: Trends in global wildfire potential in a changing climate. *Forest Ecology and Management*, **259** (4), 685-697. http://dx.doi.org/10.1016/j.foreco.2009.09.002

7. McNulty, S., S. Weiner, J. Moore Myers, H. Farahani, L. Fouladbash, D. Marshall, and R.F. Steele, 2015: Southeast Regional Climate Hub Assessment of Climate Change Vulnerability and Adaptation and Mitigation Strategies. Anderson, T., Ed. USDA Agricultural Research Service, Washington, DC, 61 pp. https://www.srs.fs.usda.gov/pubs/50521

8. Lal, P., J.R.R. Alavalapati, and E.D. Mercer, 2011: Socio-economic impacts of climate change on rural United States. *Mitigation and Adaptation Strategies for Global Change*, **16** (7), 819-844. http://dx.doi.org/10.1007/s11027-011-9295-9

9. Jurjonas, M. and E. Seekamp, 2018: Rural coastal community resilience: Assessing a framework in eastern North Carolina. *Ocean & Coastal Management*, **162**, 137-150. http://dx.doi.org/10.1016/j.ocecoaman.2017.10.010

10. ERS, 2018: Rural Poverty & Well-Being: Geography of Poverty. USDA, Economic Research Service (ERS), Washington, DC, accessed March 14. https://www.ers.usda.gov/topics/rural-economy-population/rural-poverty-well-being/#geography

11. Hsiang, S., R. Kopp, A. Jina, J. Rising, M. Delgado, S. Mohan, D.J. Rasmussen, R. Muir-Wood, P. Wilson, M. Oppenheimer, K. Larsen, and T. Houser, 2017: Estimating economic damage from climate change in the United States. *Science*, **356** (6345), 1362-1369. http://dx.doi.org/10.1126/science.aal4369

12. Habeeb, D., J. Vargo, and B. Stone, 2015: Rising heat wave trends in large US cities. *Natural Hazards*, **76** (3), 1651-1665. http://dx.doi.org/10.1007/s11069-014-1563-z

13. Vose, R.S., D.R. Easterling, K.E. Kunkel, A.N. LeGrande, and M.F. Wehner, 2017: Temperature changes in the United States. *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA, 185-206. http://dx.doi.org/10.7930/J0N29V45

14. Meehl, G.A., J.M. Arblaster, and G. Branstator, 2012: Mechanisms contributing to the warming hole and the consequent US east–west differential of heat extremes. *Journal of Climate*, **25** (2012), 6394-6408. http://dx.doi.org/10.1175/JCLI-D-11-00655.1

15. Walsh, J., D. Wuebbles, K. Hayhoe, J. Kossin, K. Kunkel, G. Stephens, P. Thorne, R. Vose, M. Wehner, J. Willis, D. Anderson, S. Doney, R. Feely, P. Hennon, V. Kharin, T. Knutson, F. Landerer, T. Lenton, J. Kennedy, and R. Somerville, 2014: Ch. 2: Our changing climate. *Climate Change Impacts in the United States: The Third National Climate Assessment*. Melillo, J.M., T.C. Richmond, and G.W. Yohe, Eds. U.S. Global Change Research Program, Washington, DC, 19-67. http://dx.doi.org/10.7930/J0KW5CXT

16. Pan, Z., R.W. Arritt, E.S. Takle, W.J. Gutowski, Jr., C.J. Anderson, and M. Segal, 2004: Altered hydrologic feedback in a warming climate introduces a "warming hole." *Geophysical Research Letters*, **31** (17), L17109. http://dx.doi.org/10.1029/2004GL020528

17. Partridge, T.F., J.M. Winter, E.C. Osterberg, D.W. Hyndman, A.D. Kendall, and F.J. Magilligan, 2018: Spatially distinct seasonal patterns and forcings of the U.S. warming hole. *Geophysical Research Letters*, **45** (4), 2055-2063. http://dx.doi.org/10.1002/2017GL076463

18. Kunkel, K., R. Frankson, J. Runkle, S. Champion, L. Stevens, D. Easterling, and B. Stewart, 2017: State Climate Summaries for the United States. NOAA Technical Report NESDIS 149. National Oceanic and Atmospheric Administration, National Centers for Environmental Information, Asheville, NC, [various] pp. https://statesummaries.ncics.org/

19. Easterling, D.R., K.E. Kunkel, J.R. Arnold, T. Knutson, A.N. LeGrande, L.R. Leung, R.S. Vose, D.E. Waliser, and M.F. Wehner, 2017: Precipitation change in the United States. *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA, 207-230. http://dx.doi.org/10.7930/J0H993CC

20. Pierce, D.W., D.R. Cayan, and B.L. Thrasher, 2014: Statistical downscaling using Localized Constructed Analogs (LOCA). *Journal of Hydrometeorology*, **15** (6), 2558-2585. http://dx.doi.org/10.1175/jhm-d-14-0082.1

21. USGCRP, 2017: Scenarios for Climate Assessment and Adaptation: LOCA Viewer [web tool]. U.S. Global Change Research Program, Washington, DC. https://scenarios.globalchange.gov/loca-viewer/

22. Census Bureau, 2017: Press kit: County and Metro Area Population. *Census Newsroom*, March 23. U.S. Census Bureau. https://www.census.gov/newsroom/press-kits/2017/20170323_popestimates.html

23. ARC 33°N, 2016: Regional Snapshot: 2016 Population Estimates. Atlanta Regional Commission (ARC), Atlanta, GA. http://33n.atlantaregional.com/regional-snapshot/regional-snapshot-2016-population-estimates

24. Census Bureau, 2017: County Population Totals and Components of Change: 2010-2016. U.S. Census Bureau. https://www.census.gov/data/datasets/2016/demo/popest/counties-total.html

25. Diem, J.E., C.E. Stauber, and R. Rothenberg, 2017: Heat in the southeastern United States: Characteristics, trends, and potential health impact. *PLOS ONE*, **12** (5), e0177937. http://dx.doi.org/10.1371/journal.pone.0177937

26. Sarofim, M.C., S. Saha, M.D. Hawkins, D.M. Mills, J. Hess, R. Horton, P. Kinney, J. Schwartz, and A. St. Juliana, 2016: Ch. 2: Temperature-related death and illness. *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. U.S. Global Change Research Program, Washington, DC, 43–68. http://dx.doi.org/10.7930/J0MG7MDX

27. Zhou, Y. and J.M. Shepherd, 2010: Atlanta's urban heat island under extreme heat conditions and potential mitigation strategies. *Natural Hazards*, **52** (3), 639-668. http://dx.doi.org/10.1007/s11069-009-9406-z

28. Sustain Louisville, 2017: 2016 Progress Report. Office of Sustainability, Louisville, KY, 24 pp. https://louisvilleky.gov/sites/default/files/sustainability/sustain_louisville_2016_progress_report.pdf

29. Beard, C.B., R.J. Eisen, C.M. Barker, J.F. Garofalo, M. Hahn, M. Hayden, A.J. Monaghan, N.H. Ogden, and P.J. Schramm, 2016: Ch. 5: Vector-borne diseases. *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. U.S. Global Change Research Program, Washington, DC, 129–156. http://dx.doi.org/10.7930/J0765C7V

30. Monaghan, A.J., C.W. Morin, D.F. Steinhoff, O. Wilhelmi, M. Hayden, D.A. Quattrochi, M. Reiskind, A.L. Lloyd, K. Smith, C.A. Schmidt, P.E. Scalf, and K. Ernst, 2016: On the seasonal occurrence and abundance of the Zika virus vector mosquito *Aedes aegypti* in the contiguous United States. *Plos Currents: Outbreaks*. http://dx.doi.org/10.1371/currents.outbreaks.50dfc7f46798675fc63e7d7da563da76

31. Butterworth, M.K., C.W. Morin, and A.C. Comrie, 2017: An analysis of the potential impact of climate change on dengue transmission in the southeastern United States. *Environmental Health Perspectives*, **125**, 579-585. http://dx.doi.org/10.1289/EHP218

32. De Jesús Crespo, R., P. Méndez Lázaro, and S.H. Yee, 2018: Linking wetland ecosystem services to vector-borne disease: Dengue fever in the San Juan Bay Estuary, Puerto Rico. *Wetlands*. http://dx.doi.org/10.1007/s13157-017-0990-5

33. Wong, G.K.L. and C.Y. Jim, 2018: Abundance of urban male mosquitoes by green infrastructure types: Implications for landscape design and vector management. *Landscape Ecology*, **33** (3), 475-489. http://dx.doi.org/10.1007/s10980-018-0616-1

34. Lindsay, S.W., A. Wilson, N. Golding, T.W. Scott, and W. Takken, 2017: Improving the built environment in urban areas to control *Aedes aegypti*-borne diseases. *Bulletin of the World Health Organization*, **95** (8), 607-608. http://dx.doi.org/10.2471/BLT.16.189688

35. EPA, 2017: Multi-model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment. EPA 430-R-17-001. U.S. Environmental Protection Agency (EPA), Washington, DC, 271 pp. https://cfpub.epa.gov/si/si_public_record_Report.cfm?dirEntryId=335095

36. Harrigan, R.J., H.A. Thomassen, W. Buermann, and T.B. Smith, 2014: A continental risk assessment of West Nile virus under climate change. *Global Change Biology*, **20** (8), 2417-2425. http://dx.doi.org/10.1111/gcb.12534

37. Schnell, J.L. and M.J. Prather, 2017: Co-occurrence of extremes in surface ozone, particulate matter, and temperature over eastern North America. *Proceedings of the National Academy of Sciences of the United States of America*, **114** (11), 2854-2859. http://dx.doi.org/10.1073/pnas.1614453114

38. Zhang, Y. and Y. Wang, 2016: Climate-driven ground-level ozone extreme in the fall over the Southeast United States. *Proceedings of the National Academy of Sciences of the United States of America*, **113** (36), 10025-10030. http://dx.doi.org/10.1073/pnas.1602563113

39. Fu, T.-M., Y. Zheng, F. Paulot, J. Mao, and R.M. Yantosca, 2015: Positive but variable sensitivity of August surface ozone to large-scale warming in the southeast United States. *Nature Climate Change*, **5**, 454-458. http://dx.doi.org/10.1038/nclimate2567

40. Ziska, L.H., D.E. Gebhard, D.A. Frenz, S. Faulkner, B.D. Singer, and J.G. Straka, 2003: Cities as harbingers of climate change: Common ragweed, urbanization, and public health. *Journal of Allergy and Clinical Immunology*, **111** (2), 290-295. http://dx.doi.org/10.1067/mai.2003.53

41. Neumann, J.E., J. Price, P. Chinowsky, L. Wright, L. Ludwig, R. Streeter, R. Jones, J.B. Smith, W. Perkins, L. Jantarasami, and J. Martinich, 2015: Climate change risks to US infrastructure: Impacts on roads, bridges, coastal development, and urban drainage. *Climatic Change*, **131** (1), 97-109. http://dx.doi.org/10.1007/s10584-013-1037-4

42. FHWA, 2017: FHWA Climate Resilience Pilot Program: Tennessee Department of Transportation. FHWA-HEP-16-076. Federal Highway Administration's (FHWA), Climate Resilience Pilot Program, Washington, DC, 4 pp. https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/tennessee/index.cfm

43. Abkowitz, M., J. Camp, and L. Dundon, 2015: Assessing the Vulnerability of Tennessee Transportation Assets to Extreme Weather. 3 Sigma Consultants for Tennessee Department of Transportation, Nashville, TN, 49 pp. https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/tennessee/final_report/tdot.pdf

