Strategic Statewide Resilience and Risk Reduction Plan

4 | CLIMATE TRENDS

OVERVIEW

This section was developed in partnership with the University of South Carolina, South Carolina State Climatology Office, and South Carolina Sea Grant Consortium. The chapter includes background information regarding the drivers of global climate trends and climate variability, long-term changes in South Carolina's instrumental record, and projected future changes in the state.

CONTENTS

KEY FINDINGS

TEMPERATURE

- Since 1895, South Carolina's average annual temperature has increased by approximately 1°F, lower than the average global increase of approximately 2°F. However, the rise during the past 60 years has matched or exceeded global increases and the past 30 years have been warmer than any other consecutive 30-year period.
- The instrumental temperature record includes considerable year-to-year and decade-to-decade variability.
- Most stations exhibit statistically significant increases in a) maximum temperature in winter, spring, and summer, and b) minimum temperature in summer. While the state has had temperature increases in the past sixty years, few stations exhibit maximum temperature trends during fall, or minimum temperature trends during winter, spring, or fall when considering records from the beginning of the early 20th century.
- Climate models project South Carolina temperature increases of 5° to 10°F by the year 2100, depending on future greenhouse gas emissions.

PRECIPITATION

- South Carolina's precipitation has varied greatly on a yearly and decadal basis.
- Summer precipitation has decreased and the number of precipitation days in fall has increased; overall, few other statistically significant trends are found for seasonal or annual total precipitation.
- There are relatively few statistically significant long-term trends in heavy precipitation. However, recent heavy precipitation events affecting the coastal regions and the Pee Dee River Basin (2015, 2016, 2018) match expectations of a warmer world with higher evaporation rates and atmospheric moisture.
- Drought has periodically affected all parts of the state. The historical record reveals considerable interannual and interdecadal variability, but no statistical trend. Rising temperatures in the 21st century will likely exacerbate agricultural and hydrologic drought.

TROPICAL CYCLONES

- South Carolina's geographic position makes it vulnerable to tropical cyclones. The impact of tropical storms and hurricanes affecting the state have fluctuated greatly across years and decades.
- Their frequency and intensity have been influenced by large-scale conditions including sea-surface temperature and wind shear.
- Future scenarios are mixed with respect to the frequency of storms, but consistently project greater intensity of wind and precipitation for those storms that do occur.

MARINE CLIMATE IMPACTS

- South Carolina's coast is low-lying and vulnerable to sea level rise. Sea levels have already risen by approximately 1 foot and will further rise by approximately 1 foot by 2050. Projections for sea level rise by 2150 range from 2 to 16 feet.
- Sea surface temperature increases off the Carolinas are statistically significant, and projected increases of 7 to 9 °F by 2100 would be among the highest nationally.
- Ocean acidification is currently stressing marine organisms and is projected to accelerate.
- Beyond sea level rise, South Carolina will experience compound changes (a combination of impacts that could be larger than each individually) in our coastal and marine waters including sea surface temperature, ocean acidification, salinity, deoxygenation, and potential disruptions to the Gulf Stream.
- Physical and chemical changes are expected to create harmful impacts for marine ecosystems and coastal economies in South Carolina.

OBSERVATIONS AND PROJECTIONS FOR SOUTH CAROLINA'S CLIMATE

GLOBAL CLIMATE

Global, regional, and local climate varies through time and is influenced by many factors. Changes in solar output, Earth's orbital cycles, volcanic eruptions, and feedbacks within the climate system are often considered "natural" causes of changes to climate. By contrast, "anthropogenic" factors include those resulting from human activities, such as the emissions of greenhouse gases. Today, both natural and anthropogenic factors affect Earth's climate across all scales – both spatial and temporal. In the absence of any changes, the earth-atmosphere system will maintain a radiation balance by which absorbed solar radiation is matched by outgoing infrared radiation (Figure 4.1). Climate scientists often use the concept of radiative forcing to quantify changes to this balance. It is possible, for example, to estimate how solar cycles, changes to Earth's axial tilt, emission of aerosols from volcanic eruptions or industrial activity, cloud type and distribution, or land use changes alter the solar radiation absorbed at Earth's surface, or how changing greenhouse gas concentrations affect the rate of radiation loss to space. The increase of greenhouse gas concentrations since the industrial revolution has slowed this latter rate such that absorbed solar radiation exceeds outgoing radiation in the lower atmosphere, causing a radiation imbalance (Loeb et al., 2021). This is an example of what is called positive radiative forcing – a net increase in available energy that alters the radiative balance. The climate system adjusts to a new radiative balance by warming the surface and lower atmosphere, which, in turn, causes greater emission of energy to space.

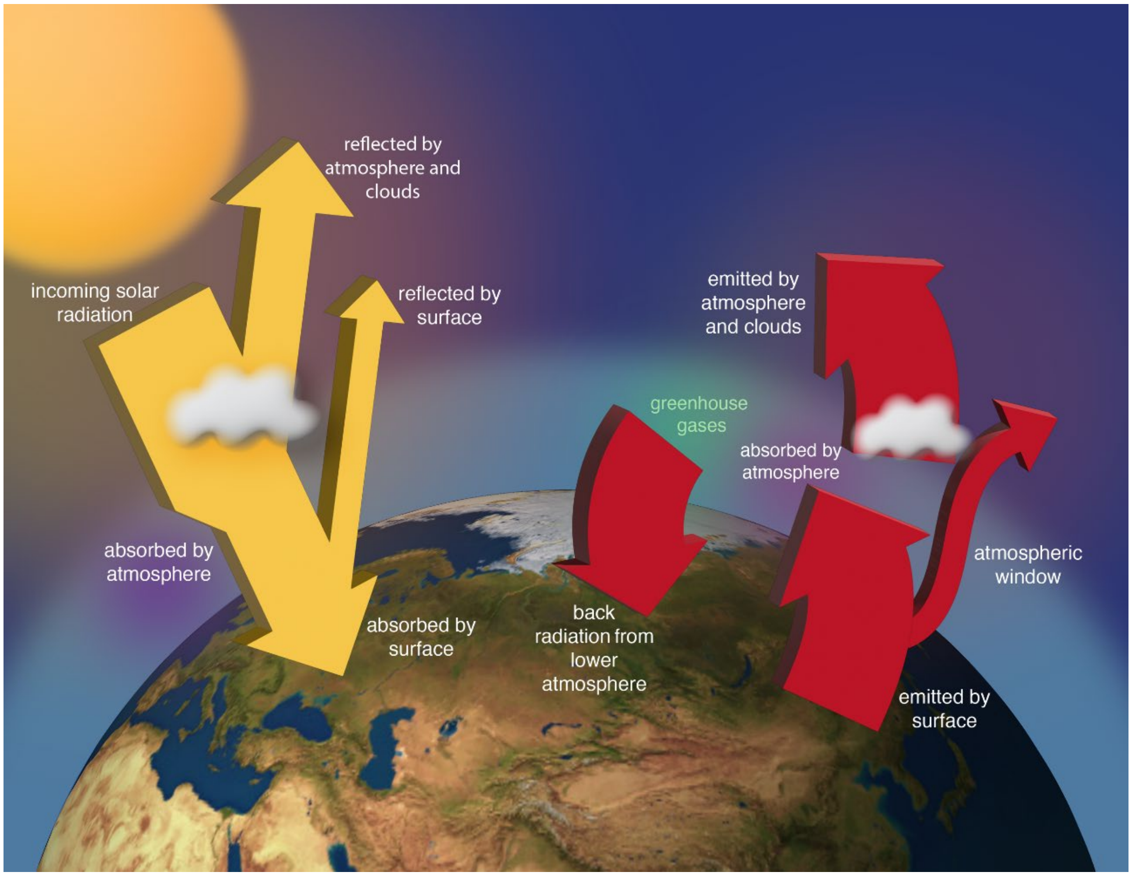

Figure 4.1: Earth's radiation budget

How much have greenhouse gases altered the radiation balance during the industrial period, and what has been the resulting climate response? Global carbon dioxide (CO_2) concentrations sampled from ice cores reveal atmospheric levels of approximately 280 parts per million (ppm) in the preindustrial period (pre-1750). Direct measurements since 1958 indicate an increase from 315 ppm to more than 415 ppm in 2022 (National Oceanic and Atmospheric Administration [NOAA], 2022b). Other greenhouse gases such as methane, nitrous oxide, and fluorinated gases have also risen during this period. The positive radiative forcing caused by these well-mixed greenhouse gas increases is large compared to other natural factors. When considering all the major factors altering Earth's radiation budget since 1850, it is estimated that human activity has caused a net global effective radiative forcing of approximately 2.75 Watts per square meter (Wm^{-2}; Smith et al., 2020). Climate models simulate a global temperature response to changes in natural and anthropogenic forcing since 1850 of approximately 2°F, consistent with the observed temperature increase (Figure 4.2). Climate simulations that exclude this human influence fail to capture the observed temperature increase of the last 60 years.

