

Chapter 2

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

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

Key Findings

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

2.1 General Description

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

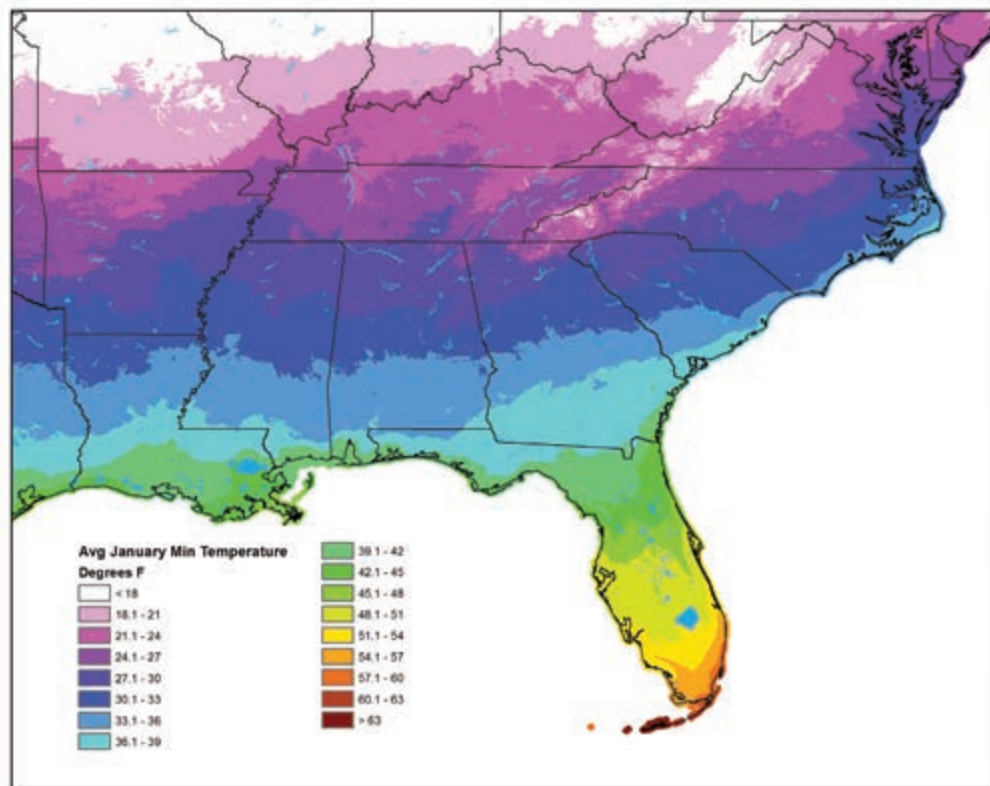


Figure 2.1 Map of average daily January minimum temperature. Source: Parameter-elevation Regressions on Independent Slopes Model, or PRISM; <http://www.prism.oregonstate.edu/>.

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

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

or immediately south of the area for extended periods, drought conditions typically develop. This places stress on water supplies and agricultural crops and can reduce hydroelectric energy production. Variations in the positioning of the Bermuda High also affect how hurricanes move across the region.

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

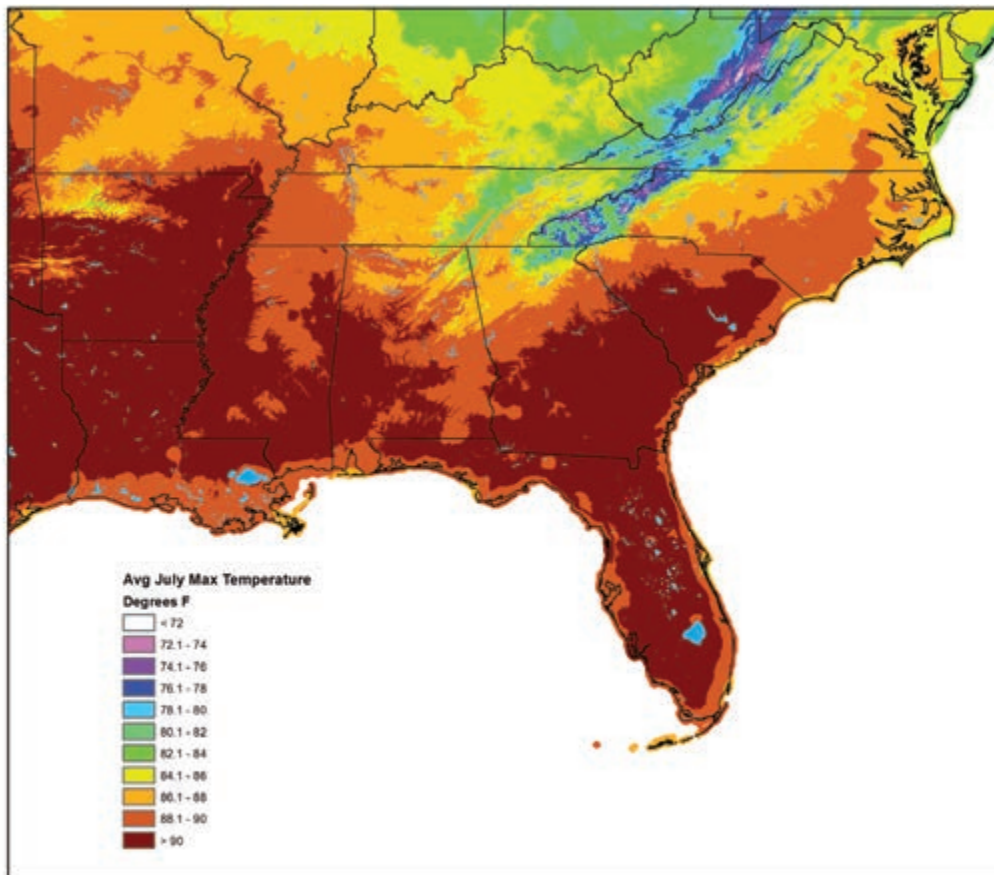


Figure 2.2 Map of average daily July maximum temperature. Source: Parameter-elevation Regressions on Independent Slopes Model, or PRISM; <http://www.prism.oregonstate.edu/>.