44. Amekudzi, A., M. Crane, D. Springstead, D. Rose, and T. Batac, 2013: Transit Climate Change Adaptation Assessment for the Metropolitan Atlanta Rapid Transit Authority. FTA Report No. 0076 Federal Transit Administration, Washington, DC, 49 pp. https://www.transit.dot.gov/research-innovation/transit-climate-change-adaptation-assessment-metropolitan-atlanta-rapid-transit

45. City of Charleston, 2015: Sea Level Rise Strategy. Mayor's Office, Charleston, SC, 17 pp. http://www.charleston-sc.gov/DocumentCenter/View/10089

46. Tampa Bay Water, 2014: Tampa Bay Water Hosts Florida Water and Climate Alliance Workshop. November 4. https://www.tampabaywater.org/newsroom/agency-news/tampa-bay-water-hosts-florida-water-and-climate-alliance-workshop

47. WUCA Strategic Planning Committee, 2016: Water Utility Climate Alliance 2017–2021 Strategic Plan. Water Utility Climate Alliance (WUCA), Las Vegas, NV, 6 pp. https://www.wucaonline.org/assets/pdf/about-strategic-plan-2021.pdf

48. Ross Strategic, 2016: International Water and Climate Forum, 2015. Synthesis Report. Association of Metropolitan Water Agencies, Washington, DC, 19 pp. https://bit.ly/2P2NL8t

49. EPA, 2015: Case Study: Water and Wastewater Utilities Planning for Climate Change. Seminole Tribe of Florida. EPA 800-Q-15-004. U.S. Environmental Protection Agency (EPA), Washington, DC, 2 pp. https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P100SHVY.txt

50. City of Atlanta, 2015: Climate Action Plan. Mayor's Office of Sustainability, Atlanta, GA, 48 pp. http://p2catl.com/wp-content/uploads/Atlanta-Climate-Action-Plan-07-23-2015.pdf

51. Sweet, W.V., R. Horton, R.E. Kopp, A.N. LeGrande, and A. Romanou, 2017: Sea level rise. *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA, 333-363. http://dx.doi.org/10.7930/J0VM49F2

52. Sweet, W.V., R.E. Kopp, C.P. Weaver, J. Obeysekera, R.M. Horton, E.R. Thieler, and C. Zervas, 2017: Global and Regional Sea Level Rise Scenarios for the United States. NOAA Tech. Rep. NOS CO-OPS 083. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD, 75 pp. https://tidesandcurrents.noaa.gov/publications/techrpt83_Global_and_Regional_SLR_Scenarios_for_the_US_final.pdf

53. Sallenger, A.H., K.S. Doran, and P.A. Howd, 2012: Hotspot of accelerated sea-level rise on the Atlantic coast of North America. *Nature Climate Change*, **2**, 884-888. http://dx.doi.org/10.1038/nclimate1597

54. Zervas, C., 2009: Sea Level Variations of the United States 1854–2006. NOAA Technical Report NOS CO-OPS 053. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD, various pp. https://tidesandcurrents.noaa.gov/publications/Tech_rpt_53.pdf

55. Mitchum, G.T., 2011: Sea Level Changes in the Southeastern United States: Past, Present and Future. Florida Climate Institute, Gainesville, FL, 20 pp. http://www.FloridaClimateInstitute.org/images/reports/201108mitchum_sealevel.pdf

56. Boon, J.D., 2012: Evidence of sea level acceleration at U.S. and Canadian tide stations, Atlantic Coast, North America. *Journal of Coastal Research*, **28**, 1437-1445. http://dx.doi.org/10.2112/JCOASTRES-D-12-00102.1

57. Hall, J.A., S. Gill, J. Obeysekera, W. Sweet, K. Knuuti, and J. Marburger, 2016: Regional Sea Level Scenarios for Coastal Risk Management: Managing the Uncertainty of Future Sea Level Change and Extreme Water Levels for Department of Defense Coastal Sites Worldwide. U.S. Department of Defense, Strategic Environmental Research and Development Program, Alexandria VA, 224 pp. https://www.usfsp.edu/icar/files/2015/08/CARSWG-SLR-FINAL-April-2016.pdf

58. Sweet, W.V. and J.J. Marra, 2016: 2015 State of U.S. Nuisance Tidal Flooding. Supplement to State of the Climate: National Overview for May 2016. National Oceanic and Atmospheric Administration, National Centers for Environmental Information, 5 pp. http://www.ncdc.noaa.gov/monitoring-content/sotc/national/2016/may/sweet-marra-nuisance-flooding-2015.pdf

59. Kopp, R.E., A.C. Kemp, K. Bittermann, B.P. Horton, J.P. Donnelly, W.R. Gehrels, C.C. Hay, J.X. Mitrovica, E.D. Morrow, and S. Rahmstorf, 2016: Temperature-driven global sea-level variability in the Common Era. *Proceedings of the National Academy of Sciences of the United States of America*, **113** (11), E1434-E1441. http://dx.doi.org/10.1073/pnas.1517056113

60. Sweet, W., J. Park, J. Marra, C. Zervas, and S. Gill, 2014: Sea Level Rise and Nuisance Flood Frequency Changes Around the United States. NOAA Technical Report NOS CO-OPS 073. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD, 58 pp. https://bit.ly/1niTPQK

61. Sweet, W.V., J.J. Marra, and Gregory Dusek, 2017: 2016 State of U.S. High Tide Flooding and a 2017 Outlook. Supplement to State of the Climate: National Overview for June 2017. National Oceanic and Atmospheric Administration, National Centers for Environmental Information, 8 pp. https://bit.ly/2svZ9O2

62. Parris, A., P. Bromirski, V. Burkett, D. Cayan, M. Culver, J. Hall, R. Horton, K. Knuuti, R. Moss, J. Obeysekera, A. Sallenger, and J. Weiss, 2012: Global Sea Level Rise Scenarios for the United States National Climate Assessment. NOAA Tech Memo OAR CPO-1. National Oceanic and Atmospheric Administration, Silver Spring, MD, 37 pp. http://scenarios.globalchange.gov/sites/default/files/NOAA_SLR_r3_0.pdf

63. Sweet, W.V. and J. Park, 2014: From the extreme to the mean: Acceleration and tipping points of coastal inundation from sea level rise. *Earth's Future*, **2** (12), 579-600. http://dx.doi.org/10.1002/2014EF000272

64. Houser, T., S. Hsiang, R. Kopp, K. Larsen, M. Delgado, A. Jina, M. Mastrandrea, S. Mohan, R. Muir-Wood, D.J. Rasmussen, J. Rising, and P. Wilson, 2015: *Economic Risks of Climate Change: An American Prospectus*. Columbia University Press, New York, 384 pp.

65. Emrich, C.T., D.P. Morath, G.C. Bowser, and R. Reeves, 2014: Climate-Sensitive Hazards in Florida: Identifying and Prioritizing Threats to Build Resilience Against Climate Effects. Florida Department of Health, Tallahassee, FL, various pp. http://www.floridahealth.gov/environmental-health/climate-and-health/_documents/climate-sensitive-hazards-in-florida-final-report.pdf

66. Anderson, D.G., T.G. Bissett, S.J. Yerka, J.J. Wells, E.C. Kansa, S.W. Kansa, K.N. Myers, R.C. DeMuth, and D.A. White, 2017: Sea-level rise and archaeological site destruction: An example from the southeastern United States using DINAA (Digital Index of North American Archaeology). PLOS ONE, **12** (11), e0188142. http://dx.doi.org/10.1371/journal.pone.0188142

67. Dahl, K.A., E. Spanger-Siegfried, A. Caldas, and S. Udvardy, 2017: Effective inundation of continental United States communities with 21st century sea level rise. *Elementa: Science of the Anthropocene*, **5**, Article 37. http://dx.doi.org/10.1525/elementa.234

68. Moftakhari, H.R., A. AghaKouchak, B.F. Sanders, D.L. Feldman, W. Sweet, R.A. Matthew, and A. Luke, 2015: Increased nuisance flooding along the coasts of the United States due to sea level rise: Past and future. *Geophysical Research Letters*, **42** (22), 9846-9852. http://dx.doi.org/10.1002/2015GL066072

69. USGCRP, 2016: *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. U.S. Global Change Research Program, Washington, DC, 312 pp. http://dx.doi.org/10.7930/J0R49NQX

70. Hauer, M.E., J.M. Evans, and D.R. Mishra, 2016: Millions projected to be at risk from sea-level rise in the continental United States. *Nature Climate Change*, **6** (7), 691-695. http://dx.doi.org/10.1038/nclimate2961

71. Hauer, M.E., 2017: Migration induced by sea-level rise could reshape the US population landscape. *Nature Climate Change*, **7** (5), 321-325. http://dx.doi.org/10.1038/nclimate3271

72. Strauss, B.H., R. Ziemlinski, J.L. Weiss, and J.T. Overpeck, 2012: Tidally adjusted estimates of topographic vulnerability to sea level rise and flooding for the contiguous United States. *Environmental Research Letters*, **7** (1), 014033. http://dx.doi.org/10.1088/1748-9326/7/1/014033

73. Burkett, M., R.R.M. Verchick, and D. Flores, 2017: Reaching Higher Ground: Avenues to Secure and Manage New Land for Communities Displaced by Climate Change. Center for Progressive Reform, Washington, DC, 43 pp. http://progressivereform.org/articles/ReachingHigherGround_1703.pdf

74. Isle de Jean Charles Tribe, 2017: Bienvenue, Aiokpanchi, Welcome to Isle de Jean Charles [web site], Isle de Jean Charles, LA, accessed October 17. http://www.isledejeancharles.com/

75. Office of Community Development, 2018: Isle de Jean Charles Resettlement Project. State of Louisiana. http://isledejeancharles.la.gov/

76. Maldonado, J.K. and K. Peterson, 2018: A community-based model for resettlement: Lessons from coastal Louisiana *Routledge Handbook of Environmental Displacement and Migration*. McLeman, R. and F. Gemenne, Eds. Routledge, 289-299.

77. Carter, L.M., J.W. Jones, L. Berry, V. Burkett, J.F. Murley, J. Obeysekera, P.J. Schramm, and D. Wear, 2014: Ch. 17: Southeast and the Caribbean. *Climate Change Impacts in the United States: The Third National Climate Assessment*. Melillo, J.M., T.C. Richmond, and G.W. Yohe, Eds. U.S. Global Change Research Program, Washington, DC, 396-417. http://dx.doi.org/10.7930/J0NP22CB

78. NDRC, 2016: National Disaster Resilience Competition (NDRC): Grantee Profiles. U.S. Department of Housing and Urban Development, Washington, DC, 23 pp. https://www.hud.gov/sites/documents/NDRCGRANTPROF.PDF

79. NDRC, 2016: State of Louisiana. *National Disaster Resilience Competition (NDRC): Grantee Profiles*. U.S. Department of Housing and Urban Development, Washington, DC, 7-8. https://www.hud.gov/sites/documents/NDRCGRANTPROF.PDF

80. Gonzalez, C.G., A. Kaswan, R. Verchick, Y. Huang, N. Jamhour, and S. Bowen, 2016: Climate Change, Resilience, and Fairness: How Nonstructural Adaptation Can Protect and Empower Socially Vulnerable Communities on the Gulf Coast. Center for Progressive Reform White Paper. Center for Progressive Reform, Washington, DC, 97 pp. https://works.bepress.com/carmen_gonzalez/42/

81. Allan, R.P. and B.J. Soden, 2008: Atmospheric warming and the amplification of precipitation extremes. *Science*, **321** (5895), 1481-1484. http://dx.doi.org/10.1126/science.1160787