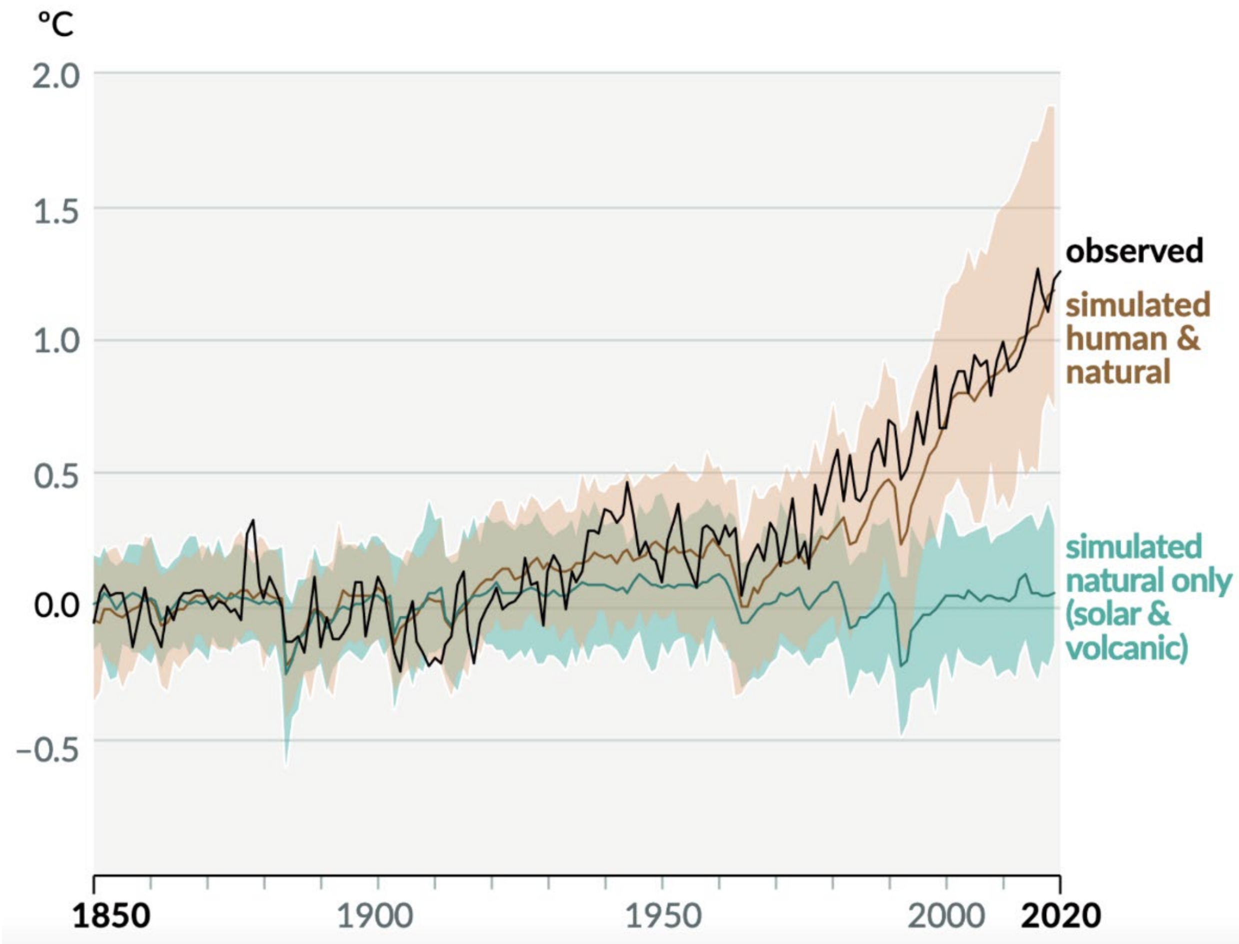

Figure 4.2: Climate model simulated temperature with and without anthropogenic forcing plotted against observed temperature (Source: IPCC, 2021).

DATA AND METHODS

The temperature record at a given place reflects global as well as local factors; detecting trends requires consistent, long-term monitoring. In South Carolina an observation network established in the late 1800s provides a rich data set to examine historic variability and trends. These data are part of the Global Historical Climatology Network-Daily (GHCN-Daily) quality-controlled dataset with long, reliable records (Menne et al., 2012). GHCN-Daily data provide the basis for aggregated data at the state and climate division level (Vose et al., 2014) and provide the foundation for analysis of temperature and precipitation trends in South Carolina. The National Centers for Environmental Information (NCEI) maintain these data sets and make them freely available. Some analysis is done using fifteen stations from the network. These were selected based on station length, completeness, and spatial distribution and in consultation with the South Carolina State Climatology Office. Most of these stations were used in a brief 2022 state-level climate summary conducted by NCEI (Kunkel et al., 2022). A Mann-Kendall Trend Test was used to determine whether significant trends exist in the temperature and precipitation records of the fifteen select stations using records from approximately 1900 to 2020. Sen's slope was used to determine a linear rate of temperature and precipitation change.

The degree of future changes in global temperature is dependent on greenhouse gases already emitted and those that will be emitted in future decades. Since future greenhouse gas emissions depend on unknown future energy technology and policies, different emission scenarios are typically considered. In this chapter we will refer to two commonly-used scenarios – as a “lower emissions” scenario (RCP4.5) and a “higher emissions” scenario (RCP8.5). These representative concentration pathways (RCPs) are linked to specific stabilized end-of-century radiative forcing of 4.5 and 8.5 Watts per square meter respectively (Moss et al., 2010). Recalling that the radiative forcing from 1850 to 2020 is approximately 2.75 Wm^{-2}, these values represent an additional 1.75 and 5.75 Wm^{-2} by 2100. To provide context, by 2100 the lower emissions (RCP4.5) scenario would lead to a CO_2 concentration of approximately 550 ppm (about double the pre-industrial value), and the higher emissions (RCP8.5) scenario would result in CO_2 concentration of about 900 ppm (more than triple the pre-industrial value). The higher emissions scenario used here would lead to an end-of-century forcing that is two to three times higher than that witnessed thus far.

The two emissions scenarios serve as inputs to global climate models that simulate Earth’s climate response. As seen in Figure 4.2 these models capture well the global temperature trends during historical periods. At a state level, it is important to consider more than one climate model, since they collectively produce a range of plausible changes at this scale. For this study, output from all models was considered in the Fifth Coupled Model Intercomparison Project (CMIP5; Taylor et al., 2012). Of these, closer consideration was given to output from nine climate models and, when available, an average from an ensemble of all models. The nine-member subset was selected largely based on model performance in the southeastern United States (Engström & Keellings, 2018; Keellings, 2016; Rupp, 2016). From this, “bookends” that capture a wide range of warm, cool, wet, and dry projections for the 21st century were selected. This methodology accounts for the variability and uncertainty associated with state-level projections. Since most GCMs produce output at coarse (50-125 mile) grid cells, state, and regional studies commonly use "downscaled" data sets for future climate scenarios. Statistically downscaled data from CMIP5 provided by the Localized Constructed Analogs (LOCA; Pierce et al., 2014) data set were used for this assessment. LOCA has several advantages for use in this state-level assessment: it was also used in the Fourth National Climate Assessment (Hayhoe et al., 2017) and corrects for regional bias by comparing simulations against observations during the historic period and adjusting output to match general statistical properties. In the examples shown below, climate model output from LOCA was produced using historic greenhouse emissions, 1950-2005, and projected emissions 2005-2100 according to the lower (RCP 4.5) and higher (RCP 8.5) emissions scenarios.

SOUTH CAROLINA TEMPERATURE

OBSERVED TEMPERATURE

Statewide average data provide a snapshot of general temperature trends for the past 125 years (Figure 4.3). The state experienced a relatively warm period from the mid- 1920s to the mid-1950s, a cooler period during the next three decades, and an increase since the early 1980s. Average temperature during the past 30 years is warmer than any other consecutive 30-year period in the record. The state's average annual temperature increased by approximately 0.9°F per century. These increases are slightly lower for annual maximum temperature (approximately 0.8°F per century) and slightly higher for annual minimum temperature (approximately 1.0°F per century). South Carolina's average annual temperature pattern is typical of the broader southeastern United States during the last 125 years.

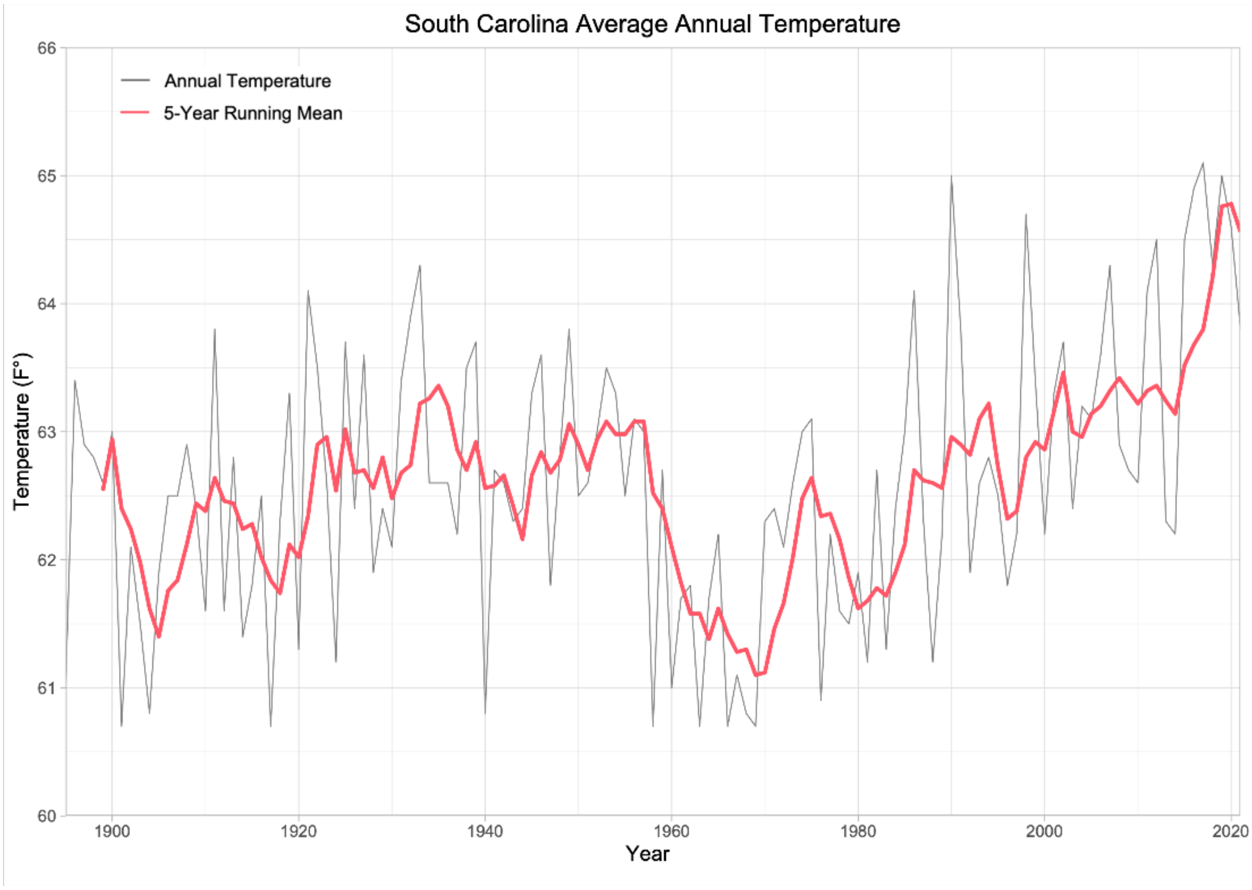

Figure 4.3: South Carolina average annual temperature

Additional comparison with global and national (lower 48 states) patterns reveals at least two key points (Figure 4.4). First, interannual and interdecadal variability is typically higher at an individual state level than at national or global scales. This is because atmospheric and ocean circulation patterns smooth trends much more at global than regional scales. Second, while South Carolina's average rate of temperature rise from 1895 to 2020 is lower than the average global rate, the 3°F increase in the most recent fifty years is comparable to or even higher than the global average increase.