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

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

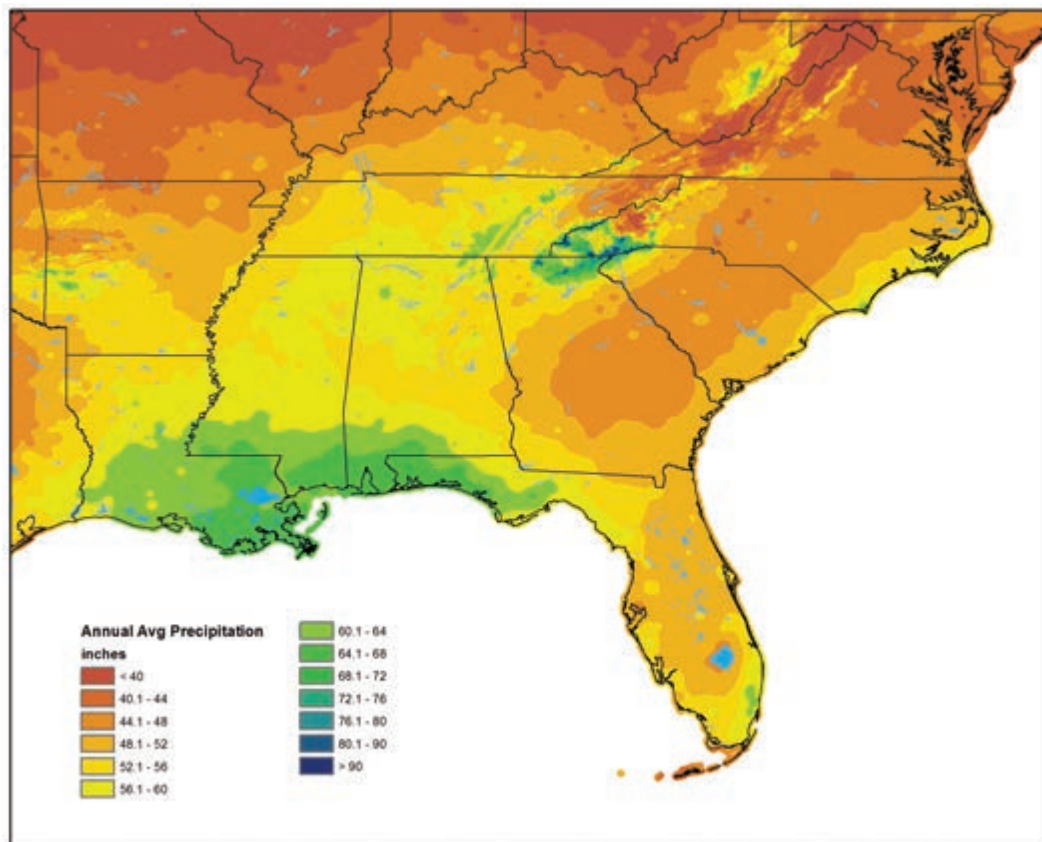


Figure 2.3 Map of annual average precipitation. Source: *Parameter-elevation Regressions on Independent Slopes Model, or PRISM*; <http://www.prism.oregonstate.edu/>.

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

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

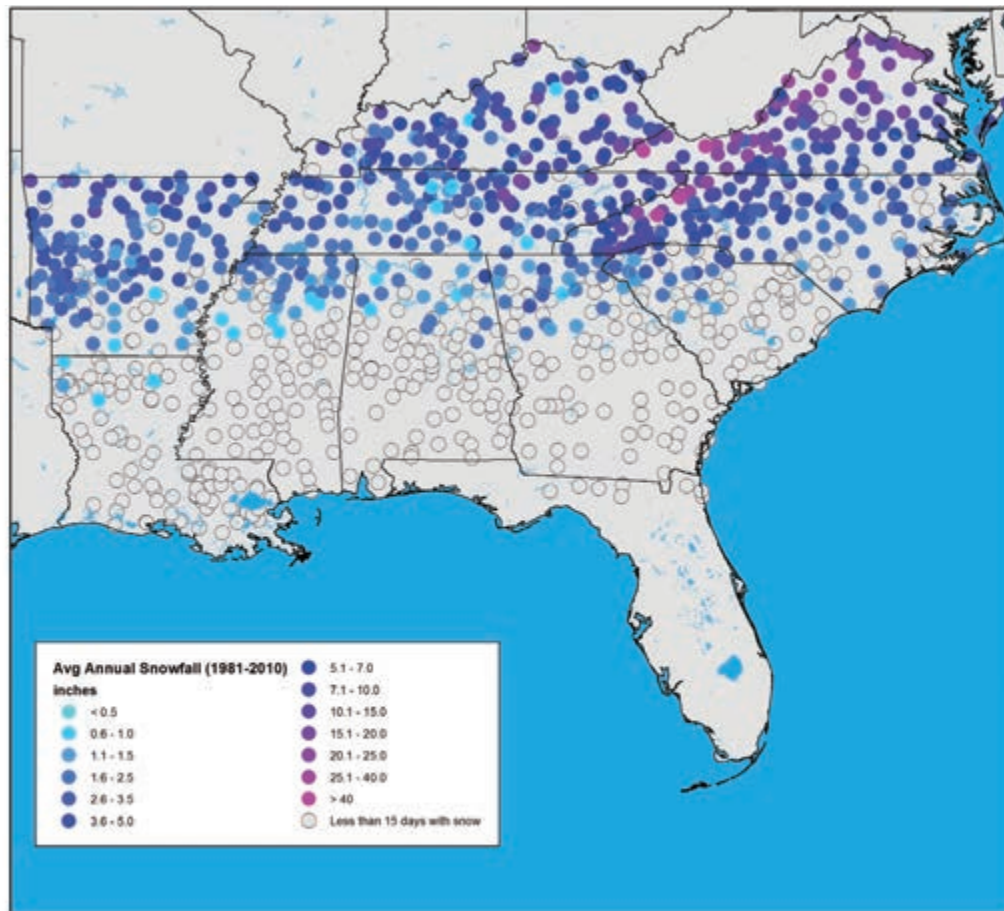


Figure 2.4 Annual average snowfall from 1981 to 2010. Source: *Global Historical Climatology Network, or GHCN*; <http://www.ncdc.noaa.gov/oa/climate/ghcn-daily/>.