82. Perica, S., D. Martin, S. Pavlovic, I. Roy, M.S. Laurent, C. Trypaluk, D. Unruh, M. Yekta, and G. Bonnin, 2013: Precipitation-Frequency Atlas of the United States. Volume 9 Version 2.0: Southeastern States (Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi) NOAA Atlas 14 Volume 9. NOAA National Weather Service, Silver Spring, MD, various pp. http://www.nws.noaa.gov/oh/hdsc/PF_documents/Atlas14_Volume9.pdf

83. NOAA RCC, 2017: xmACIS2 [Applied Climate Information System online tool]. National Oceanic and Atmospheric Administration (NOAA), Regional Climate Centers (RCC). http://xmacis.rcc-acis.org/

84. NOAA NCEI, 2018: Billion-Dollar Weather and Climate Disasters [web page]. NOAA National Centers for Environmental Information, Asheville, NC. https://www.ncdc.noaa.gov/billions/events/US/1980-2017

85. Gallo, A., 2016: "Which Baton Rouge ZIP codes were hit hardest? New data lends scope to flooding devastation." *The Advocate*, Sep 2. http://www.theadvocate.com/louisiana_flood_2016/article_e8832d38-714d-11e6-b2c7-ab4b6ed62f15.html

86. Colten, C., 2017: Floods collide with sprawl in Louisiana's Amite River Basin. *Focus on Geography*, **60**. http://dx.doi.org/10.21690/foge/2017.60.2f

87. van der Wiel, K., S.B. Kapnick, G.J. van Oldenborgh, K. Whan, S. Philip, G.A. Vecchi, R.K. Singh, J. Arrighi, and H. Cullen, 2017: Rapid attribution of the August 2016 flood-inducing extreme precipitation in south Louisiana to climate change. *Hydrology and Earth System Sciences*, **21** (2), 897-921. http://dx.doi.org/10.5194/hess-21-897-2017

88. NWS, 2016: The Historic South Carolina Floods of October 1–5, 2015. Service Assessment. NOAA National Weather Service (NWS), Silver Spring, MD, various pp. https://www.weather.gov/media/publications/assessments/SCFlooding_072216_Signed_Final.pdf

89. Wahl, T., S. Jain, J. Bender, S.D. Meyers, and M.E. Luther, 2015: Increasing risk of compound flooding from storm surge and rainfall for major US cities. *Nature Climate Change*, **5** (12), 1093-1097. http://dx.doi.org/10.1038/nclimate2736

90. Wdowinski, S., R. Bray, B.P. Kirtman, and Z. Wu, 2016: Increasing flooding hazard in coastal communities due to rising sea level: Case study of Miami Beach, Florida. *Ocean & Coastal Management*, **126**, 1-8. http://dx.doi.org/10.1016/j.ocecoaman.2016.03.002

91. SFRCCC, 2017: Regional Climate Action Plan 2.0 [web tool]. South Florida Regional Climate Change Compact (SFRCCC), Broward, Miami-Dade, Monroe, and Palm Beach Counties, FL. http://www.southeastfloridaclimatecompact.org/regional-climate-action-plan/

92. Morales, J., 2016: Miami Beach coastal flooding forum. In *Forum on Indicators of Coastal Flooding and Flood Impacts*, West Palm Beach, FL, May 26. South Flordia Water Management District, 3-25. ftp://ftp.sfwmd.gov/pub/jabarne/Coastal_Flooding_25May2016.pdf

93. Behr, J.G., R. Diaz, and M. Mitchell, 2016: Building resiliency in response to sea level rise and recurrent flooding: Comprehensive planning in Hampton Roads. *The Virginia News Letter*, **92** (1), 1-6. https://vig.coopercenter.org/sites/vig/files/VirginiaNewsLetter_2016_V92-N1.pdf

94. Biloxi Mississippi Code of Ordinances, 2017: Flood damage prevention: Specific standards. Chapter 8, Art. III, Sec. 8-3-2. https://library.municode.com/ms/biloxi/codes/code_of_ordinances?nodeId=COOR_CH8FLDAPR_ARTIIIFLHAPRST_S8-3-2SPST

95. Evans, J.M., J. Gambill, R.J. McDowell, P.W. Prichard, and C.S. Hopkinson, 2016: Tybee Island: Sea Level Rise Adaptation Plan. NOAA, Georgia Sea Grant, Athens, GA, 82 pp. http://dx.doi.org/10.13140/RG.2.1.3825.9604/1

96. Acadiana Planning Commission, 2018: APC Board allocates $25 million in HMGP funding to regional flood mitigation projects. Lafayette, LA. February 20. http://planacadiana.org/uncategorized/apc-board-allocates-25-million-in-hmgp-funding-to-regional-flood-mitigation-projects/

97. FEMA, 2016: Community Rating System (CRS) Communities and Their Classes. Federal Emergency Management Agency (FEMA), National Flood Insurance Program. https://www.fema.gov/media-library/assets/documents/15846

98. CISA, 2016: The South Carolina Floods of October 2015. Carolinas Integrated Sciences & Assessments (CISA), Columbia, SC, 4 pp. http://www.cisa.sc.edu/PDFs/October%202015%20Flood%20Event%204%20Pager.pdf

99. Smith, A.B., 2018: 2017 U.S. billion-dollar weather and climate disasters: A historic year in context. Climate.gov. https://www.climate.gov/news-features/blogs/beyond-data/2017-us-billion-dollar-weather-and-climate-disasters-historic-year

100. Cangialosi, J.P., A.S. Latto, and R. Berg, 2018: Tropical Cyclone Report: Hurricane Irma (AL112017), 30 August-12 September 2017. National Hurricane Center, 111 pp. https://www.nhc.noaa.gov/data/tcr/AL112017_Irma.pdf

101. NWS, 2017: Detailed Meteorological Summary on Hurricane Irma [web page]. NOAA National Weather Service (NWS), Tallahassee, FL. https://www.weather.gov/tae/Irma_technical_summary

102. Voiland, A., 2017: Hot water ahead for Hurricane Irma. NASA *Earth Observatory*, September 6. NASA. https://earthobservatory.nasa.gov/images/90912/hot-water-ahead-for-hurricane-irma

103. Kossin, J.P., T. Hall, T. Knutson, K.E. Kunkel, R.J. Trapp, D.E. Waliser, and M.F. Wehner, 2017: Extreme storms. *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA, 257-276. http://dx.doi.org/10.7930/J07S7KXX

104. Emanuel, K., 2017: Will global warming make hurricane forecasting more difficult? *Bulletin of the American Meteorological Society*, **98** (3), 495-501. http://dx.doi.org/10.1175/bams-d-16-0134.1

105. AJC Staff, 2017: "Gov. Deal: 'Virtually the entire state' to be impacted by Irma." *The Atlanta Journal-Constitution*, September 10. https://www.ajc.com/news/gov-deal-virtually-the-entire-state-impacted-irma/pm6pW2vlt4GQpM34a7s4TO/

106. Shaffer, J., A. Bennett, and A. Bylythe, 2017: "NC governor declares state of emergency ahead of 'powerful' Hurricane Irma: 'Get ready.'" *The News & Observer*, September 6. https://www.newsobserver.com/news/weather/article171616057.html

107. Townsend, E. and M. Tomasic, 2017: "S.C. Governor declares state of emergency as Hurricane Irma's forecast path shifts." *The Sun News*, September 6. https://www.myrtlebeachonline.com/news/local/article171519002.html

108. Wise, S., 2017: "Virginia Governor declares state of emergency ahead of Hurricane Irma." WTVR (CBS *Affiliate*), September 8. https://wtvr.com/2017/09/08/hurricane-irma-virginia-state-of-emergency/

109. Florida House of Representatives, 2018: Select Committee on Hurricane Response and Preparedness Final Report. Tallahassee, FL, 113 pp. https://bit.ly/2mRD7Rw

110. Deal, N., 2017: Deal declares state of emergency ahead of Hurricane Irma. Office of the Governor, Atlanta, GA. September 6. https://gov.georgia.gov/press-releases/2017-09-06/deal-declares-state-emergency-ahead-hurricane-irma

111. Simmons, K.M., J. Czajkowski, and J. Done, 2017: Economic Effectiveness of Implementing a Statewide Building Code: The Case of Florida. SSRN, 64 pp. http://dx.doi.org/10.2139/ssrn.2963244

112. Scott, R., 2017: Gov. Scott issues updates on Hurricane Irma preparedness. Tallahassee, FL. September 9. https://www.flgov.com/2017/09/09/gov-scott-issues-updates-on-hurricane-irma-preparedness-10/

113. Cartwright, J.M. and W.J. Wolfe, 2016: Insular Ecosystems of the Southeastern United States: A Regional Synthesis to Support Biodiversity Conservation in a Changing Climate. USGS Professional Paper 1828. U.S. Geological Survey, Reston, VA, 162 pp. http://dx.doi.org/10.3133/pp1828

114. Jenkins, C.N., K.S. Van Houtan, S.L. Pimm, and J.O. Sexton, 2015: US protected lands mismatch biodiversity priorities. *Proceedings of the National Academy of Sciences of the United States of America*, **112** (16), 5081-5086. http://dx.doi.org/10.1073/pnas.1418034112

115. Noss, R.F., 2012: *Forgotten Grasslands of the South: Natural History and Conservation*. Island Press, Washington, DC, 320 pp.

116. Noss, R.F., W.J. Platt, B.A. Sorrie, A.S. Weakley, D.B. Means, J. Costanza, and R.K. Peet, 2015: How global biodiversity hotspots may go unrecognized: Lessons from the North American Coastal Plain. *Diversity and Distributions*, **21** (2), 236-244. http://dx.doi.org/10.1111/ddi.12278

117. Stein, B.A., L.S. Kutner, and J.S. Adams, Eds., 2000: *Precious Heritage: The Status of Biodiversity in the United States*. Oxford University Press, Oxford; New York, 432 pp.

118. Barbier, E.B., S.D. Hacker, C. Kennedy, E.W. Koch, A.C. Stier, and B.R. Silliman, 2011: The value of estuarine and coastal ecosystem services. *Ecological Monographs*, **81** (2), 169-193. http://dx.doi.org/10.1890/10-1510.1

119. Costanza, R., R. de Groot, P. Sutton, S. van der Ploeg, S.J. Anderson, I. Kubiszewski, S. Farber, and R.K. Turner, 2014: Changes in the global value of ecosystem services. *Global Environmental Change*, **26**, 152-158. http://dx.doi.org/10.1016/j.gloenvcha.2014.04.002

120. Millennium Ecosystem Assessment, 2005: *Ecosystems and Human Well-Being: Synthesis*. Sarukhán, J., A. Whyte, and MA Board of Review Editors, Eds. Island Press, Washington, DC, 137 pp. https://www.millenniumassessment.org/documents/document.356.aspx.pdf

121. Clark, P.U., A.S. Dyke, J.D. Shakun, A.E. Carlson, J. Clark, B. Wohlfarth, J.X. Mitrovica, S.W. Hostetler, and A.M. McCabe, 2009: The last glacial maximum. *Science*, **325** (5941), 710-714. http://dx.doi.org/10.1126/science.1172873

122. Jackson, S.T., R.S. Webb, K.H. Anderson, J.T. Overpeck, T. Webb III, J.W. Williams, and B.C.S. Hansen, 2000: Vegetation and environment in Eastern North America during the Last Glacial Maximum. *Quaternary Science Reviews*, **19** (6), 489-508. http://dx.doi.org/10.1016/S0277-3791(99)00093-1

123. Williams, J.W., B.N. Shuman, T. Webb, P.J. Bartlein, and P.L. Leduc, 2004: Late-quaternary vegetation dynamics in North America: Scaling from taxa to biomes. *Ecological Monographs*, **74** (2), 309-334. http://dx.doi.org/10.1890/02-4045