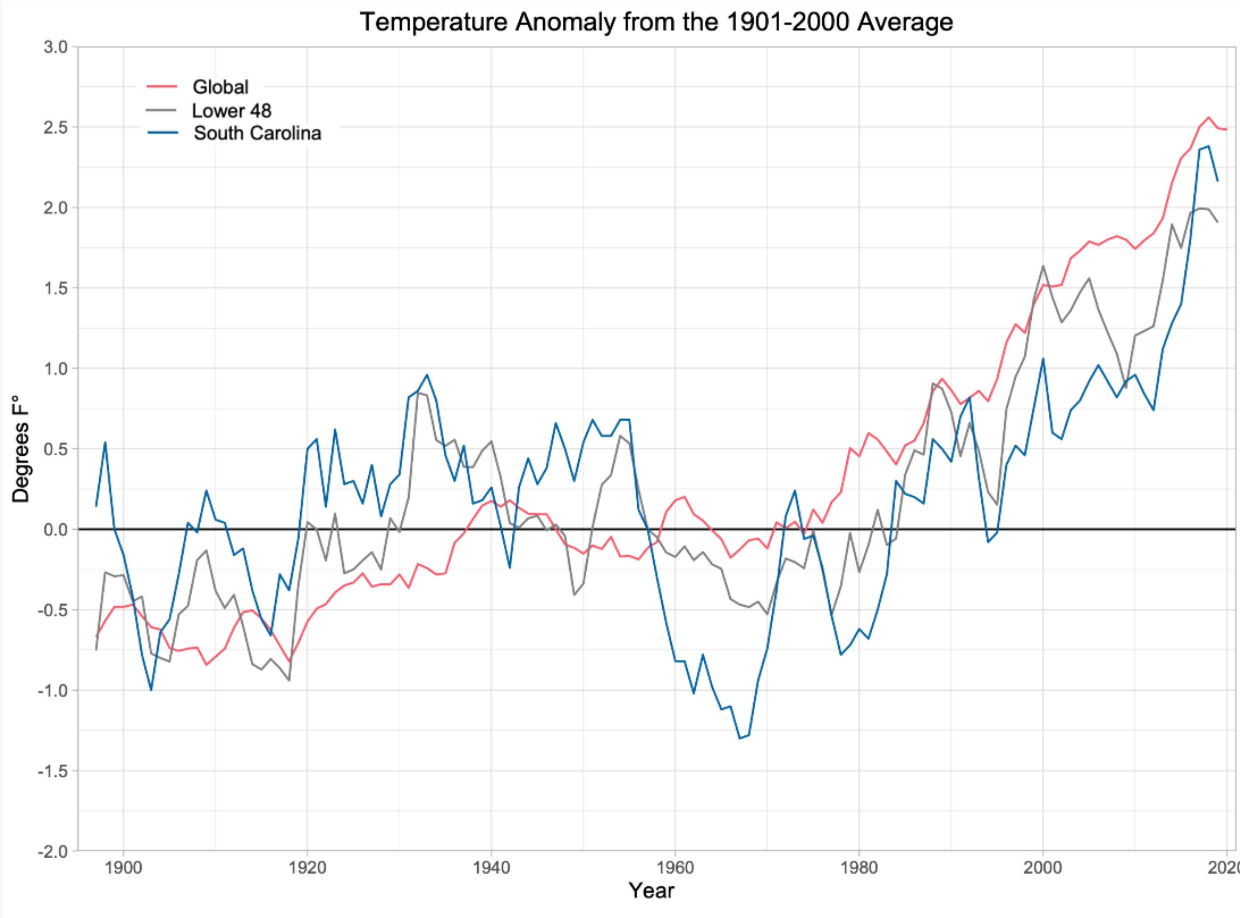

Figure 4.4: Global, Contiguous United States, and South Carolina average temperature anomalies from 20th century mean

A selection of South Carolina's most complete GHCN-Daily stations allows for identification of statistically significant temperature trends by season. Like the South Carolina versus global temperature anomalies (Figure 4.4), individual stations often experience higher year-to-year and decade-to-decade variability than spatially averaged data.

Because of this, detecting a statistically significant trend for the entire period requires large changes through time. Many stations do not show such changes, but there are some examples where the changes are dramatic enough to reveal a clear, statistically significant signal. For example, eight of the fifteen long-term and most reliable stations have experienced significant spring maximum temperature increases (Figure 4.4). Five of the stations show significant summer maximum temperature increases at a 99% confidence level (Figure 4.5). Winter maximum temperature increased at all but two stations; it was statistically significant at seven of the fifteen stations (Figure 4.6).