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

2.2 Extreme Events

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

Heavy Rainfall and Floods

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

associated with tropical cyclones from 1970 to 1999, nearly 60% resulted from inland freshwater floods (Rappaport 2000). As air passes over mountains the very moist air in tropical cyclones rises quickly, which can produce extraordinary precipitation totals, resulting in flash and river flooding as well as landslides on the steeper slopes of the southern Appalachians (Fuhrmann et al. 2008).

Droughts

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

Extreme Heat and Cold

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

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

Box 2.1*Extreme Drought amongst a Record Flood*

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

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



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

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

Winter Storms

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

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

Severe Thunderstorms and Tornadoes

Thunderstorms are frequent occurrences across the SE during the warmer months of the year. Severe thunderstorms, which are defined by the occurrence of winds in excess of 58 mph, hail at least 1 in diameter, or a tornado, occur most frequently in the late winter and spring months. Damaging winds and large hail occur most frequently across Alabama, Mississippi, Arkansas, western Tennessee, and northern Louisiana. These states also experience the highest number of strong tornadoes (F2 and greater) and experiences more killer tornadoes than the notorious “Tornado Alley” of the Great Plains (Ashley 2007) (see Figure 9 in Kunkel et al. 2013). The high death tolls can be attributed to increased mobile home density, longer path lengths, and a greater number of cool season and nocturnal tornadoes (Brooks et al. 2003, Ashley 2007, Ashley et

al. 2008, Dixon et al. 2011). Cloud-to-ground lightning is also a significant hazard. The greatest frequencies of lightning strikes in the USA are found across the Gulf Coast and the Florida Peninsula. Moreover, eight of the eleven SE states rank in the top 20 for lightning-related fatalities from 1959 to 2006 (Ashley and Gilson 2009). Cloud-to-ground lightning also starts many house fires during the warm season and in rare instances can ignite wildfires.

Tropical Cyclones

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

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

2.3 Trends

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

Precipitation

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

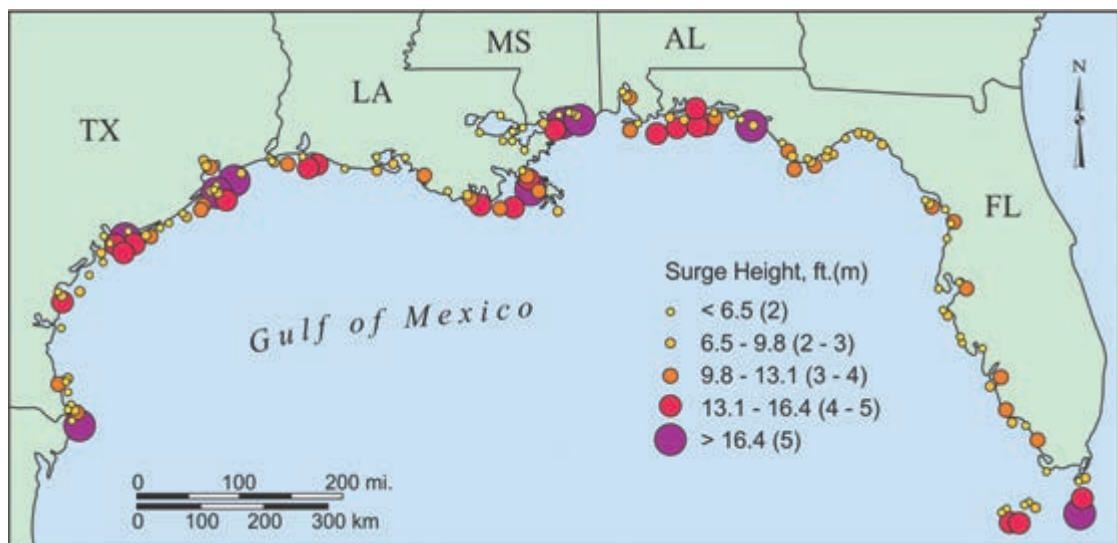
Box 2.2*Gulf Coast Storm Surge Database*

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

Analysis of storm surge activity along the USA Gulf of Mexico reveals that the greatest storm surge activity, in terms of both surge magnitudes and frequencies, generally occurs along the northern and western coast, as well as the Florida Keys. Florida's West Coast, from the eastern Panhandle to the Everglades, has generally observed less storm surge activity. Along the USA East Coast

the largest surges have generally occurred in South Florida and the Carolinas, although several large surges have also impacted the Mid-Atlantic and Southern New England Coasts.