124. Davis, M.B. and R.G. Shaw, 2001: Range shifts and adaptive responses to quaternary climate change. *Science*, **292** (5517), 673-679. http://dx.doi.org/10.1126/science.292.5517.673

125. Doyle, T.W., B. Chivoiu, and N.M. Enwright, 2015: Sea-Level Rise Modeling Handbook: Resource Guide for Coastal Land Managers, Engineers, and Scientists. USGS Professional Paper 1815. U.S. Geological Survey, Reston, VA, 76 pp. http://dx.doi.org/10.3133/pp1815

126. Kennedy, J.P., M.W. Pil, C.E. Proffitt, W.A. Boeger, A.M. Stanford, and D.J. Devlin, 2016: Postglacial expansion pathways of red mangrove, *Rhizophora mangle*, in the Caribbean Basin and Florida. *American Journal of Botany*, **103** (2), 260-276. http://dx.doi.org/10.3732/ajb.1500183

127. 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** (9), 129-140. http://hdl.handle.net/1969.3/19073

128. Williams, K., Z.S. Pinzon, R.P. Stumpf, and E.A. Raabe, 1999: Sea-Level Rise and Coastal Forests on the Gulf of Mexico. Open-File Report 99-441. U.S. Geological Survey, Center for Coastal Geology, St. Petersburg, FL, various pp. http://pubs.er.usgs.gov/publication/ofr99441

129. Woodroffe, C.D. and J. Grindrod, 1991: Mangrove biogeography: The role of quaternary environmental and sea-level change. *Journal of Biogeography*, **18** (5), 479-492. http://dx.doi.org/10.2307/2845685

130. Costanza, J., S. Beck, M. Pyne, A. Terando, M.J. Rubino, R. White, and J. Collazo, 2016: Assessing Climate-Sensitive Ecosystems in the Southeastern United States. USGS Open-File Report 2016-1073. US Geological Survey, Reston, VA, 278 pp. http://dx.doi.org/10.3133/ofr20161073

131. Dale, V.H., L.A. Joyce, S. 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, and B.M. Wotton, 2001: Climate change and forest disturbances: Climate change can affect forests by altering the frequency, intensity, duration, and timing of fire, drought, introduced species, insect and pathogen outbreaks, hurricanes, windstorms, ice storms, or landslides. *BioScience*, **51** (9), 723-734. http://dx.doi.org/10.1641/0006-3568(2001)051[0723:ccafd]2.0.co;2

132. Gabler, C.A., M.J. Osland, J.B. Grace, C.L. Stagg, R.H. Day, S.B. Hartley, N.M. Enwright, A.S. From, M.L. McCoy, and J.L. McLeod, 2017: Macroclimatic change expected to transform coastal wetland ecosystems this century. *Nature Climate Change*, **7**, 142-147. http://dx.doi.org/10.1038/nclimate3203

133. IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, UK and New York, NY, 1535 pp. http://www.climatechange2013.org/report/

134. Mitchell, R.J., Y. Liu, J.J. O'Brien, K.J. Elliott, G. Starr, C.F. Miniat, and J.K. Hiers, 2014: Future climate and fire interactions in the southeastern region of the United States. *Forest Ecology and Management*, **327**, 316-326. http://dx.doi.org/10.1016/j.foreco.2013.12.003

135. Osland, M.J., N. Enwright, R.H. Day, and T.W. Doyle, 2013: Winter climate change and coastal wetland foundation species: Salt marshes vs. mangrove forests in the southeastern United States. *Global Change Biology*, **19** (5), 1482-1494. http://dx.doi.org/10.1111/gcb.12126

136. Jackson, S.T. and J.T. Overpeck, 2000: Responses of plant populations and communities to environmental changes of the late Quaternary. *Paleobiology*, **26** (sp4), 194-220. http://dx.doi.org/10.1666/0094-8373(2000)26[194:ROPPAC]2.0.CO;2

137. 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. http://dx.doi.org/10.1890/070037

138. Boucek, R.E., E.E. Gaiser, H. Liu, and J.S. Rehage, 2016: A review of subtropical community resistance and resilience to extreme cold spells. *Ecosphere*, **7** (10), e01455. http://dx.doi.org/10.1002/ecs2.1455

139. Daly, C., M.P. Widrlechner, M.D. Halbleib, J.I. Smith, and W.P. Gibson, 2012: Development of a new USDA plant hardiness zone map for the United States. *Journal of Applied Meteorology and Climatology*, **51**, 242-264. http://dx.doi.org/10.1175/2010JAMC2536.1

140. Kozlowski, T.T. and S.G. Pallardy, 1997: *Growth Control in Woody Plants*. Roy, J., Ed. Academic Press, San Diego, 641 pp.

141. Larcher, W., 2003: *Physiological Plant Ecology: Ecophysiology and Stress Physiology of Functional Groups*, 4th ed. Springer, Berlin, 514 pp.

142. Parker, L.E. and J.T. Abatzoglou, 2016: Projected changes in cold hardiness zones and suitable overwinter ranges of perennial crops over the United States. *Environmental Research Letters*, **11** (3), 034001. http://dx.doi.org/10.1088/1748-9326/11/3/034001

143. Sakai, A. and W. Larcher, 1987: *Frost Survival of Plants: Responses and Adaptation to Freezing Stress*. 321 pp. http://dx.doi.org/10.1007/978-3-642-71745-1

144. Williams, C.M., H.A.L. Henry, and B.J. Sinclair, 2015: Cold truths: How winter drives responses of terrestrial organisms to climate change. *Biological Reviews*, **90** (1), 214-235. http://dx.doi.org/10.1111/brv.12105

145. Osland, M.J., N.M. Enwright, R.H. Day, C.A. Gabler, C.L. Stagg, and J.B. Grace, 2016: Beyond just sea-level rise: Considering macroclimatic drivers within coastal wetland vulnerability assessments to climate change. *Global Change Biology*, **22** (1), 1-11. http://dx.doi.org/10.1111/gcb.13084

146. Krakauer, N.Y., 2012: Estimating climate trends: Application to United States plant hardiness zones. *Advances in Meteorology*, **2012**, Article ID 404876. http://dx.doi.org/10.1155/2012/404876

147. McKenney, D.W., J.H. Pedlar, K. Lawrence, P. Papadopol, K. Campbell, and M.F. Hutchinson, 2014: Change and evolution in the plant hardiness zones of Canada. *BioScience*, **64** (4), 341-350. http://dx.doi.org/10.1093/biosci/biu016

148. Attaway, J.A., 1997: *A History of Florida Citrus Freezes*. Flordia Science Source, Ocala, FL, 368 pp.

149. Cavanaugh, K.C., J.D. Parker, S.C. Cook-Patton, I.C. Feller, A.P. Williams, and J.R. Kellner, 2015: Integrating physiological threshold experiments with climate modeling to project mangrove species' range expansion. *Global Change Biology*, **21** (5), 1928-1938. http://dx.doi.org/10.1111/gcb.12843

150. Cavanaugh, K.C., J.R. Kellner, A.J. Forde, D.S. Gruner, J.D. Parker, W. Rodriguez, and I.C. Feller, 2014: Poleward expansion of mangroves is a threshold response to decreased frequency of extreme cold events. *Proceedings of the National Academy of Sciences of the United States of America*, **111** (2), 723-727. http://dx.doi.org/10.1073/pnas.1315800111

151. Osland, M.J., R.H. Day, C.T. Hall, M.D. Brumfield, J.L. Dugas, and W.R. Jones, 2017: Mangrove expansion and contraction at a poleward range limit: Climate extremes and land-ocean temperature gradients. *Ecology*, **98** (1), 125-137. http://dx.doi.org/10.1002/ecy.1625

152. Osland, M.J., L.C. Feher, K.T. Griffith, K.C. Cavanaugh, N.M. Enwright, R.H. Day, C.L. Stagg, K.W. Krauss, R.J. Howard, J.B. Grace, and K. Rogers, 2017: Climatic controls on the global distribution, abundance, and species richness of mangrove forests. *Ecological Monographs*, **87** (2), 341-359. http://dx.doi.org/10.1002/ecm.1248

153. Engle, V.D., 2011: Estimating the provision of ecosystem services by Gulf of Mexico coastal wetlands. *Wetlands*, **31** (1), 179-193. http://dx.doi.org/10.1007/s13157-010-0132-9

154. Field, D.W., A.J. Reyer, P.V. Genovese, and B.D. Shearer, 1991: Coastal Wetlands of the United States: An Accounting of a Valuable National Resource. A Special NOAA 20th Anniversary Report. National Oceanic and Atmospheric Administration, Washington, DC, 59 pp. https://catalog.hathitrust.org/Record/002499265

155. Batker, D., I. de la Torre, R. Costanza, P. Swedeen, J. Day, R. Boumans, and K. Bagstad, 2010: Gaining Ground: Wetlands, Hurricanes and the Economy: The Value of Restoring the Mississippi River Delta. Earth Economics, Tacoma, WA, 98 pp. http://pdxscholar.library.pdx.edu/cgi/viewcontent.cgi?article=1038&context=iss_pub

156. Dayton, P.K., 1972: Toward an understanding of community resilience and the potential effects of enrichments to the benthos at McMurdo Sound, Antarctica. In *Proceedings of the Colloquium on Conservation Problems in Antarctica*, Blacksburg, VA. Allen Press. Parker, B.C., Ed., 81-96. http://daytonlab.ucsd.edu/Publications/Dayton72_Understanding.pdf

157. Ellison, A.M., M.S. Bank, B.D. Clinton, E.A. Colburn, K. Elliott, C.R. Ford, D.R. Foster, B.D. Kloeppel, J.D. Knoepp, G.M. Lovett, J. Mohan, D.A. Orwig, N.L. Rodenhouse, W.V. Sobczak, K.A. Stinson, J.K. Stone, C.M. Swan, J. Thompson, B. Von Holle, and J.R. Webster, 2005: Loss of foundation species: Consequences for the structure and dynamics of forested ecosystems. *Frontiers in Ecology and the Environment*, **3** (9), 479-486. http://dx.doi.org/10.1890/1540-9295(2005)003[0479:LOFSCF]2.0.CO;2

158. Bianchi, T.S., M.A. Allison, J. Zhao, X. Li, R.S. Comeaux, R.A. Feagin, and R.W. Kulawardhana, 2013: Historical reconstruction of mangrove expansion in the Gulf of Mexico: Linking climate change with carbon sequestration in coastal wetlands. *Estuarine, Coastal and Shelf Science*, **119**, 7-16. http://dx.doi.org/10.1016/j.ecss.2012.12.007

159. Chavez-Ramirez, F. and W. Wehtje, 2012: Potential impact of climate change scenarios on whooping crane life history. *Wetlands*, **32** (1), 11-20. http://dx.doi.org/10.1007/s13157-011-0250-z

160. Comeaux, R.S., M.A. Allison, and T.S. Bianchi, 2012: Mangrove expansion in the Gulf of Mexico with climate change: Implications for wetland health and resistance to rising sea levels. *Estuarine, Coastal and Shelf Science*, **96**, 81-95. http://dx.doi.org/10.1016/j.ecss.2011.10.003

161. Doughty, C.L., J.A. Langley, W.S. Walker, I.C. Feller, R. Schaub, and S.K. Chapman, 2016: Mangrove range expansion rapidly increases coastal wetland carbon storage. *Estuaries and Coasts*, **39** (2), 385-396. http://dx.doi.org/10.1007/s12237-015-9993-8

162. Guo, H., C. Weaver, S.P. Charles, A. Whitt, S. Dastidar, P. D'Odorico, J.D. Fuentes, J.S. Kominoski, A.R. Armitage, and S.C. Pennings, 2017: Coastal regime shifts: Rapid responses of coastal wetlands to changes in mangrove cover. *Ecology*, **98** (3), 762-772. http://dx.doi.org/10.1002/ecy.1698