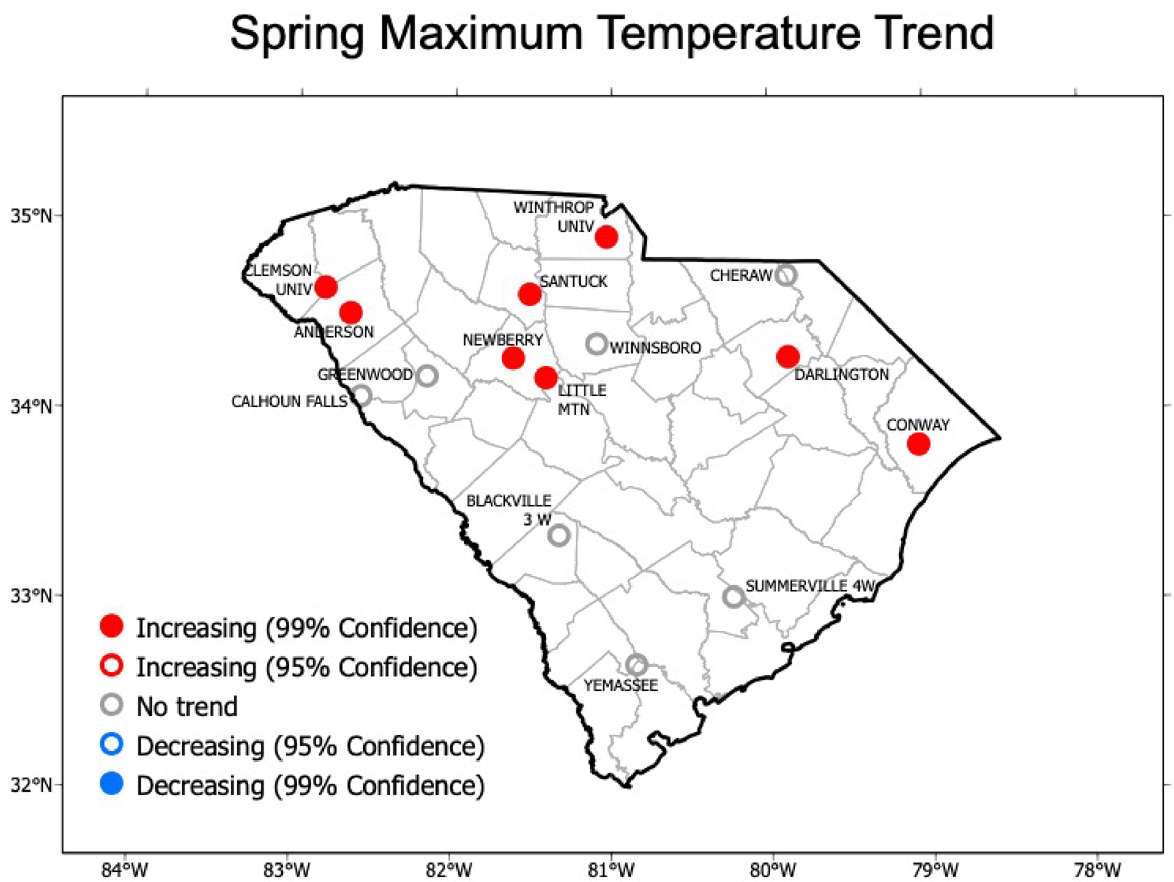

Figure 4.4: Spring maximum temperature trend, 1900-2020

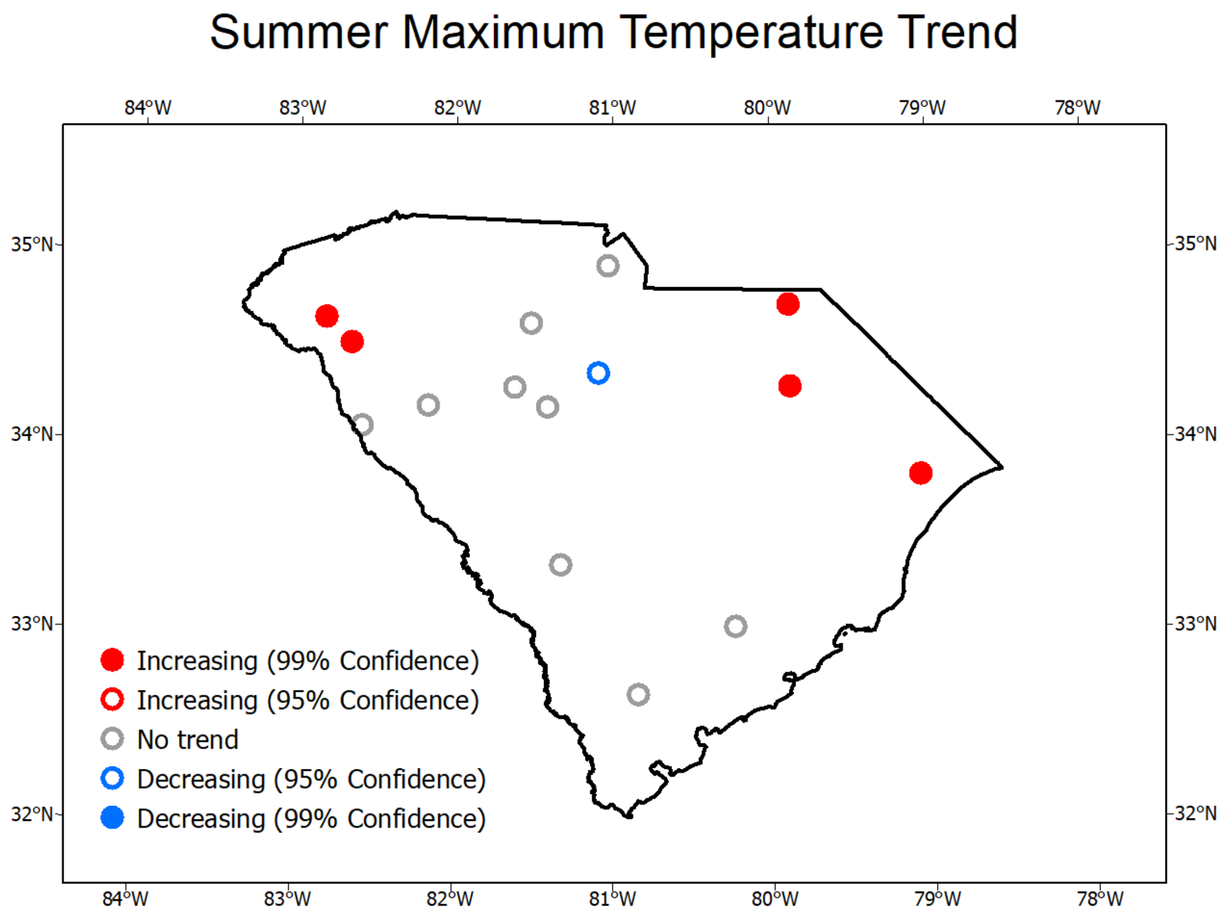

Figure 4.5: Summer maximum temperature trend, 1900-2020

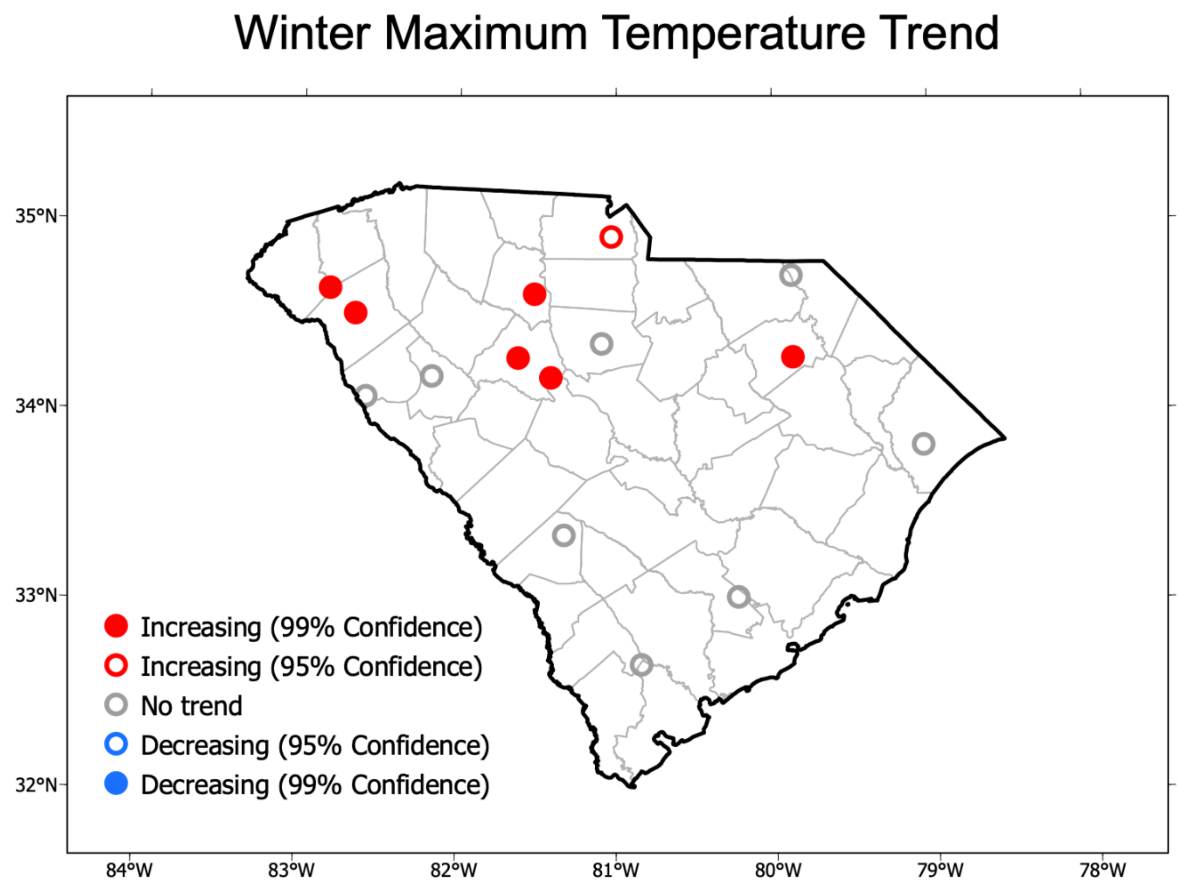

Figure 4.6: Winter maximum temperature trend, 1900-2020

Summer minimum temperature increases occurred at ten stations, nine of which were statistically significant (Figure 4.7). Two stations had decreasing trends, significant at the 99% confidence level.

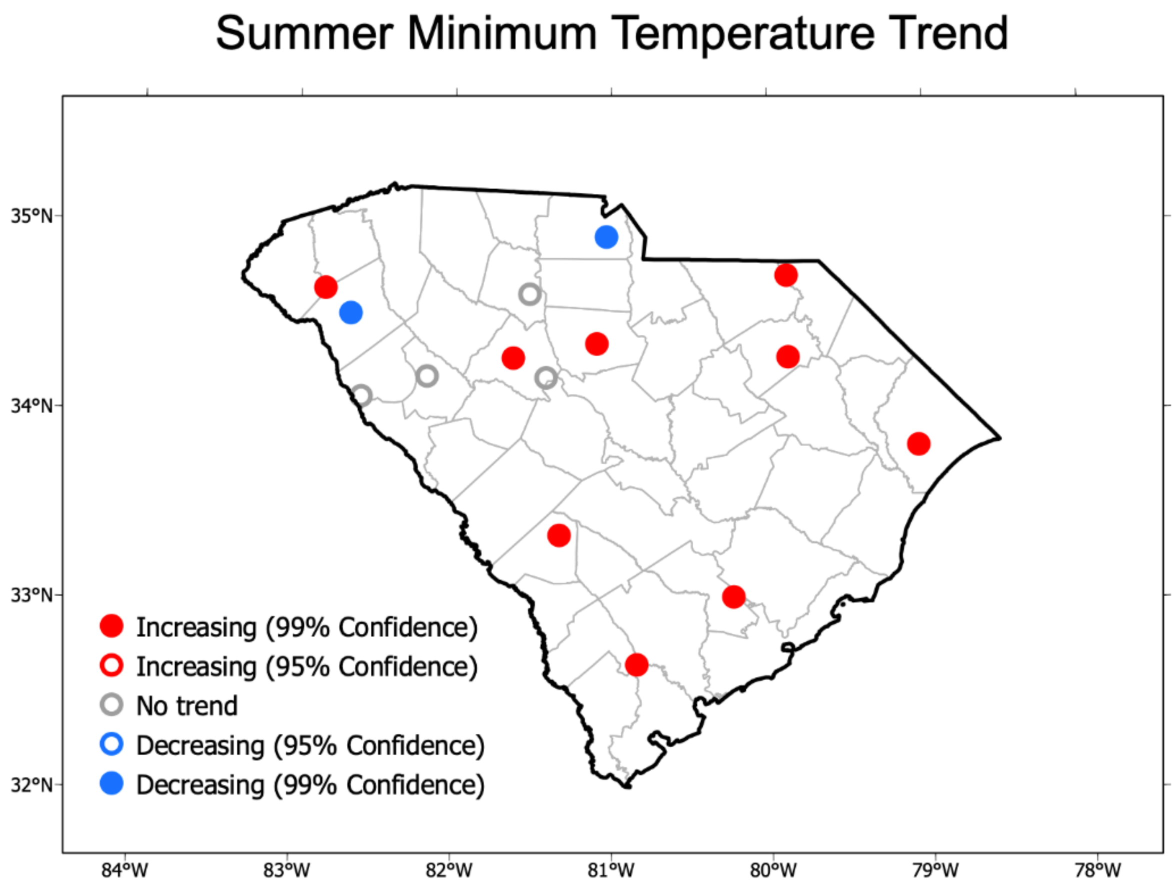

Figure 4.7: Summer minimum temperature trend, 1900-2020

Temperature plots from Little Mountain illustrate how dramatic the changes must be for trends to be statistically significant given the high interannual and interdecadal variability in South Carolina temperature records (Figure 4.8). The bars in the graph show departures from the 1901-1960 spring temperature average, also called anomalies. Note that, despite the strong year to year variability, warmer than average temperatures are more frequent in recent decades, with cooler than average temperatures less common.