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



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

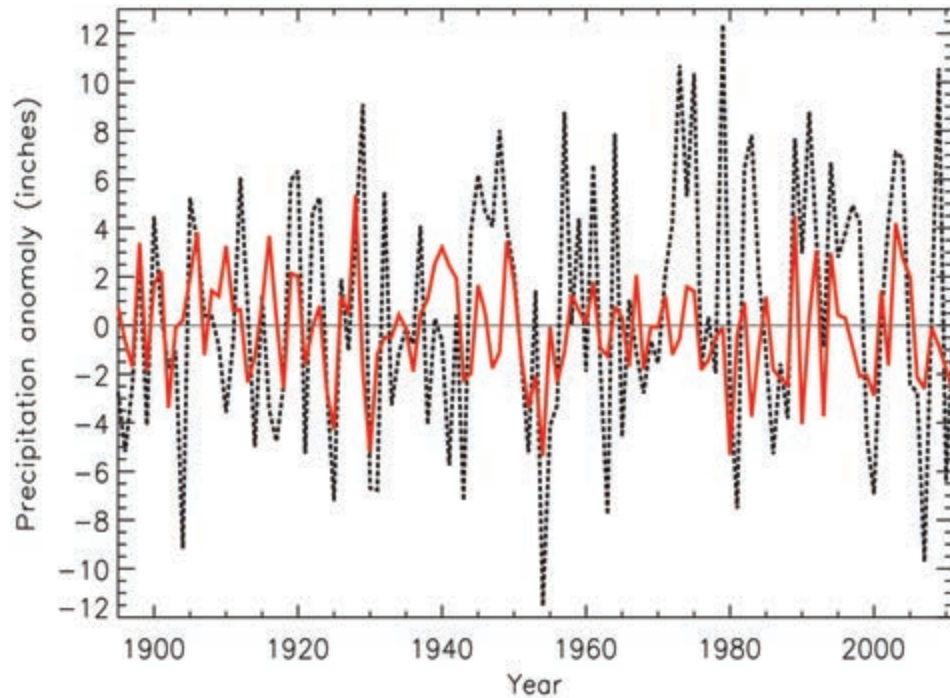


Figure 2.5 Annual (black/dotted line) and summer season (red/grey) precipitation anomalies for the SE. Source: Cooperative Observer data from the National Climatic Data Center.

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

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

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

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

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

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

Heavy Rainfall and Floods

The frequency of extreme precipitation events has been increasing across the southeastern region, particularly over the past two decades (Figure 2.6). Increases in extreme precipitation events are most pronounced across the lower Mississippi River Valley and along the northern Gulf Coast (see Figures 22 and 23 in Kunkel et al. 2013). Despite a long-term increase in extreme precipitation events, there is no discernible trend in the

magnitude of floods along ex-urban, unregulated streams across the region (Hirsch and Ryberg 2011). The increase in extreme precipitation, coupled with increased runoff due to the expansion of impervious surfaces and urbanization, has led to an increased risk of flooding in the region's urban areas (e.g., the record-breaking Atlanta, GA flood in 2009) (Shepherd et al. 2011). Time series of extreme precipitation events are available at the climate division level from the following website: <http://charts.srcc.lsu.edu/ghcn/>.

Temperature

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

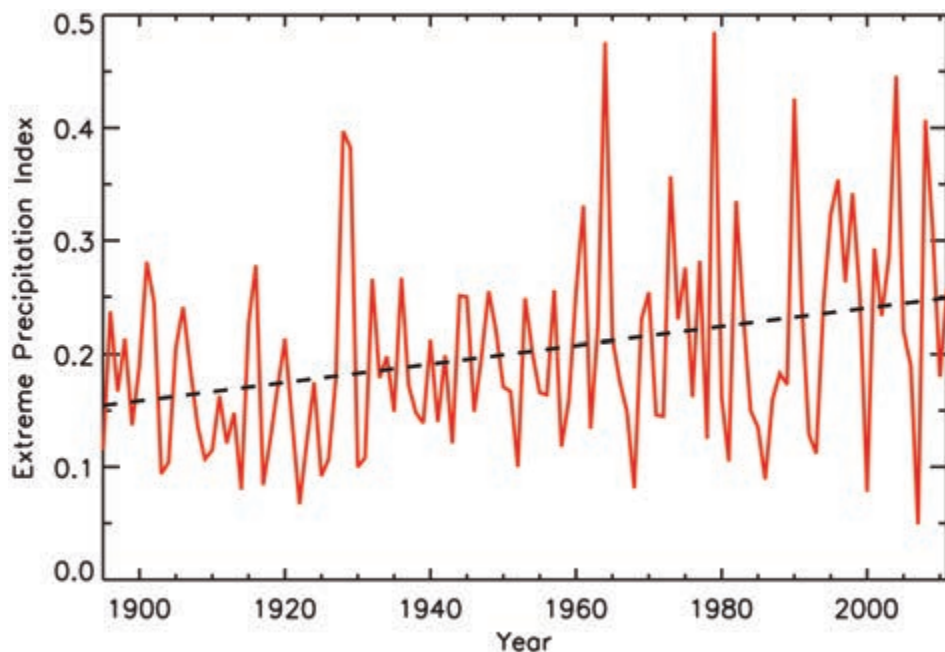


Figure 2.6 Time series of the extreme precipitation index (using a 5-year running average) for the SE for the occurrence of 1-day, 1 in 5 year extreme precipitation events (red/grey line) and 5-day, 1 in 5 year events (black/dashed line). Source: Cooperative observer data from the National Climatic Data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

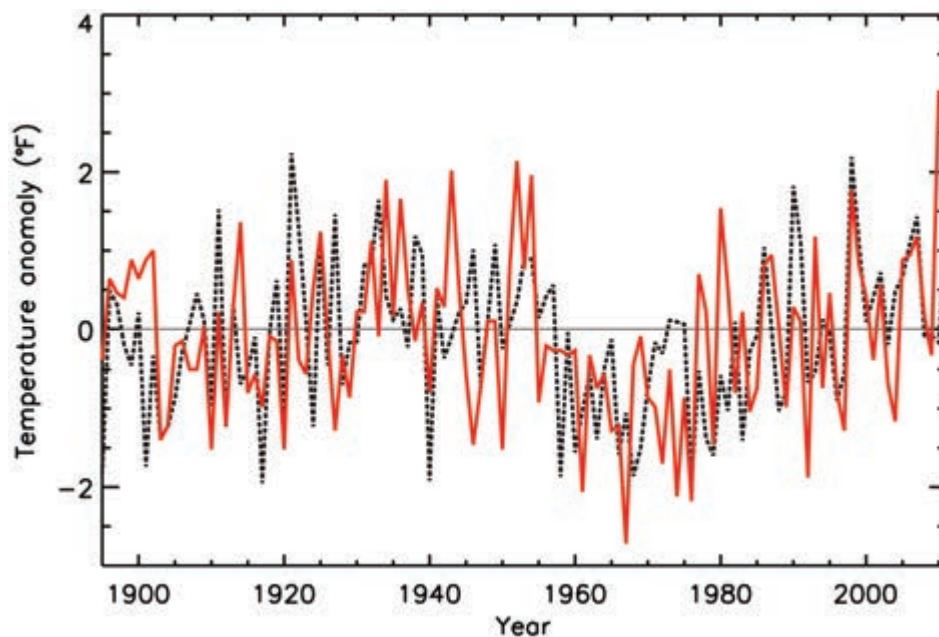


Figure 2.7 Annual (black/dotted line) and summer season (red/grey) temperature anomalies for the SE. Source: Cooperative observer data from the National Climatic Data Center.