163. Smee, D.L., J.A. Sanchez, M. Diskin, and C. Trettin, 2017: Mangrove expansion into salt marshes alters associated faunal communities. *Estuarine, Coastal and Shelf Science*, **187**, 306-313. http://dx.doi.org/10.1016/j.ecss.2017.02.005

164. Yando, E.S., M.J. Osland, J.M. Willis, R.H. Day, K.W. Krauss, and M.W. Hester, 2016: Salt marsh-mangrove ecotones: Using structural gradients to investigate the effects of woody plant encroachment on plant–soil interactions and ecosystem carbon pools. *Journal of Ecology*, **104** (4), 1020-1031. http://dx.doi.org/10.1111/1365-2745.12571

165. Kelleway, J.J., K. Cavanaugh, K. Rogers, I.C. Feller, E. Ens, C. Doughty, and N. Saintilan, 2017: Review of the ecosystem service implications of mangrove encroachment into salt marshes. *Global Change Biology*, **23** (10), 3967-3983. http://dx.doi.org/10.1111/gcb.13727

166. Ayres, M.P. and M.a.J. Lombardero, 2000: Assessing the consequences of global change for forest disturbance from herbivores and pathogens. *Science of the Total Environment*, **262** (3), 263-286. http://dx.doi.org/10.1016/S0048-9697(00)00528-3

167. Bentz, B.J. and A.M. Jönsson, 2015: Chapter 13: Modeling bark beetle responses to climate change. *Bark Beetles: Biology and Ecology of Native and Invasive Species*. Hofstetter, R.W., Ed. Academic Press, San Diego, 533-553. http://dx.doi.org/10.1016/B978-0-12-417156-5.00013-7

168. Duehl, A.J., F.H. Koch, and F.P. Hain, 2011: Southern pine beetle regional outbreaks modeled on landscape, climate and infestation history. *Forest Ecology and Management*, **261** (3), 473-479. http://dx.doi.org/10.1016/j.foreco.2010.10.032

169. Ebi, K.L. and J. Nealon, 2016: Dengue in a changing climate. *Environmental Research*, **151**, 115-123. http://dx.doi.org/10.1016/j.envres.2016.07.026

170. Morin, C.W., A.C. Comrie, and K. Ernst, 2013: Climate and dengue transmission: Evidence and implications. *Environmental Health Perspectives*, **121**, 1264-1277. http://dx.doi.org/10.1289/ehp.1306556

171. Robinet, C. and A. Roques, 2010: Direct impacts of recent climate warming on insect populations. *Integrative Zoology*, **5** (2), 132-142. http://dx.doi.org/10.1111/j.1749-4877.2010.00196.x

172. Ungerer, M.J., M.P. Ayres, and M.J. Lombardero, 1999: Climate and the northern distribution limits of *Dendroctonus frontalis* Zimmermann (Coleoptera: Scolytidae). *Journal of Biogeography*, **26** (6), 1133-1145. http://dx.doi.org/10.1046/j.1365-2699.1999.00363.x

173. Notaro, M., M. Schummer, Y. Zhong, S. Vavrus, L. Van Den Elsen, J. Coluccy, and C. Hoving, 2016: Projected influences of changes in weather severity on autumn-winter distributions of dabbling ducks in the Mississippi and Atlantic flyways during the twenty-first century. *PLOS ONE*, **11** (12), e0167506. http://dx.doi.org/10.1371/journal.pone.0167506

174. Boucek, R.E. and J.S. Rehage, 2014: Climate extremes drive changes in functional community structure. *Global Change Biology*, **20** (6), 1821-1831. http://dx.doi.org/10.1111/gcb.12574

175. Martin, J.H. and L.W. McEachron, 1996: Historical Annotated Review of Winter Kills of Marine Organisms in Texas Bays. Management Data Series No. 118. Texas Parks and Wildlife Department, Coastal Fisheries Division, Austin, TX, 20 pp. https://tpwd.texas.gov/publications/pwdpubs/media/mds_coastal/Series%202_MDS118.pdf

176. Rehage, J.S., J.R. Blanchard, R.E. Boucek, J.J. Lorenz, and M. Robinson, 2016: Knocking back invasions: Variable resistance and resilience to multiple cold spells in native vs. nonnative fishes. *Ecosphere*, **7** (6), e01268. http://dx.doi.org/10.1002/ecs2.1268

177. Stevens, P.W., D.A. Blewett, R.E. Boucek, J.S. Rehage, B.L. Winner, J.M. Young, J.A. Whittington, and R. Paperno, 2016: Resilience of a tropical sport fish population to a severe cold event varies across five estuaries in southern Florida. *Ecosphere*, **7** (8), e01400. http://dx.doi.org/10.1002/ecs2.1400

178. Storey, M. and E.W. Gudger, 1936: Mortality of fishes due to cold at Sanibel Island, Florida, 1886-1936. *Ecology*, **17** (4), 640-648. http://dx.doi.org/10.2307/1932762

179. Vergés, A., P.D. Steinberg, M.E. Hay, A.G.B. Poore, A.H. Campbell, E. Ballesteros, K.L. Heck, D.J. Booth, M.A. Coleman, D.A. Feary, W. Figueira, T. Langlois, E.M. Marzinelli, T. Mizerek, P.J. Mumby, Y. Nakamura, M. Roughan, E. van Sebille, A.S. Gupta, D.A. Smale, F. Tomas, T. Wernberg, and S.K. Wilson, 2014: The tropicalization of temperate marine ecosystems: Climate-mediated changes in herbivory and community phase shifts. *Proceedings of the Royal Society B: Biological Sciences*, **281** (1789). http://dx.doi.org/10.1098/rspb.2014.0846

180. Avery, M.L., R.M. Engeman, K.L. Keacher, J.S. Humphrey, W.E. Bruce, T.C. Mathies, and R.E. Mauldin, 2010: Cold weather and the potential range of invasive Burmese pythons. *Biological Invasions*, **12** (11), 3649-3652. http://dx.doi.org/10.1007/s10530-010-9761-4

181. Dorcas, M.E., J.D. Willson, R.N. Reed, R.W. Snow, M.R. Rochford, M.A. Miller, W.E. Meshaka, P.T. Andreadis, F.J. Mazzotti, C.M. Romagosa, and K.M. Hart, 2012: Severe mammal declines coincide with proliferation of invasive Burmese pythons in Everglades National Park. *Proceedings of the National Academy of Sciences of the United States of America*, **109** (7), 2418-2422. http://dx.doi.org/10.1073/pnas.1115226109

182. Ferriter, A., Ed. 1997: *Brazilian Pepper Management Plan for Florida*. Florida Exotic Pest Plant Council, Gainesville, FL, 26 pp. http://www.fleppc.org/Manage_Plans/schinus.pdf

183. Jacobson, E.R., D.G. Barker, T.M. Barker, R. Mauldin, M.L. Avery, R. Engeman, and S. Secor, 2012: Environmental temperatures, physiology and behavior limit the range expansion of invasive Burmese pythons in southeastern USA. *Integrative Zoology*, **7** (3), 271-285. http://dx.doi.org/10.1111/j.1749-4877.2012.00306.x

184. Jones, W.D., 1979: Effects of the 1978 freeze on native plants of Sonora, Mexico. *Desert Plants*, **1**, 33-36. http://hdl.handle.net/10150/528203

185. Mazzotti, F.J., M.S. Cherkiss, K.M. Hart, R.W. Snow, M.R. Rochford, M.E. Dorcas, and R.N. Reed, 2011: Cold-induced mortality of invasive Burmese pythons in south Florida. *Biological Invasions*, **13** (1), 143-151. http://dx.doi.org/10.1007/s10530-010-9797-5

186. Mazzotti, F.J., M.S. Cherkiss, M. Parry, J. Beauchamp, M. Rochford, B. Smith, K. Hart, and L.A. Brandt, 2016: Large reptiles and cold temperatures: Do extreme cold spells set distributional limits for tropical reptiles in Florida? *Ecosphere*, **7** (8), e01439. http://dx.doi.org/10.1002/ecs2.1439

187. Morton, J.F., 1978: Brazilian pepper—Its impact on people, animals and the environment. *Economic Botany*, **32** (4), 353-359. http://dx.doi.org/10.1007/bf02907927

188. Provancha, M.J., P.A. Schmalzer, and C.R. Hall, 1986: Effects of the December 1983 and January 1985 freezing air temperatures on select aquatic poikilotherms and plant species of Merritt Island, Florida. *Florida Scientist*, **49** (4), 199-212. http://www.jstor.org/stable/24320159

189. Christensen, N.L., 1981: Fire regimes in southeastern ecosystems. In *Fire Regimes and Ecosystem Properties*, Honolulu, HI. Mooney, H.A., T.M. Bonnicksen, N.L. Christensen, J.E. Lotan, and W.A. Reiners, Eds., 112-136. https://archive.org/stream/CAT83781017#page/112/mode/2up/search/christensen

190. Melvin, M.A., 2015: 2015 National Prescribed Fire Use Survey Report. Technical Report 02-15. Coalition of Prescribed Fire Councils, 17 pp. https://stateforesters.org/sites/default/files/publication-documents/2015%20Prescribed%20Fire%20Use%20Survey%20Report.pdf

191. Prestemon, J.P., U. Shankar, A. Xiu, K. Talgo, D. Yang, E. Dixon, D. McKenzie, and K.L. Abt, 2016: Projecting wildfire area burned in the south-eastern United States, 2011–60. *International Journal of Wildland Fire*, **25** (7), 715-729. http://dx.doi.org/10.1071/WF15124

192. Gandhi, K.J.K. and D.A. Herms, 2010: Direct and indirect effects of alien insect herbivores on ecological processes and interactions in forests of eastern North America. *Biological Invasions*, **12** (2), 389-405. http://dx.doi.org/10.1007/s10530-009-9627-9

193. Kreye, J.K., J.M. Varner, J.K. Hiers, and J. Mola, 2013: Toward a mechanism for eastern North American forest mesophication: Differential litter drying across 17 species. *Ecological Applications*, **23** (8), 1976-1986. http://dx.doi.org/10.1890/13-0503.1

194. Nowacki, G.J. and M.D. Abrams, 2008: The demise of fire and "mesophication" of forests in the eastern United States. *BioScience*, **58** (2), 123-138. http://dx.doi.org/10.1641/B580207

195. Mercer, D.E., J.P. Prestemon, D.T. Butry, and J.M. Pye, 2007: Evaluating alternative prescribed burning policies to reduce net economic damages from wildfire. *American Journal of Agricultural Economics*, **89** (1), 63-77. http://dx.doi.org/10.1111/j.1467-8276.2007.00963.x

196. Swanteson-Franz, R.J., D.J. Krofcheck, and M.D. Hurteau, 2018: Quantifying forest carbon dynamics as a function of tree species composition and management under projected climate. *Ecosphere*, **9** (4), e02191. http://dx.doi.org/10.1002/ecs2.2191

197. Mitchell, R.J., L.K. Kirkman, S.D. Pecot, C.A. Wilson, B.J. Palik, and L.R. Boring, 1999: Patterns and controls of ecosystem function in longleaf pine-wiregrass savannas. I. Aboveground net primary productivity. *Canadian Journal of Forest Research*, **29** (6), 743-751. http://dx.doi.org/10.1139/x99-051

198. Kirkman, L.K., R.J. Mitchell, R.C. Helton, and M.B. Drew, 2001: Productivity and species richness across an environmental gradient in a fire-dependent ecosystem. *American Journal of Botany*, **88** (11), 2119-2128. http://dx.doi.org/10.2307/3558437

199. Starr, G., C.L. Staudhammer, H.W. Loescher, R. Mitchell, A. Whelan, J.K. Hiers, and J.J. O'Brien, 2015: Time series analysis of forest carbon dynamics: Recovery of *Pinus palustris* physiology following a prescribed fire. *New Forests*, **46** (1), 63-90. http://dx.doi.org/10.1007/s11056-014-9447-3

200. Doyle, T.W., G.F. Girod, and M.A. Books, 2003: Modeling mangrove forest migration along the southwest coast of Florida under climate change. *Integrated Assessment of the Climate Change Impacts on the Gulf Coast Region*. Ning, Z.H., R.E. Turner, T. Doyle, and K.K. Abdollahi, Eds. Gulf Coast Climate Change Assessment Council (GCRCC) and Louisiana State University (LSU) Graphic Services, Baton Rouge, LA, 211-222. http://www.climateimpacts.org/us-climate-assess-2000/regions/gulf-coast/gulfcoast-chapter12.pdf

201. Woodroffe, C.D., K. Rogers, K.L. McKee, C.E. Lovelock, I.A. Mendelssohn, and N. Saintilan, 2016: Mangrove sedimentation and response to relative sea-level rise. *Annual Review of Marine Science*, **8** (1), 243-266. http://dx.doi.org/10.1146/annurev-marine-122414-034025

202. Conner, W.H., T.W. Doyle, and K.W. Krauss, Eds., 2007: *Ecology of Tidal Freshwater Forested Wetlands of the Southeastern United States*. Springer, Dordrecht, The Netherlands, 518 pp.