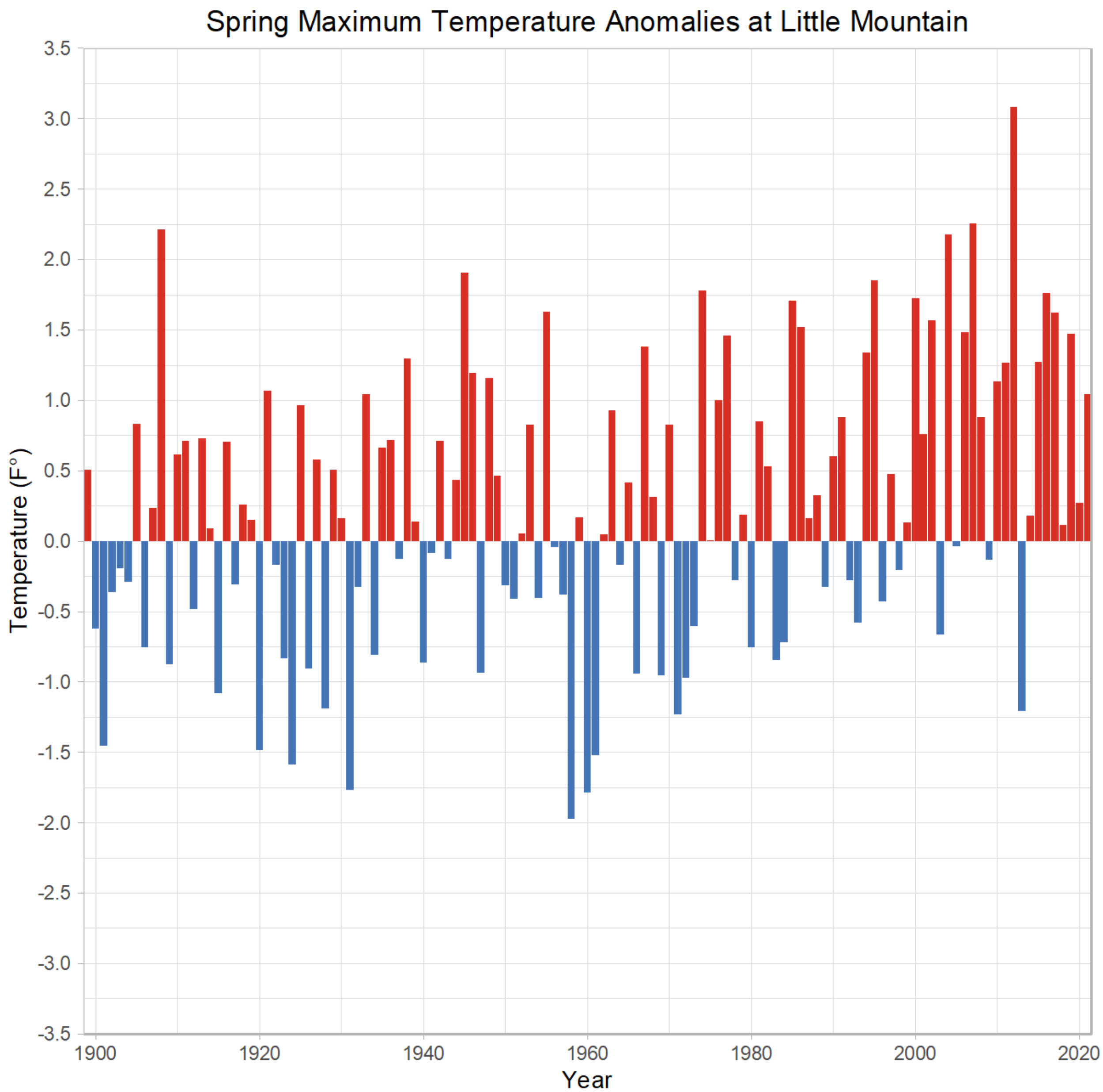

Figure 4.8: 1900-2020 Little Mountain, South Carolina Spring maximum temperature anomalies (from 1900-1960 average)

FUTURE TEMPERATURE PROJECTIONS

Climate model simulations capture the average temperature increase seen in South Carolina from 1950 to the early 2000s (Figure 4.9). In the lower emissions scenario, the ensemble average of all models projects an additional increase of 4°F from the 1991-2020 average by 2100; it ranges from an increase of approximately 3°F in a cooler model to 5°F in a warmer model (Figure 4.10). It is important to note that this lower emissions scenario assumes decreasing greenhouse gas emissions in the next decade and leveling CO_2 concentrations below 450 ppm by the end of the century. By contrast, the high emissions scenario leads to a much greater temperature increase – projected at 6°F, 8°F, and 10°F during the 21st century for the cooler model, ensemble average, and warmer model respectively (Figure 4.11).

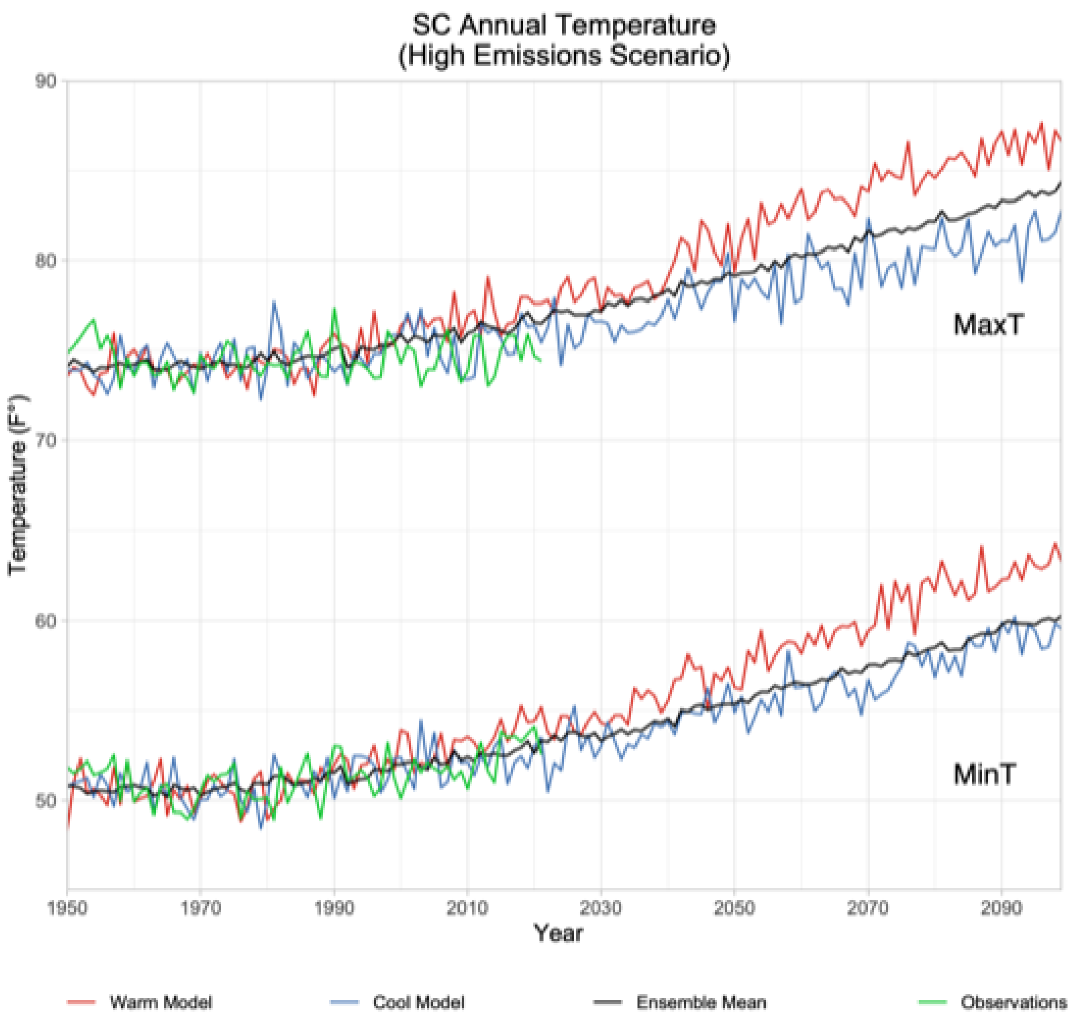

Figure 4.9: Modeled vs. observed annual, state-averaged

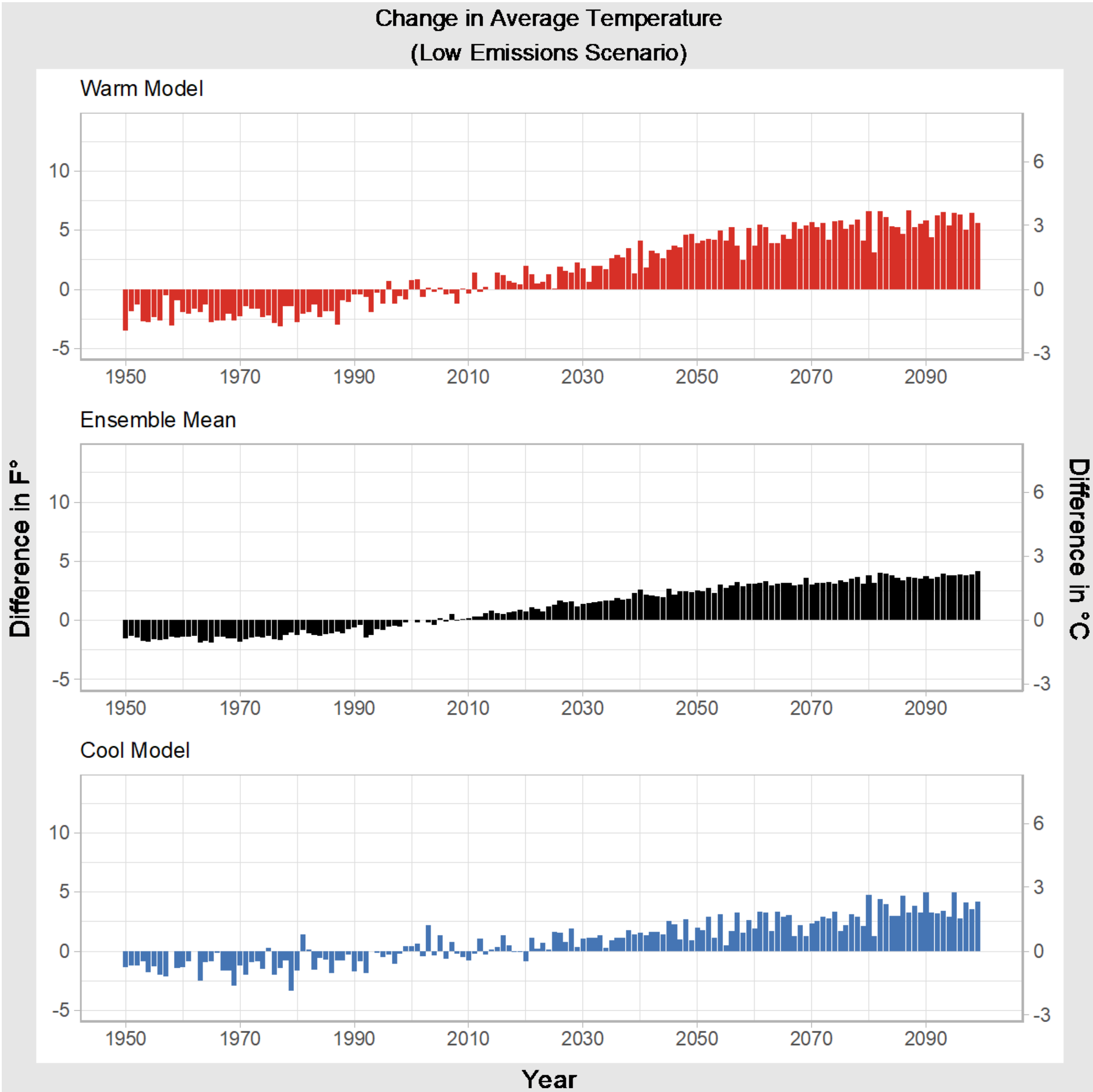

Figure 4.10: Model simulated average temperature for South Carolina. Projections are measured as departures (anomalies) from the 1991-2020 mean (RCP 4.5 emissions scenario)