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

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

Extreme Heat and Cold

The frequency of maximum temperatures exceeding 95°F has been declining across much of the SE since the early 20th century, particularly across the lower Mississippi River Valley (see Figure 13 in Kunkel et al. 2013). Higher frequencies of extreme maximum temperatures are noted in the 1930s and 1950s and correspond to periods of exceptionally dry weather. Following a period of relatively few extreme maximum temperatures in the 1960s and 1970s, there has been an upward trend over the last three decades, particularly across the northern Gulf Coast, Florida Peninsula, and northern Virginia. The frequency of minimum temperatures exceeding 75°F has generally been

increasing across most of the SE region. This increase is most pronounced over the past few decades (see Figure 14 in Kunkel et al. 2013) and has been attributed largely to human development of the surface (Christy 2002, DeGaetano and Allen 2002). Time series of extreme heat and cold are available at the climate division level from the following website: <http://charts.srcc.lsu.edu/ghcn/>.

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

Winter Storms

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

Severe Thunderstorms and Tornadoes

There has been a marked increase in the number of severe thunderstorm reports, including tornadoes over the last 50 years; however, this increase is associated with a much-improved ability to identify and record storm damage. In the case of tornadoes, improved radar technology (Doppler) has allowed meteorologists to resolve storm circulations and identify where to anticipate storm damage (Verbout et al. 2006). The annual frequencies of strong tornadoes (F1 and greater) have remained relatively con-

stant nationally over the last 50 years (Brooks and Doswell 2001). Preliminary statistics suggest that the 2011 storm season was one of the most active and deadliest on record; however, this is not part of an upward trend. Due to increased public awareness as well as improved weather forecasting and technology, tornado fatalities have declined dramatically since the 1930s (Ashley 2007) in spite of the fact that the population has increased in tornado-prone areas.

Hurricanes

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

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

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

Trends in Atlantic basin tropical cyclone frequency and landfalls dating back 1,500 years have been estimated using various proxy reconstructions that include the use of

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

Sea Level Rise and Sea Surface Temperatures

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

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

2.4 Future Projections

This section provides a summary of future climate projections for the southeastern USA based on recently published studies and an independent analysis of model output from statistically and dynamically downscaled datasets. These include global climate

model output and statistically downscaled monthly and daily climate projections from phase 3 of the Coupled Model Inter-comparison Project (CMIP3) as well as dynamically downscaled output from the North American Regional Climate Change Assessment Program (NARCCAP). The reader is directed to Kunkel et al. (2013) for a detailed description of the model datasets and methods used as well as measures of model uncertainty and agreement.

Precipitation

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

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

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

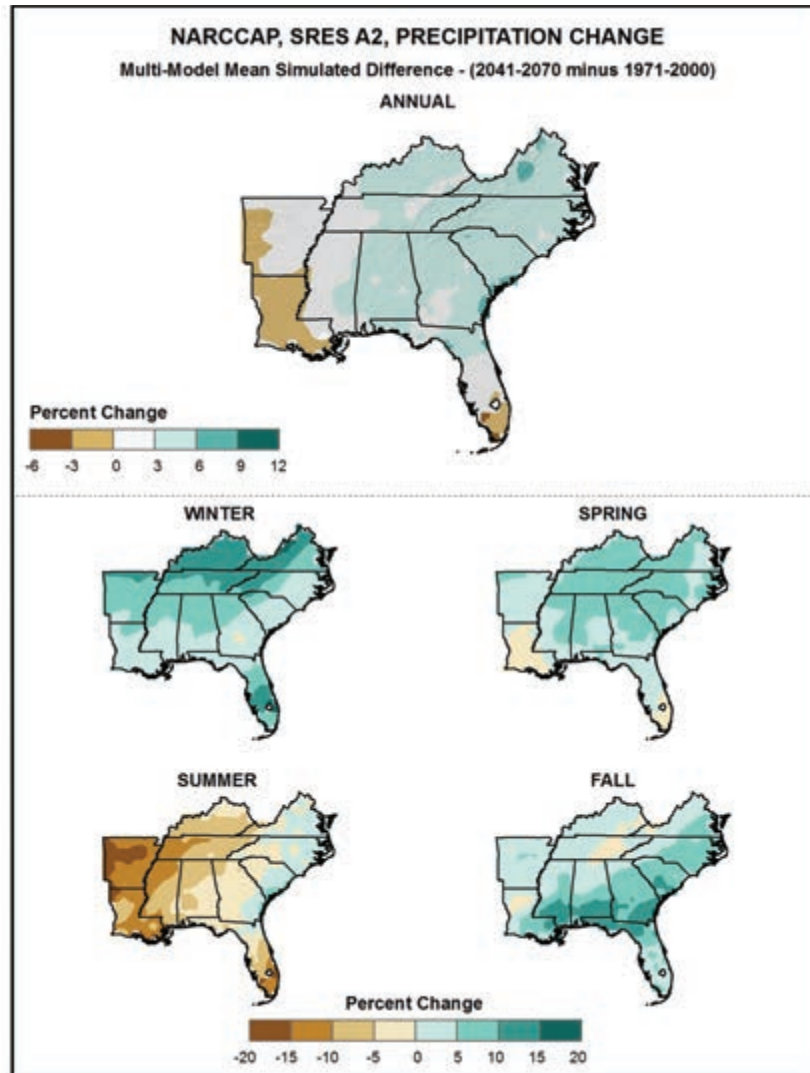


Figure 2.8 Annual and seasonal difference in precipitation (percent) between projections for 2041–2070 and the baseline of 1971–2000. *Source: North American Regional Climate Change Assessment Program (NARCCAP).*