203. Doyle, T.W., K.W. Krauss, W.H. Conner, and 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. http://dx.doi.org/10.1016/j.foreco.2009.10.023

204. Enwright, N.M., K.T. Griffith, and M.J. Osland, 2016: Barriers to and opportunities for landward migration of coastal wetlands with sea-level rise. *Frontiers in Ecology and the Environment*, **14** (6), 307-316. http://dx.doi.org/10.1002/fee.1282

205. Howard, R.J., R.H. Day, K.W. Krauss, A.S. From, L. Allain, and N. Cormier, 2017: Hydrologic restoration in a dynamic subtropical mangrove-to-marsh ecotone. *Restoration Ecology*, **25** (3), 471-482. http://dx.doi.org/10.1111/rec.12452

206. Neubauer, S.C., 2013: Ecosystem responses of a tidal freshwater marsh experiencing saltwater intrusion and altered hydrology. *Estuaries and Coasts*, **36** (3), 491-507. http://dx.doi.org/10.1007/s12237-011-9455-x

207. Saha, A.K., S. Saha, J. Sadle, J. Jiang, M.S. Ross, R.M. Price, L.S.L.O. Sternberg, and K.S. Wendelberger, 2011: Sea level rise and South Florida coastal forests. *Climatic Change*, **107** (1), 81-108. http://dx.doi.org/10.1007/s10584-011-0082-0

208. Williams, K., K.C. Ewel, R.P. Stumpf, F.E. Putz, and T.W. Workman, 1999: Sea-level rise and coastal forest retreat on the West Coast of Florida, USA. *Ecology*, **80** (6), 2045-2063. http://dx.doi.org/10.1890/0012-9658(1999)080[2045:SLRACF]2.0.CO;2

209. Doyle, T.W., T.J. Smith, III, and M.B. Robblee, 1995: Wind damage effects of Hurricane Andrew on mangrove communities along the southwest coast of Florida, USA. *Journal of Coastal Research*, **SI 21**, 159-168. http://www.jstor.org/stable/25736006

210. Smith, T.J., III, M.B. Robblee, H.R. Wanless, and T.W. Doyle, 1994: Mangroves, hurricanes, and lightning strikes: Assessment of Hurricane Andrew suggests an interaction across two differing scales of disturbance. *BioScience*, **44** (4), 256-262. http://dx.doi.org/10.2307/1312230

211. Couvillion, B.R., H. Beck, D. Schoolmaster, and M. Fischer, 2017: Land Area Change in Coastal Louisiana (1932 to 2016). Scientific Investigations Map 3381. U.S. Geological Survey, Reston, VA, 16 pp. http://dx.doi.org/10.3133/sim3381

212. 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. http://dx.doi.org/10.1038/ngeo553

213. Day, J.W., Jr., D.F. Boesch, E.J. Clairain, G.P. Kemp, S.B. Laska, W.J. Mitsch, K. Orth, H. Mashriqui, D.J. Reed, L. Shabman, C.A. Simenstad, B.J. Streever, R.R. Twilley, C.C. Watson, J.T. Wells, and D.F. Whigham, 2007: Restoration of the Mississippi Delta: Lessons from Hurricanes Katrina and Rita. *Science*, **315** (5819), 1679-1684. http://dx.doi.org/10.1126/science.1137030

214. Jankowski, K.L., T.E. Törnqvist, and A.M. Fernandes, 2017: Vulnerability of Louisiana's coastal wetlands to present-day rates of relative sea-level rise. *Nature Communications*, **8**, Article 14792. http://dx.doi.org/10.1038/ncomms14792

215. Twilley, R.R., S.J. Bentley, Q. Chen, D.A. Edmonds, S.C. Hagen, N.S.-N. Lam, C.S. Willson, K. Xu, D. Braud, R. Hampton Peele, and A. McCall, 2016: Co-evolution of wetland landscapes, flooding, and human settlement in the Mississippi River Delta Plain. *Sustainability Science*, **11** (4), 711-731. http://dx.doi.org/10.1007/s11625-016-0374-4

216. Coastal Protection and Restoration Authority of Louisiana, 2017: Louisiana's Comprehensive Master Plan for a Sustainable Coast. Coastal Protection and Restoration Authority of Louisiana, Baton Rouge, LA, 171 pp. http://coastal.la.gov/our-plan/2017-coastal-master-plan/

217. Allen, C.D., D.D. Breshears, and N.G. McDowell, 2015: On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene. *Ecosphere*, **6** (8), 1-55. http://dx.doi.org/10.1890/ES15-00203.1

218. Allen, C.D., A.K. Macalady, H. Chenchouni, D. Bachelet, N. McDowell, M. Vennetier, T. Kitzberger, A. Rigling, D.D. Breshears, E.H. Hogg, P. Gonzalez, R. Fensham, Z. Zhang, J. Castro, N. Demidova, J.-H. Lim, G. Allard, S.W. Running, A. Semerci, and N. Cobb, 2010: A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management*, **259** (4), 660-684. http://dx.doi.org/10.1016/j.foreco.2009.09.001

219. Berdanier, A.B. and J.S. Clark, 2016: Multiyear drought-induced morbidity preceding tree death in southeastern U.S. forests. *Ecological Applications*, **26** (1), 17-23. http://dx.doi.org/10.1890/15-0274

220. Clark, J.S., L. Iverson, C.W. Woodall, C.D. Allen, D.M. Bell, D.C. Bragg, A.W. D'Amato, F.W. Davis, M.H. Hersh, I. Ibanez, S.T. Jackson, S. Matthews, N. Pederson, M. Peters, M.W. Schwartz, K.M. Waring, and N.E. Zimmermann, 2016: The impacts of increasing drought on forest dynamics, structure, and biodiversity in the United States. *Global Change Biology*, **22** (7), 2329-2352. http://dx.doi.org/10.1111/gcb.13160

221. Luce, C.H., J.M. Vose, N. Pederson, J. Campbell, C. Millar, P. Kormos, and R. Woods, 2016: Contributing factors for drought in United States forest ecosystems under projected future climates and their uncertainty. *Forest Ecology and Management*, **380**, 299-308. http://dx.doi.org/10.1016/j.foreco.2016.05.020

222. Moore, G.W., C.B. Edgar, J.G. Vogel, R.A. Washington-Allen, Rosaleen G. March, and R. Zehnder, 2016: Tree mortality from an exceptional drought spanning mesic to semiarid ecoregions. *Ecological Applications*, **26** (2), 602-611. http://dx.doi.org/10.1890/15-0330

223. Williams, A.P., C.D. Allen, A.K. Macalady, D. Griffin, C.A. Woodhouse, D.M. Meko, T.W. Swetnam, S.A. Rauscher, R. Seager, H.D. Grissino-Mayer, J.S. Dean, E.R. Cook, C. Gangodagamage, M. Cai, and N.G. McDowell, 2013: Temperature as a potent driver of regional forest drought stress and tree mortality. *Nature Climate Change*, **3** (3), 292-297. http://dx.doi.org/10.1038/nclimate1693

224. Brock, M.A., D.L. Nielsen, R.J. Shiel, J.D. Green, and J.D. Langley, 2003: Drought and aquatic community resilience: The role of eggs and seeds in sediments of temporary wetlands. *Freshwater Biology*, **48** (7), 1207-1218. http://dx.doi.org/10.1046/j.1365-2427.2003.01083.x

225. McKee, K.L., I.A. Mendelssohn, and 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. http://dx.doi.org/10.1111/j.1466-882X.2004.00075.x

226. Silliman, B.R., J. van de Koppel, M.D. Bertness, L.E. Stanton, and I.A. Mendelssohn, 2005: Drought, snails, and large-scale die-off of southern U.S. salt marshes. *Science*, **310** (5755), 1803-1806. http://dx.doi.org/10.1126/science.1118229

227. Diop, E.S., A. Soumare, N. Diallo, and A. Guisse, 1997: Recent changes of the mangroves of the Saloum River Estuary, Senegal. *Mangroves and Salt Marshes*, **1** (3), 163-172. http://dx.doi.org/10.1023/a:1009900724172

228. Duke, N.C., J.M. Kovacs, A.D. Griffiths, L. Preece, D.J.E. Hill, P. van Oosterzee, J. Mackenzie, H.S. Morning, and D. Burrows, 2017: Large-scale dieback of mangroves in Australia's Gulf of Carpentaria: A severe ecosystem response, coincidental with an unusually extreme weather event. *Marine & Freshwater Research*, **68** (10), 1816-1829. http://dx.doi.org/10.1071/MF16322

229. Lovelock, C.E., K.W. Krauss, M.J. Osland, R. Reef, and M.C. Ball, 2016: The physiology of mangrove trees with changing climate. *Tropical Tree Physiology: Adaptations and Responses in a Changing Environment*. Goldstein, G. and L.S. Santiago, Eds. Springer, Switzerland, 149-179.