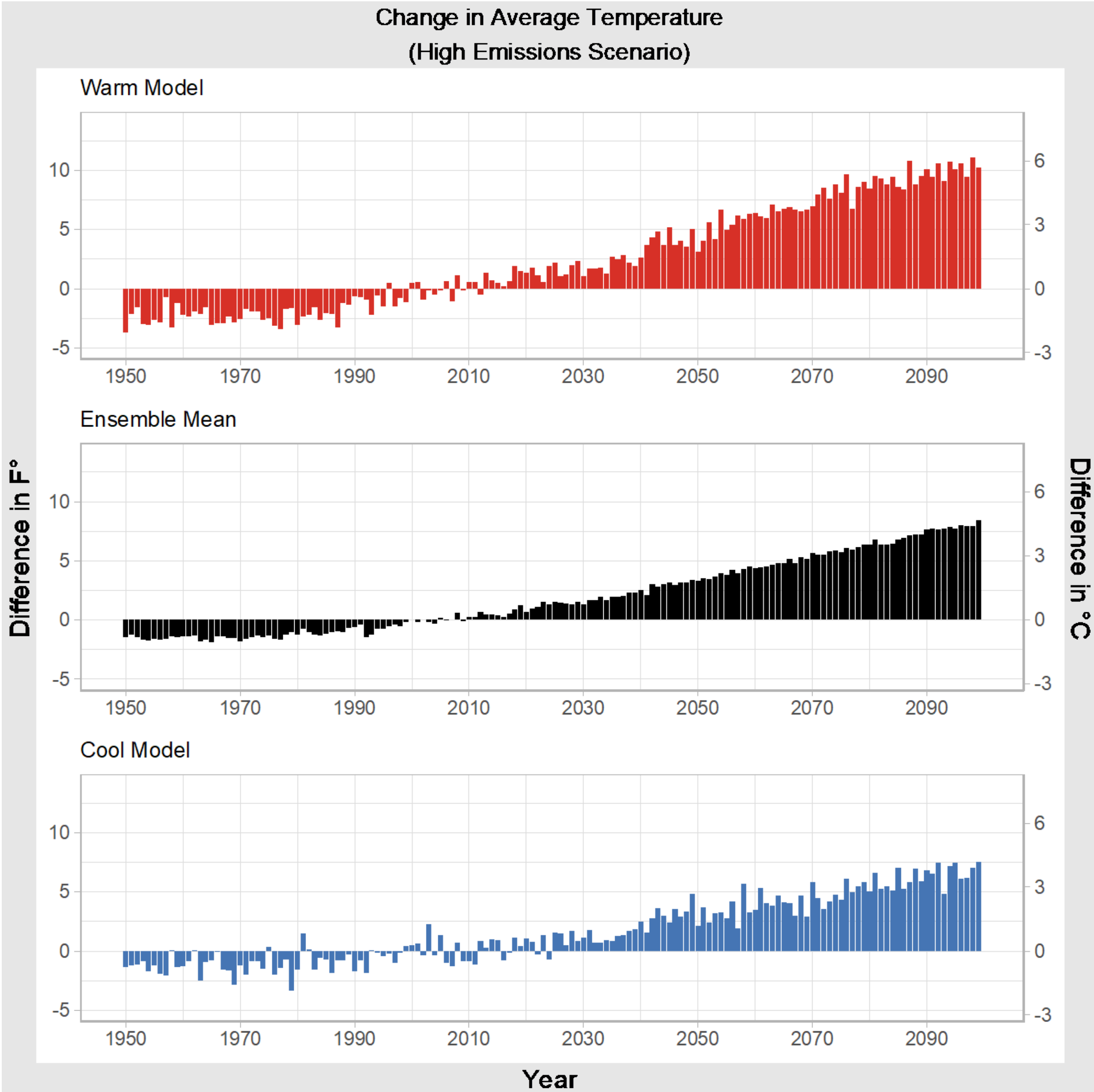

Figure 4.11: Same as Figure 11, but for the high emissions scenario (RCP 8.5)

Projected changes in temperature extremes also vary by emissions scenario and individual model. By the end of the century, the number of days in which state averaged maximum temperature would exceed 95°F doubles in the lower emissions scenario, using output from a cooler model. In the higher emissions scenario with a warmer model, the number increases five-fold. Projections from a model ensemble average show changes in hot days across space and contrasts between emissions scenarios (Figure 4.12 and Figure 4.13). Such increases would likely have ecological impacts, as well as implications for human health and cooling costs during the warm season. Warm nights, as measured by state averaged minimum temperature above 75°F, also increase in future scenarios, from double to six times the number of days per year, depending on emissions scenario and model (Figure 4.14). Meanwhile, cold extremes, in this case defined by number of days in which the statewide average minimum temperature is cooler than 32°F, drop by half in the high emissions scenario by 2100 (Figure 4.15).

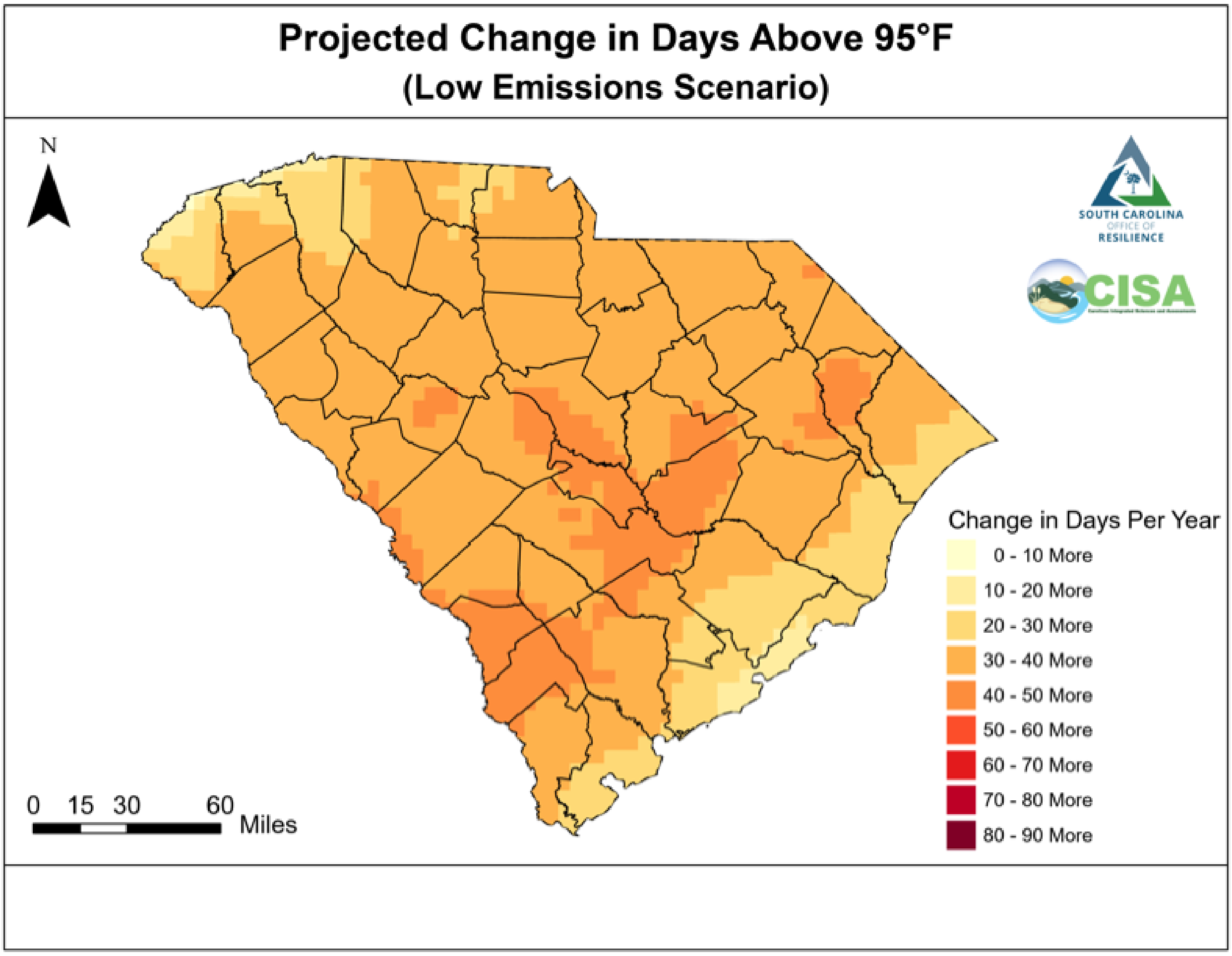

Figure 4.12: Projected increase in the number of days per year with maximum temperature above 95F (RCP 4.5 emissions scenario)