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

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

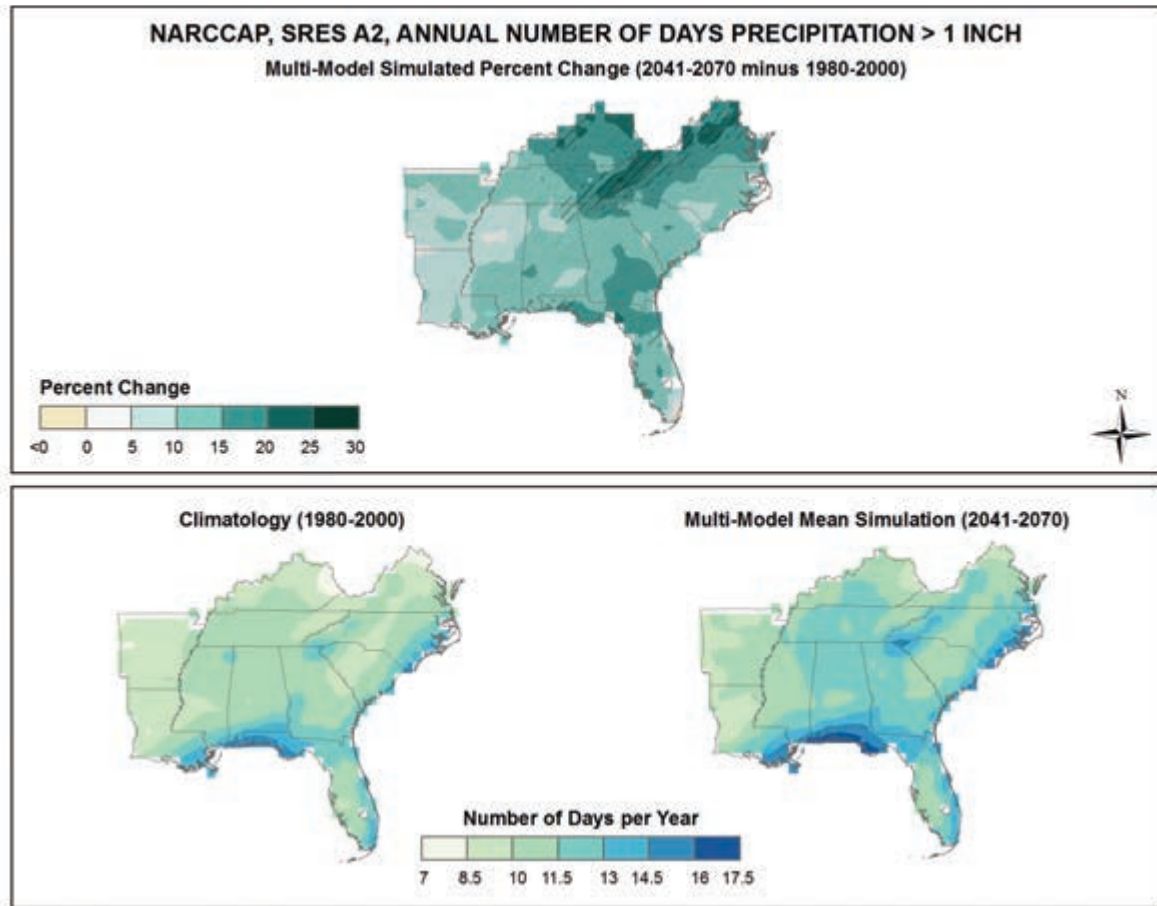
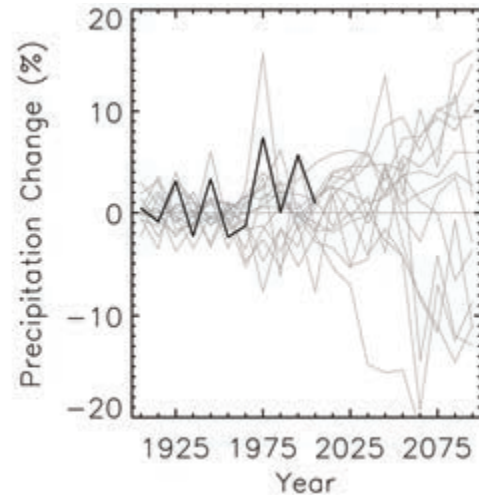


Figure 2.9 Mean change in annual number of days with precipitation exceeding 1 inch (projections for 2041–2070 minus the baseline of 1971–2000). *Source: North American Regional Climate Change Assessment Program (NARCCAP).*