230. Lovelock, C.E., I.C. Feller, R. Reef, S. Hickey, and M.C. Ball, 2017: Mangrove dieback during fluctuating sea levels. *Scientific Reports*, **7** (1), Article 1680. http://dx.doi.org/10.1038/s41598-017-01927-6

231. Reef, R. and C.E. Lovelock, 2015: Regulation of water balance in mangroves. *Annals of Botany*, **115** (3), 385-395. http://dx.doi.org/10.1093/aob/mcu174

232. Desantis, L.R.G., S. Bhotika, K. Williams, and 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. http://dx.doi.org/10.1111/j.1365-2486.2007.01440.x

233. Mitsch, W.J. and J.G. Gosselink, 2007: *Wetlands*, 4th ed. Wiley, New York, 600 pp.

234. Doney, S.C., M. Ruckelshaus, J.E. Duffy, J.P. Barry, F. Chan, C.A. English, H.M. Galindo, J.M. Grebmeier, A.B. Hollowed, N. Knowlton, J. Polovina, N.N. Rabalais, W.J. Sydeman, and L.D. Talley, 2012: Climate change impacts on marine ecosystems. *Annual Review of Marine Science*, **4**, 11-37. http://dx.doi.org/10.1146/annurev-marine-041911-111611

235. Hoegh-Guldberg, O. and J.F. Bruno, 2010: The impact of climate change on the world's marine ecosystems. *Science*, **328** (5985), 1523-1528. http://dx.doi.org/10.1126/science.1189930

236. Poloczanska, E.S., C.J. Brown, W.J. Sydeman, W. Kiessling, D.S. Schoeman, P.J. Moore, K. Brander, J.F. Bruno, L.B. Buckley, M.T. Burrows, C.M. Duarte, B.S. Halpern, J. Holding, C.V. Kappel, M.I. O'Connor, J.M. Pandolfi, C. Parmesan, F. Schwing, S.A. Thompson, and A.J. Richardson, 2013: Global imprint of climate change on marine life. *Nature Climate Change*, **3**, 919-925. http://dx.doi.org/10.1038/nclimate1958

237. Bjorndal, K.A., A.B. Bolten, M. Chaloupka, V.S. Saba, C. Bellini, M.A.G. Marcovaldi, A.J.B. Santos, L.F.W. Bortolon, A.B. Meylan, P.A. Meylan, J. Gray, R. Hardy, B. Brost, M. Bresette, J.C. Gorham, S. Connett, B.V.S. Crouchley, M. Dawson, D. Hayes, C.E. Diez, R.P. van Dam, S. Willis, M. Nava, K.M. Hart, M.S. Cherkiss, A.G. Crowder, C. Pollock, Z. Hillis-Starr, F.A. Muñoz Tenería, R. Herrera-Pavón, V. Labrada-Martagón, A. Lorences, A. Negrete-Philippe, M.M. Lamont, A.M. Foley, R. Bailey, R.R. Carthy, R. Scarpino, E. McMichael, J.A. Provancha, A. Brooks, A. Jardim, M. López-Mendilaharsu, D. González-Paredes, A. Estrades, A. Fallabrino, G. Martínez-Souza, G.M. Vélez-Rubio, R.H. Boulon, J.A. Collazo, R. Wershoven, V. Guzmán Hernández, T.B. Stringell, A. Sanghera, P.B. Richardson, A.C. Broderick, Q. Phillips, M. Calosso, J.A.B. Claydon, T.L. Metz, A.L. Gordon, A.M. Landry, D.J. Shaver, J. Blumenthal, L. Collyer, B.J. Godley, A. McGowan, M.J. Witt, C.L. Campbell, C.J. Lagueux, T.L. Bethel, and L. Kenyon, 2017: Ecological regime shift drives declining growth rates of sea turtles throughout the West Atlantic. *Global Change Biology*, **23** (11), 4556-4568. http://dx.doi.org/10.1111/gcb.13712

238. Ferrario, F., M.W. Beck, C.D. Storlazzi, F. Micheli, C.C. Shepard, and L. Airoldi, 2014: The effectiveness of coral reefs for coastal hazard risk reduction and adaptation. *Nature Communications*, **5**, 3794. http://dx.doi.org/10.1038/ncomms4794

239. Moberg, F. and C. Folke, 1999: Ecological goods and services of coral reef ecosystems. *Ecological Economics*, **29** (2), 215-233. http://dx.doi.org/10.1016/S0921-8009(99)00009-9

240. 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, and M.E. Hatziolos, 2007: Coral reefs under rapid climate change and ocean acidification. *Science*, **318** (5857), 1737-1742. http://dx.doi.org/10.1126/science.1152509

241. 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, and J. Roughgarden, 2003: Climate change, human impacts, and the resilience of coral reefs. *Science*, **301** (5635), 929-933. http://dx.doi.org/10.1126/science.1085046

242. Kuffner, I.B., B.H. Lidz, J.H. Hudson, and J.S. Anderson, 2015: A century of ocean warming on Florida Keys coral reefs: Historic in situ observations. *Estuaries and Coasts*, **38** (3), 1085-1096. http://dx.doi.org/10.1007/s12237-014-9875-5

243. Manzello, D.P., 2015: Rapid recent warming of coral reefs in the Florida Keys. *Scientific Reports*, **5**, Article 16762. http://dx.doi.org/10.1038/srep16762

244. McClenachan, L., G. O'Connor, B.P. Neal, J.M. Pandolfi, and J.B.C. Jackson, 2017: Ghost reefs: Nautical charts document large spatial scale of coral reef loss over 240 years. *Science Advances*, **3** (9), e1603155. http://dx.doi.org/10.1126/sciadv.1603155

245. Yates, K.K., D.G. Zawada, N.A. Smiley, and G. Tiling-Range, 2017: Divergence of seafloor elevation and sea level rise in coral reef ecosystems. *Biogeosciences*, **14** (6), 1739-1772. http://dx.doi.org/10.5194/bg-14-1739-2017

246. EPA, 2015: Climate Change in the United States: Benefits of Global Action. EPA 430-R-15-001. U.S. Environmental Protection Agency (EPA), Office of Atmospheric Programs, Washington, DC, 93 pp. https://www.epa.gov/cira/downloads-cira-report

247. Lane, D.R., R.C. Ready, R.W. Buddemeier, J.A. Martinich, K.C. Shouse, and C.W. Wobus, 2013: Quantifying and valuing potential climate change impacts on coral reefs in the United States: Comparison of two scenarios. *PLOS ONE*, **8** (12), e82579. http://dx.doi.org/10.1371/journal.pone.0082579

248. Anthony, K.R.N., J.A. Maynard, G. Diaz-Pulido, P.J. Mumby, P.A. Marshall, L. Cao, and O.V.E. Hoegh-Guldberg, 2011: Ocean acidification and warming will lower coral reef resilience. *Global Change Biology*, **17** (5), 1798-1808. http://dx.doi.org/10.1111/j.1365-2486.2010.02364.x

249. Doney, S.C., V.J. Fabry, R.A. Feely, and J.A. Kleypas, 2009: Ocean acidification: The other CO_2 problem. *Annual Review of Marine Science*, **1** (1), 169-192. http://dx.doi.org/10.1146/annurev.marine.010908.163834

250. ERS, 2017: Atlas of Rural and Small-Town America [web tool]. USDA, Economic Research Service (ERS), Washington, DC, accessed April 25. https://www.ers.usda.gov/data-products/atlas-of-rural-and-small-town-america/

251. NASS, 2017: Farm Labor Methodology and Quality Measures. USDA National Agricultural Statistics Service (NASS), Washington, DC, 11 pp. https://www.nass.usda.gov/Publications/Methodology_and_Data_Quality/Farm_Labor/11_2017/Quality%20Measures%20and%20Methodology

252. Lovett, H.B., S.B. Snider, K.K. Gore, and R.C. Muñoz, Eds., 2016: *Gulf of Mexico Regional Action Plan to Implement the NOAA Fisheries Climate Science Strategy*. NOAA Technical Memorandum NMFS-SEFSC-699. NOAA Southeast Fisheries Science Center, Miami, FL, 40 pp. http://dx.doi.org/10.7289/V5/TM-SEFSC-699

253. C3P, 2017: Carolinas Precipitation Patterns & Probabilities (C3P): An Atlas of Hydroclimate Extremes [web page]. Drought Indexes. Carolinas Integrated Sciences and Assessments, Columbia, SC, accessed June 4. https://www.cisa.sc.edu/atlas/carolinas-drought.html

254. Griffith, J.A., S.V. Stehman, and T.R. Loveland, 2003: Landscape trends in mid-Atlantic and southeastern United States ecoregions. *Environmental Management*, **32** (5), 572-588. http://dx.doi.org/10.1007/s00267-003-0078-2

255. Kinniburgh, F., M.G. Simonton, and C. Allouch, 2015: Come Heat and High Water: Climate Risk in the Southeastern U.S. and Texas. Gordon, K., Ed. Risky Business Project, New York, 109 pp. https://riskybusiness.org/site/assets/uploads/2015/09/Climate-Risk-in-Southeast-and-Texas.pdf

256. Ernst, K.M. and B.L. Preston, 2017: Adaptation opportunities and constraints in coupled systems: Evidence from the U.S. energy-water nexus. *Environmental Science & Policy*, **70**, 38-45. http://dx.doi.org/10.1016/j.envsci.2017.01.001

257. Sun, L., K.E. Kunkel, L.E. Stevens, A. Buddenberg, J.G. Dobson, and D.R. Easterling, 2015: Regional Surface Climate Conditions in CMIP3 and CMIP5 for the United States: Differences, Similarities, and Implications for the U.S. National Climate Assessment. NOAA Technical Report NESDIS 144. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, 111 pp. http://dx.doi.org/10.7289/V5RB72KG

258. USDA-NASS, 2017: Statistics by State [web site]. USDA, National Agricultural Statistical Service (NASS), Washington, DC, accessed July 18, 2017. https://www.nass.usda.gov/Statistics_by_State/

259. Clemson Cooperative Extension, 2018: About Peaches. Clemson University, Clemson, SC. https://www.clemson.edu/extension/peach/index.html

260. Luedeling, E., E.H. Girvetz, M.A. Semenov, and P.H. Brown, 2011: Climate change affects winter chill for temperate fruit and nut trees. *PLOS ONE*, **6** (5), e20155. http://dx.doi.org/10.1371/journal.pone.0020155

261. Luedeling, E., 2012: Climate change impacts on winter chill for temperate fruit and nut production: A review. *Scientia Horticulturae*, **144** (0), 218-229. http://dx.doi.org/10.1016/j.scienta.2012.07.011

262. Oswalt, S.N., W.B. Smith, P.D. Miles, and S.A. Pugh, 2014: Forest Resources of the United States, 2012: A Technical Document Supporting the Forest Service 2010 Update of the RPA Assessment. Gen. Tech. Rep. WO-91. USDA, Forest Service, Washington Office, Washington, DC, 218 pp. https://srs.fs.usda.gov/pubs/47322

263. Census Bureau, 2017: Annual Survey of Manufactures (ASM) [web site]. U.S. Census Bureau, accessed May 17. https://www.census.gov/programs-surveys/asm.html

264. Howell, B.J., 2002: Appalachian culture and environmental planning: Expanding the role of cultural sciences. *Culture, Environment, and Conservation in the Appalachian South*. Howell, B.J., Ed. University of Illinois Press, Urbana and Chicago (IL), 1–16.