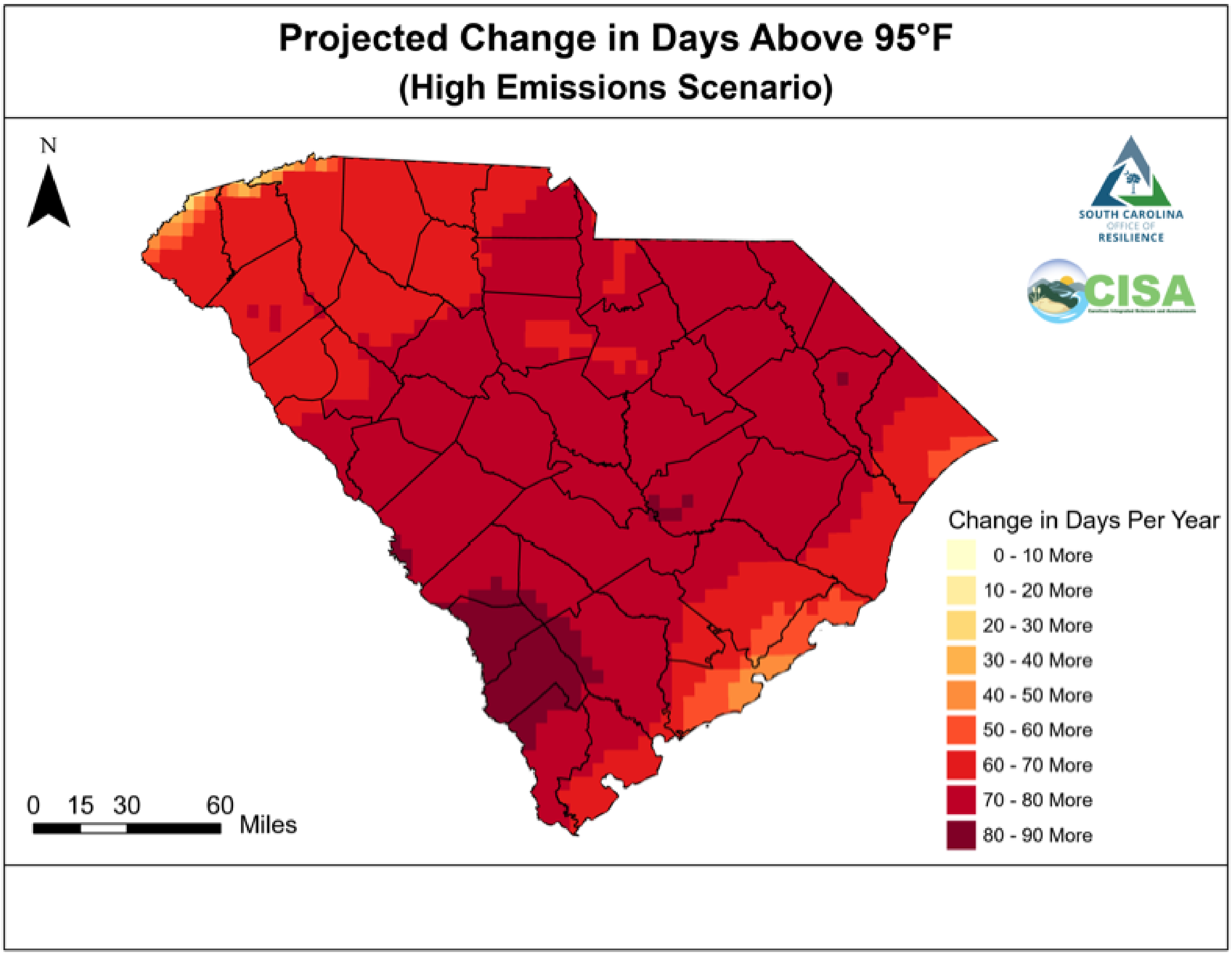

Figure 4.13: Projected increase in the number of days per year with maximum temperature above 95F (RCP 8.5 emissions)

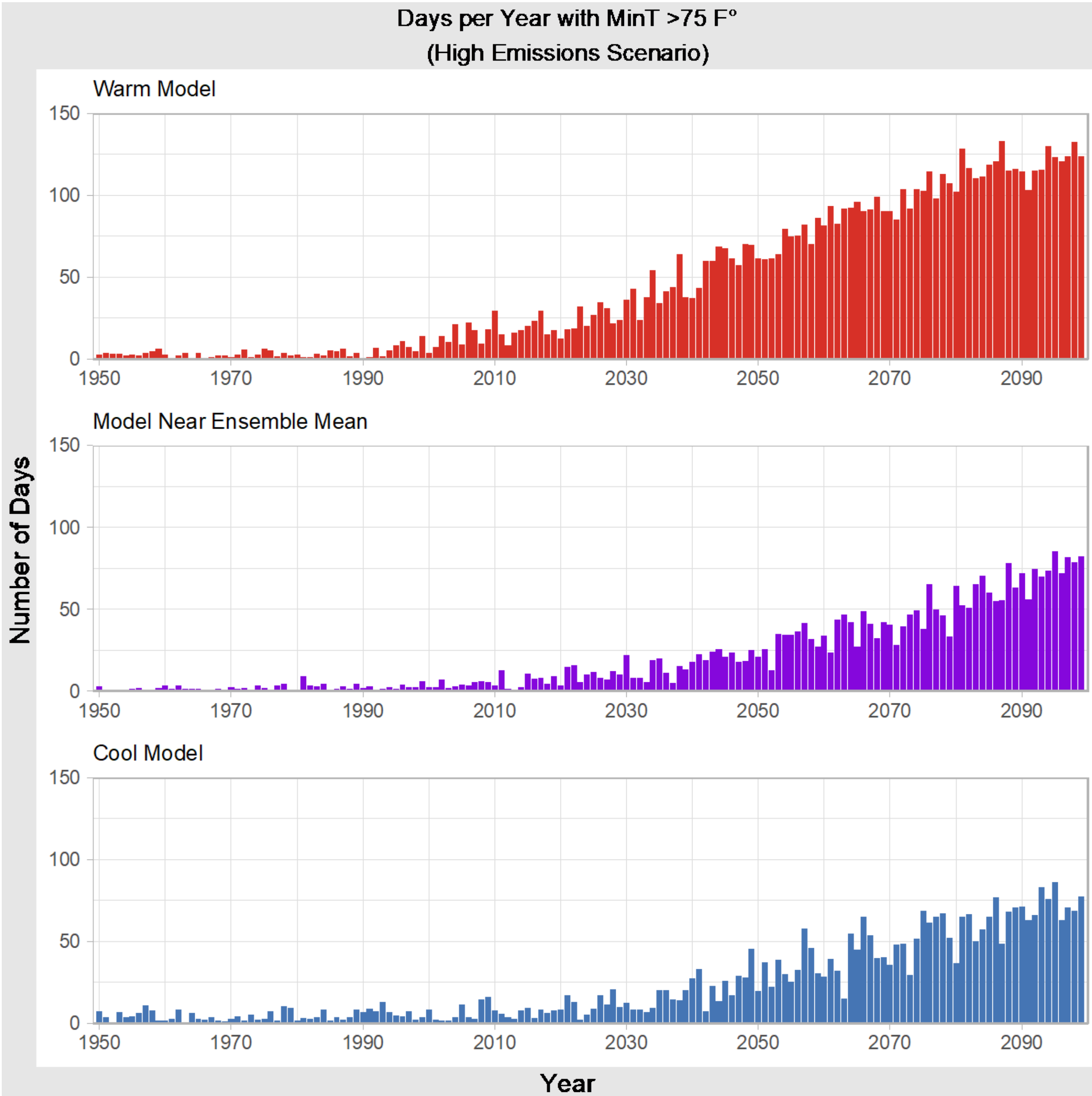

Figure 4.14: Projected number of days per year with maximum temperature above 75F (RCP 8.5 emissions scenario)