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

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



Temperature

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

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

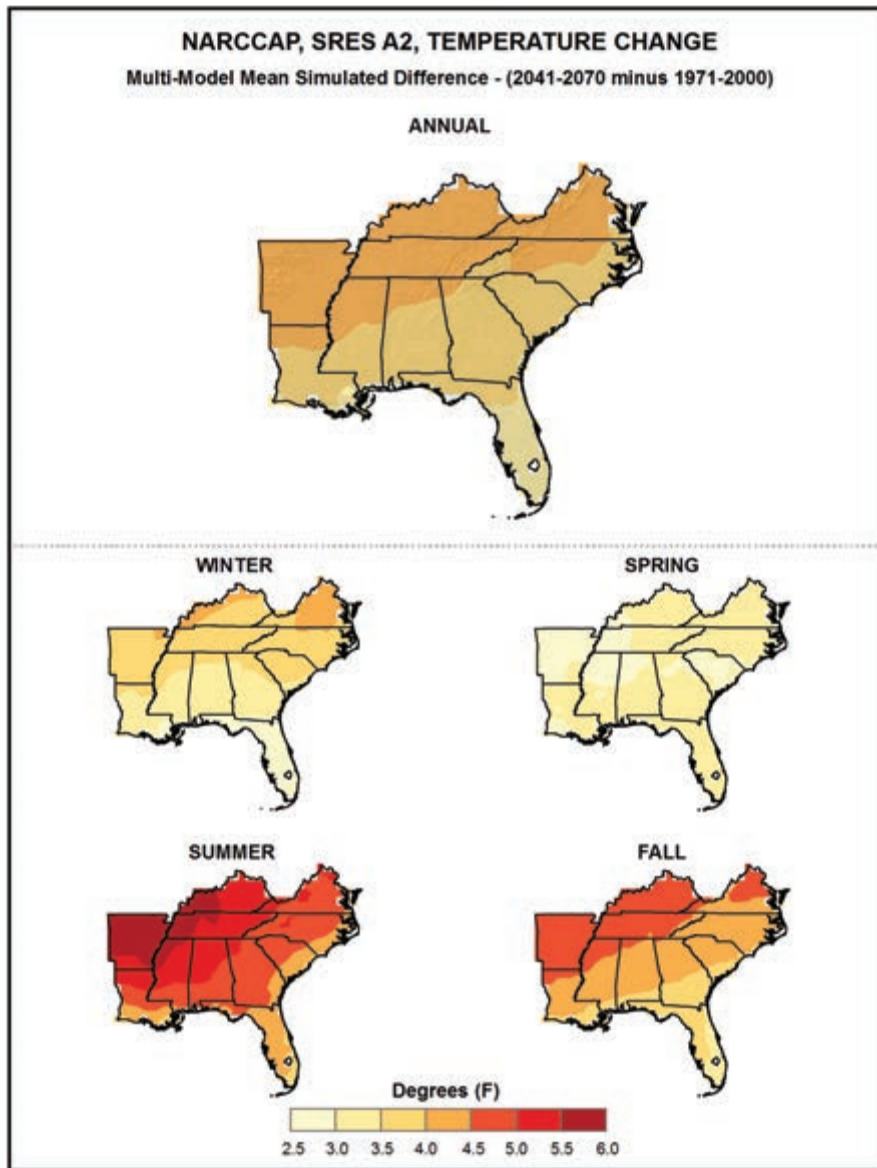


Figure 2.11 Annual and seasonal difference in temperature (°F) (projections for 2041–2070 minus the baseline of 1971–2000). Source: North American Regional Climate Change Assessment Program (NARCCAP).

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

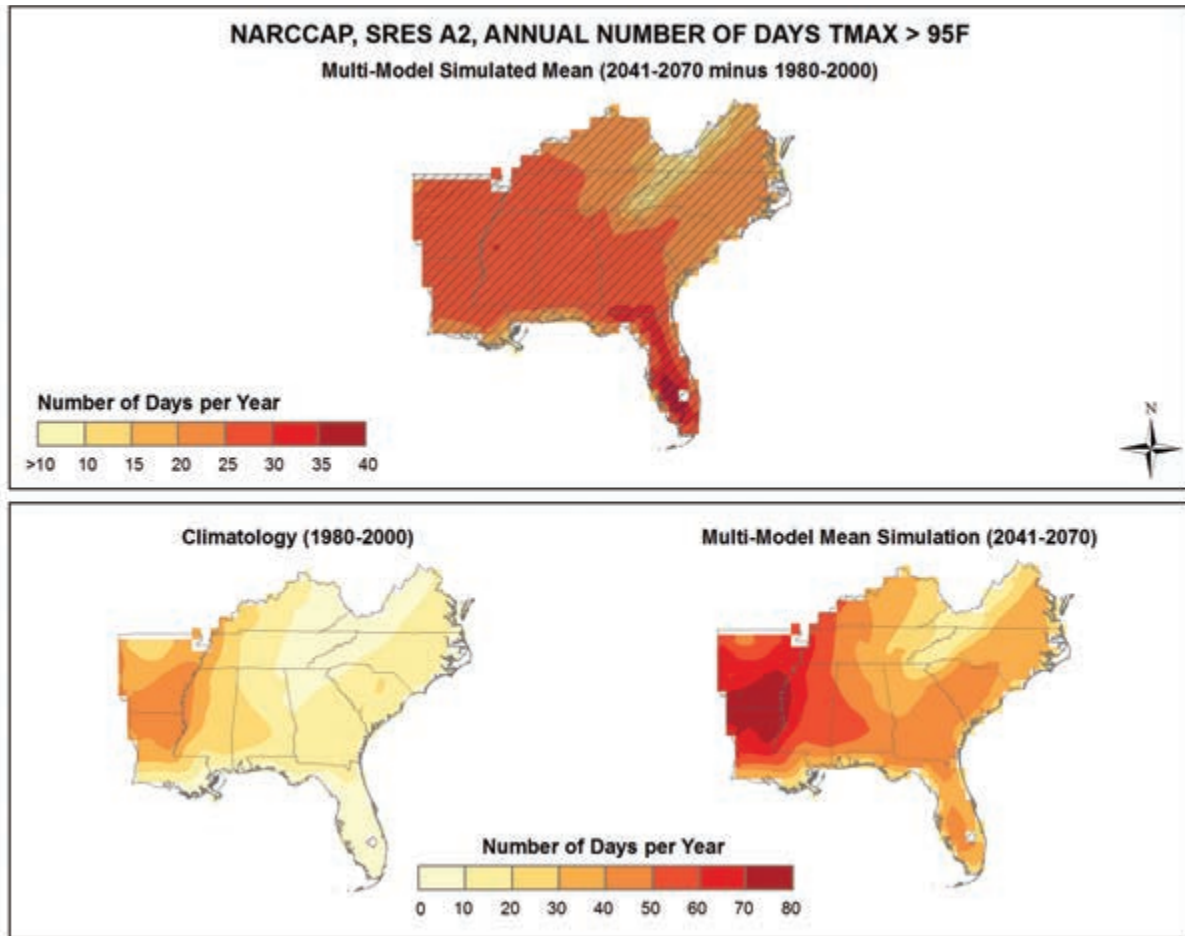


Figure 2.12 Mean change in annual number of days with a maximum temperature exceeding 95°F (projections for 2041–2070 and baseline of 1980–2000). Areas with hatching indicate more than 50% of the models show a statistically significant change in the number of days with a maximum temperature exceeding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