265. Lewis, C., 2012: The case of the wild onions: The impact of ramps on Cherokee rights. *Southern Cultures*, **18** (2), 104-117. http://dx.doi.org/10.1353/scu.2012.0019

266. Bernatchez, A. and L. Lapointe, 2012: Cooler temperatures favour growth of wild leek (*Allium tricoccum*), a deciduous forest spring ephemeral. *Botany*, **90** (11), 1125-1132. http://dx.doi.org/10.1139/b2012-089

267. Leopold, S., 2017: Ramps now on the "to-watch" list: Time to ramp up conservation efforts. *United Plant Savers*. https://unitedplantsavers.org/ramps-now-on-the-to-watch-list/

268. NRCS, 2017: Plant profile: *Allium tricoccum* Aiton ramp. USDA Natural Resources Conservation Service (NRCS). https://plants.usda.gov/core/profile?symbol=ALTR3

269. Hansen, M.C., P.V. Potapov, R. Moore, M. Hancher, S.A. Turubanova, A. Tyukavina, D. Thau, S.V. Stehman, S.J. Goetz, T.R. Loveland, A. Kommareddy, A. Egorov, L. Chini, C.O. Justice, and J.R.G. Townshend, 2013: High-resolution global maps of 21st-century forest cover change. *Science*, **342** (6160), 850-853. http://dx.doi.org/10.1126/science.1244693

270. Brown, D.G., K.M. Johnson, T.R. Loveland, and D.M. Theobald, 2005: Rural land-use trends in the conterminous United States, 1950-2000. *Ecological Applications*, **15** (6), 1851-1863. http://dx.doi.org/10.1890/03-5220

271. 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. http://dx.doi.org/10.1525/bio.2010.60.4.7

272. Pederson, N., A.W. D'Amato, J.M. Dyer, D.R. Foster, D. Goldblum, J.L. Hart, A.E. Hessl, L.R. Iverson, S.T. Jackson, D. Martin-Benito, B.C. McCarthy, R.W. McEwan, D.J. Mladenoff, A.J. Parker, B. Shuman, and J.W. Williams, 2015: Climate remains an important driver of post-European vegetation change in the eastern United States. *Global Change Biology*, **21** (6), 2105-2110. http://dx.doi.org/10.1111/gcb.12779

273. Fei, S., J.M. Desprez, K.M. Potter, I. Jo, J.A. Knott, and C.M. Oswalt, 2017: Divergence of species responses to climate change. *Science Advances*, **3** (5), e1603055. http://dx.doi.org/10.1126/sciadv.1603055

274. McEwan, R.W., J.M. Dyer, and N. Pederson, 2011: Multiple interacting ecosystem drivers: Toward an encompassing hypothesis of oak forest dynamics across eastern North America. *Ecography*, **34** (2), 244-256. http://dx.doi.org/10.1111/j.1600-0587.2010.06390.x

275. Balch, J.K., B.A. Bradley, J.T. Abatzoglou, R.C. Nagy, E.J. Fusco, and A.L. Mahood, 2017: Human-started wildfires expand the fire niche across the United States. *Proceedings of the National Academy of Sciences of the United States of America*, **114** (11), 2946-2951. http://dx.doi.org/10.1073/pnas.1617394114

276. Stephens, S.L., J.J. Moghaddas, C. Edminster, C.E. Fiedler, S. Haase, M. Harrington, J.E. Keeley, E.E. Knapp, J.D. McIver, K. Metlen, C.N. Skinner, and A. Youngblood, 2009: Fire treatment effects on vegetation structure, fuels, and potential fire severity in western U.S. forests. *Ecological Applications*, **19** (2), 305-320. http://dx.doi.org/10.1890/07-1755.1

277. Terando, A.J., B. Reich, K. Pacifici, J. Costanza, A. McKerrow, and J.A. Collazo, 2016: Uncertainty quantification and propagation for projections of extremes in monthly area burned under climate change: A case study in the coastal plain of Georgia, USA. *Natural Hazard Uncertainty Assessment: Modeling and Decision Support*. Riley, K., P. Webley, and M. Thompson, Eds. American Geophysical Union, 245-256. http://dx.doi.org/10.1002/9781119028116.ch16

278. Newman, S., M. Carroll, P. Jakes, and L. Higgins, 2014: Hurricanes and wildfires: Generic characteristics of community adaptive capacity. *Environmental Hazards*, **13** (1), 21-37. http://dx.doi.org/10.1080/17477891.2013.841090

279. Wyman, M., S. Malone, T. Stein, and C. Johnson, 2012: Race and wildfire risk perceptions among rural forestland owners in north-central Florida. *Society & Natural Resources*, **25** (12), 1293-1307. http://dx.doi.org/10.1080/08941920.2012.681752

280. Kovach, M.M., C.E. Konrad, and C.M. Fuhrmann, 2015: Area-level risk factors for heat-related illness in rural and urban locations across North Carolina, USA. *Applied Geography*, **60**, 175-183. http://dx.doi.org/10.1016/j.apgeog.2015.03.012

281. Sugg, M.M., C.E. Konrad, and C.M. Fuhrmann, 2016: Relationships between maximum temperature and heat-related illness across North Carolina, USA. *International Journal of Biometeorology*, **60** (5), 663-675. http://dx.doi.org/10.1007/s00484-015-1060-4

282. Gubernot, D.M., G.B. Anderson, and K.L. Hunting, 2015: Characterizing occupational heat-related mortality in the United States, 2000–2010: An analysis using the census of fatal occupational injuries database. *American Journal of Industrial Medicine*, **58** (2), 203-211. http://dx.doi.org/10.1002/ajim.22381

283. Gutierrez, K. and C. LePrevost, 2016: Climate justice in rural southeastern United States: A review of climate change impacts and effects on human health. *International Journal of Environmental Research and Public Health*, **13** (2), 189. http://dx.doi.org/10.3390/ijerph13020189

284. Morss, R.E., O.V. Wilhelmi, G.A. Meehl, and L. Dilling, 2011: Improving societal outcomes of extreme weather in a changing climate: An integrated perspective. *Annual Review of Environment and Resources*, **36** (1), 1-25. http://dx.doi.org/10.1146/annurev-environ-060809-100145

285. Pye, S., A. Dobbins, C. Baffert, J. Brajković, I. Grgurev, R. De Miglio, and P. Deane, 2015: Energy Poverty and Vulnerable Consumers in the Energy Sector Across the EU: Analysis of Policies and Measures. Policy Report 2. European Commission, Insight_E, Stockholm, Sweden, 77 pp. https://ec.europa.eu/energy/en/studies/energy-poverty-and-vulnerable-consumers-energy-sector-across-eu-analysis-policies-and

286. Harrison, C. and J. Popke, 2011: "Because you got to have heat": The networked assemblage of energy poverty in eastern North Carolina. *Annals of the Association of American Geographers*, **101** (4), 949-961. http://dx.doi.org/10.1080/00045608.2011.569659

287. NWS, [2018]: What Are Heating and Cooling Degree Days [web page]. NOAA National Weather Service (NWS), Key West, FL, accessed February 27. https://www.weather.gov/key/climate_heat_cool

288. Horney, J., M. Nguyen, D. Salvesen, C. Dwyer, J. Cooper, and P. Berke, 2017: Assessing the quality of rural hazard mitigation plans in the southeastern United States. *Journal of Planning Education and Research*, **37** (1), 56-65. http://dx.doi.org/10.1177/0739456x16628605

289. NC Rural Health Research Program, 2017: Rural Hospital Closures: January 2010–Present. UNC, Cecil G. Sheps Center for Health Services Research, Chapel Hill, NC. http://www.shepscenter.unc.edu/programs-projects/rural-health/rural-hospital-closures/

290. Houghton, A., J. Austin, A. Beerman, and C. Horton, 2017: An approach to developing local climate change environmental public health indicators in a rural district. *Journal of Environmental and Public Health*, **2017**, 16. http://dx.doi.org/10.1155/2017/3407325

291. Douglas, E., J. Jacobs, K. Hayhoe, L. Silka, J. Daniel, M. Collins, A. Alipour, B. Anderson, C. Hebson, E. Mecray, R. Mallick, Q. Zou, P. Kirshen, H. Miller, J. Kartez, L. Friess, A. Stoner, E. Bell, C. Schwartz, N. Thomas, S. Miller, B. Eckstrom, and C. Wake, 2017: Progress and challenges in incorporating climate change information into transportation research and design. *Journal of Infrastructure Systems*, **23** (4), 04017018. http://dx.doi.org/10.1061/(ASCE)IS.1943-555X.0000377

292. Miller, R., D. Arthur, B. Barami, A. Breck, S. Costa, K. Lewis, K. McCoy, and E. Morrison, 2016: Hampton Roads Climate Impact Quantification Initiative: Baseline Assessment of the Transportation Assets & Overview of Economic Analyses Useful in Quantifying Impacts. DOT-VNTSC-OSTR-17-01. Volpe National Transportation Systems Center, Cambridge, MA, 167 pp. https://trid.trb.org/view/1428258

293. Arnbjerg-Nielsen, K., P. Willems, J. Olsson, S. Beecham, A. Pathirana, I. Bülow Gregersen, H. Madsen, and V.-T.-V. Nguyen, 2013: Impacts of climate change on rainfall extremes and urban drainage systems: A review. *Water Science and Technology*, **68** (1), 16-28. http://dx.doi.org/10.2166/wst.2013.251

294. Bell, M.L., R. Goldberg, C. Hogrefe, P.L. Kinney, K. Knowlton, B. Lynn, J. Rosenthal, C. Rosenzweig, and J.A. Patz, 2007: Climate change, ambient ozone, and health in 50 US cities. *Climatic Change*, **82** (1-2), 61-76. http://dx.doi.org/10.1007/s10584-006-9166-7

295. Census Bureau, 2015: Press release: New Census Bureau Population Estimates Reveal Metro Areas and Counties That Propelled Growth in Florida and the Nation. *Census Newsroom*, March 26. U.S. Census Brueau. https://www.census.gov/newsroom/press-releases/2015/cb15-56.html

296. ARC, 2017: Population & Employment Forecasts. Atlanta Regional Commission (ARC), Atlanta, GA. http://www.atlantaregional.com/info-center/forecasts

297. Gregg, R.M., W.A. Reynier, A. Score, and L. Hilberg, 2017: State of Climate Adaptation in Water Resources Management: Southeastern United States and U.S. Caribbean. EcoAdapt, Bainbridge Island, WA, 214 pp. https://www.cakex.org/sites/default/files/documents/EcoAdapt_State%20of%20Adaptation_U.S.%20Southeast%20and%20Caribbean_December%202017.pdf

298. City of Fayetteville, 2017: Arkansans Can Take Steps to Respond to Climate Change. Fayetteville, AR. http://www.fayetteville-ar.gov/DocumentCenter/View/14890/Commentary_Climate-Change?bidId=

299. City of Atlanta, 2017: Resilient Atlanta: Actions to Build a More Equitable Future. 100 Resilient Cities, 150 pp. http://100resilientcities.org/wp-content/uploads/2017/11/Atlanta-Resilience-Strategy-PDF-v2.pdf

300. Stone, B., J. Vargo, P. Liu, Y.T. Hu, and A. Russell, 2013: Climate change adaptation through urban heat management in Atlanta, Georgia. *Environmental Science & Technology*, **47** (14), 7780-7786. http://dx.doi.org/10.1021/es304352e

301. Rosenzweig, C., W. Solecki, P. Romero-Lankao, S. Mehrotra, S. Dhakal, T. Bowman, and S. Ali Ibrahim, 2015: ARC3.2 Summary for City Leaders. Urban Climate Change Research Network, Columbia University, New York. http://uccrn.org/arc3-2/

302. Demuzere, M., K. Orru, O. Heidrich, E. Olazabal, D. Geneletti, H. Orru, A.G. Bhave, N. Mittal, E. Feliu, and M. Faehnle, 2014: Mitigating and adapting to climate change: Multi-functional and multi-scale assessment of green urban infrastructure. *Journal of Environmental Management*, **146**, 107-115. http://dx.doi.org/10.1016/j.jenvman.2014.07.025

303. Masson, V., C. Marchadier, L. Adolphe, R. Aguejdad, P. Avner, M. Bonhomme, G. Bretagne, X. Briottet, B. Bueno, C. de Munck, O. Doukari, S. Hallegatte, J. Hidalgo, T. Houet, J. Le Bras, A. Lemonsu, N. Long, M.P. Moine, T. Morel, L. Nolorgues, G. Pigeon, J.L. Salagnac, V. Viguié, and K. Zibouche, 2014: Adapting cities to climate change: A systemic modelling approach. *Urban Climate*, **10**, 407-429. http://dx.doi.org/10.1016/j.uclim.2014.03.004

304. Gill, S.E., J.F. Handley, A.R. Ennos, and S. Pauleit, 2007: Adapting cities for climate change: The role of the green infrastructure. *Built Environment*, **33** (1), 115-133. http://dx.doi.org/10.2148/benv.33.1.115

305. Binita, K.-C., J.M. Shepherd, and C.J. Gaither, 2015: Climate change vulnerability assessment in Georgia. *Applied Geography*, **62**, 62-74. http://dx.doi.org/10.1016/j.apgeog.2015.04.007