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

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

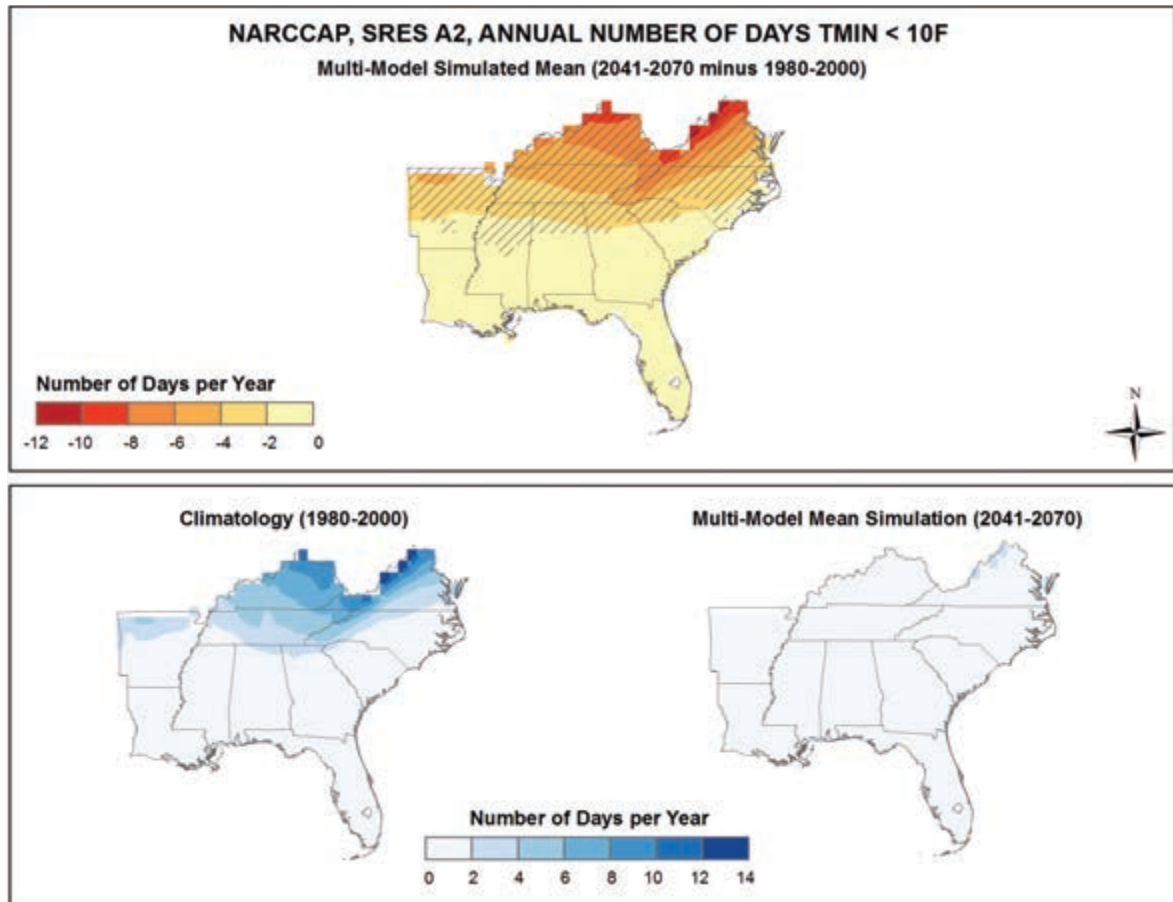


Figure 2.13 Mean change in annual number of days with minimum temperatures below 10°F (projections for 2041–2070 and baseline of 1980–2000). Areas with hatching indicate more than 50% of the models show a statistically significant change in the number of days with a maximum temperature exceeding 95°F,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

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

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

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

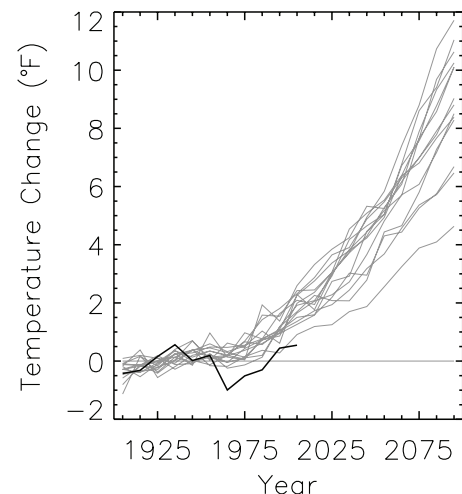
Droughts

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

Severe Thunderstorms and Tornadoes

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

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



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

Hurricanes

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

Sea Level Rise and Sea Surface Temperatures

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

North Atlantic sea surface temperatures are expected to increase by the end of the 21st century, with the greatest increases (3°C) noted in a region extending eastward across the subtropics from South Florida and the Bahamas. Smaller increases are projected across the higher latitudes of the North Atlantic as well as the Caribbean Sea and Gulf of Mexico (Biasutti et al. 2009, Leloup and Clement 2009). However, there is signifi-

cant uncertainty in SST projections in these regions, as recent studies indicate significant model errors and biases in the IPCC AR4 projections, for instance, a cold bias in sea surface temperatures across the Gulf of Mexico (Richer and Xie 2008, Misra et al. 2009).

Air Quality

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

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