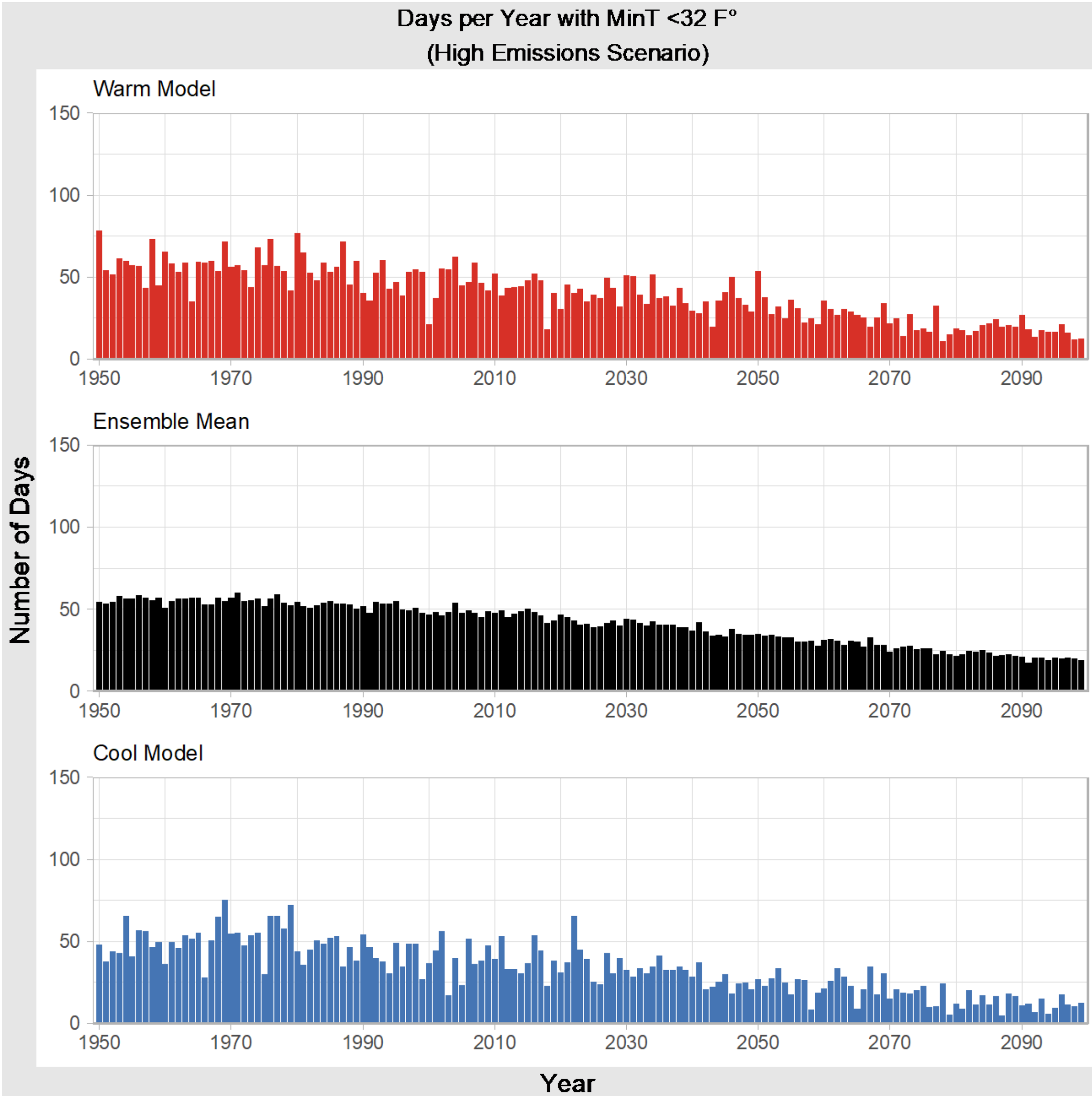

Figure 4.15: Projected number of days per year with minimum temperature below 32F (RCP 8.5 emissions scenario)

SOUTH CAROLINA PRECIPITATION

OBSERVED PRECIPITATION

South Carolina's precipitation varies across years and decades (Figure 4.16), influenced by the paths and frequency of extratropical cyclones and tropical cyclones, the position of the sub-tropical high, and sea-surface temperatures in the Gulf of Mexico and Atlantic (Curtis, 2008; Diem, 2006; Labosier & Quiring, 2013; Qian et al., 2021; Rickenbach et al., 2015). Consequently, there are few statistically significant trends in the annual or seasonal precipitation record. One exception is summer (June, July, August total) precipitation which has decreased at all long-term stations and is statistically significant at two-thirds of these stations, mostly those away from the coast (Figure 4.17).

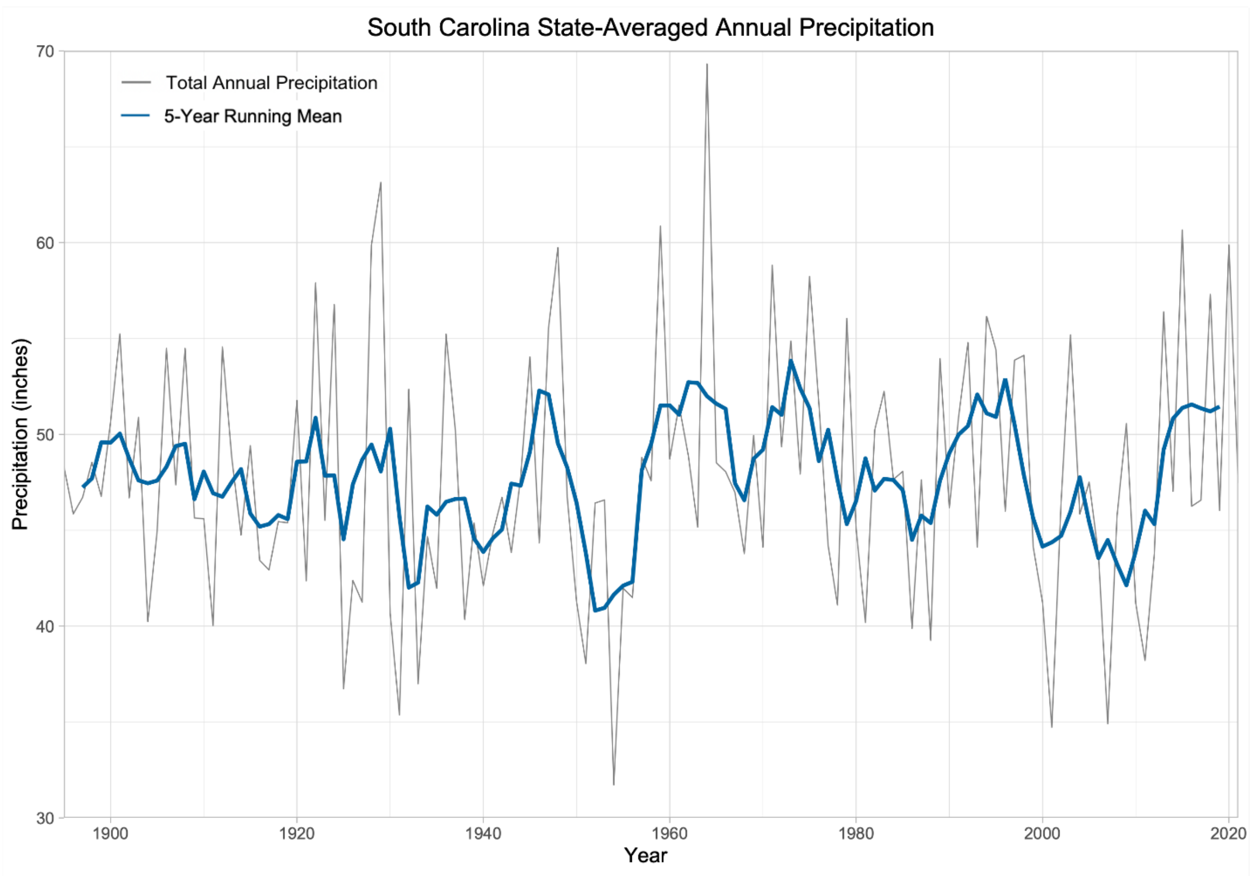

Figure 4.16: State-averaged total annual precipitation

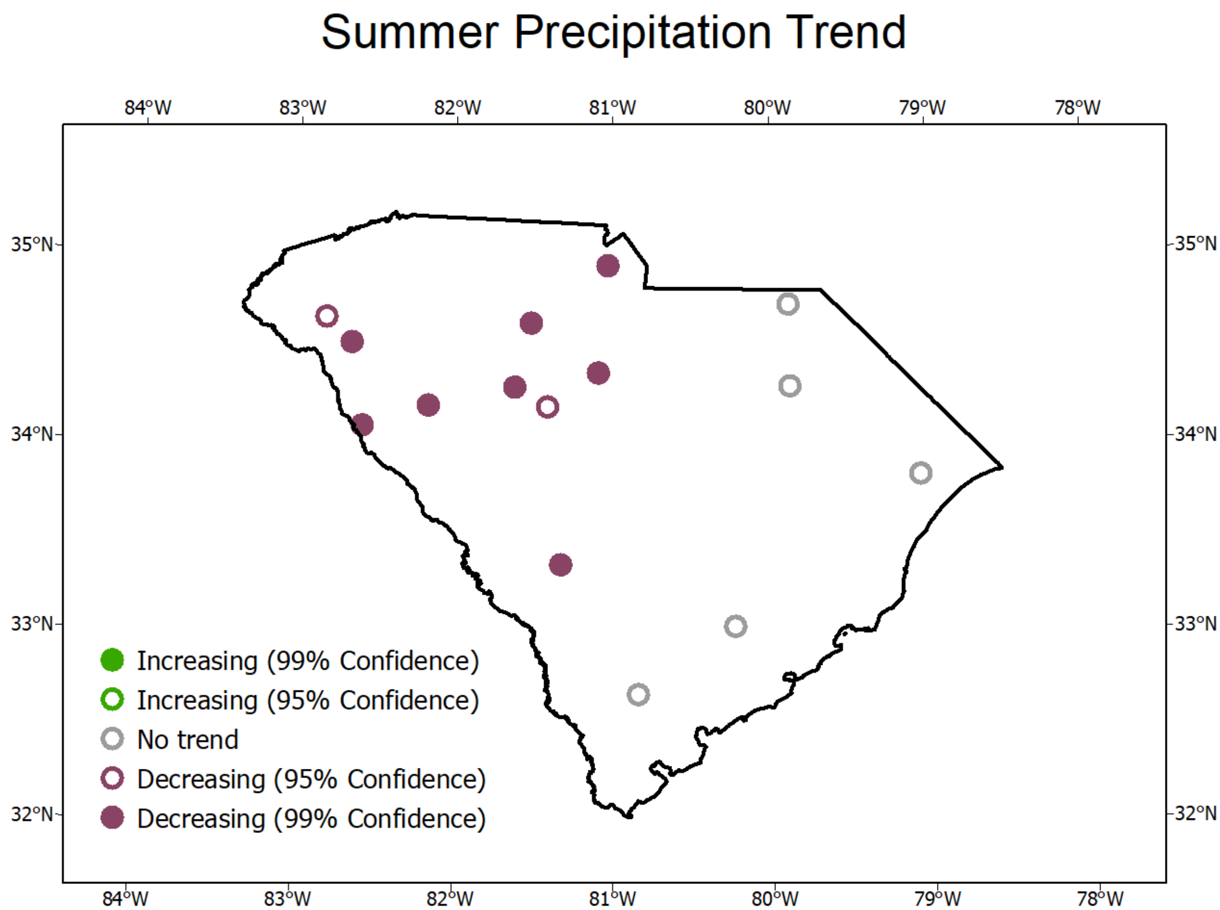

Figure 4.17: Summer precipitation trend, 1900-2020

Data from the Santuck station illustrate the statistically significant decrease of total summer precipitation found at many South Carolina stations (Figure 4.18). The bars in this time series represent the difference of each summer's precipitation from the 1901- 1960 average. The Santuck example also shows the considerable variability of precipitation from year to year and decade to decade, common to all South Carolina stations. It is large enough at many stations that long-term monthly or seasonal precipitation changes do not have statistically significant trends relative to this interannual and interdecadal variability. Three exceptions include a decrease in February and an increase in November precipitation totals at all long-term stations (statistically significant at 60-70% of them), and an increase in rain days during fall at most South Carolina stations.

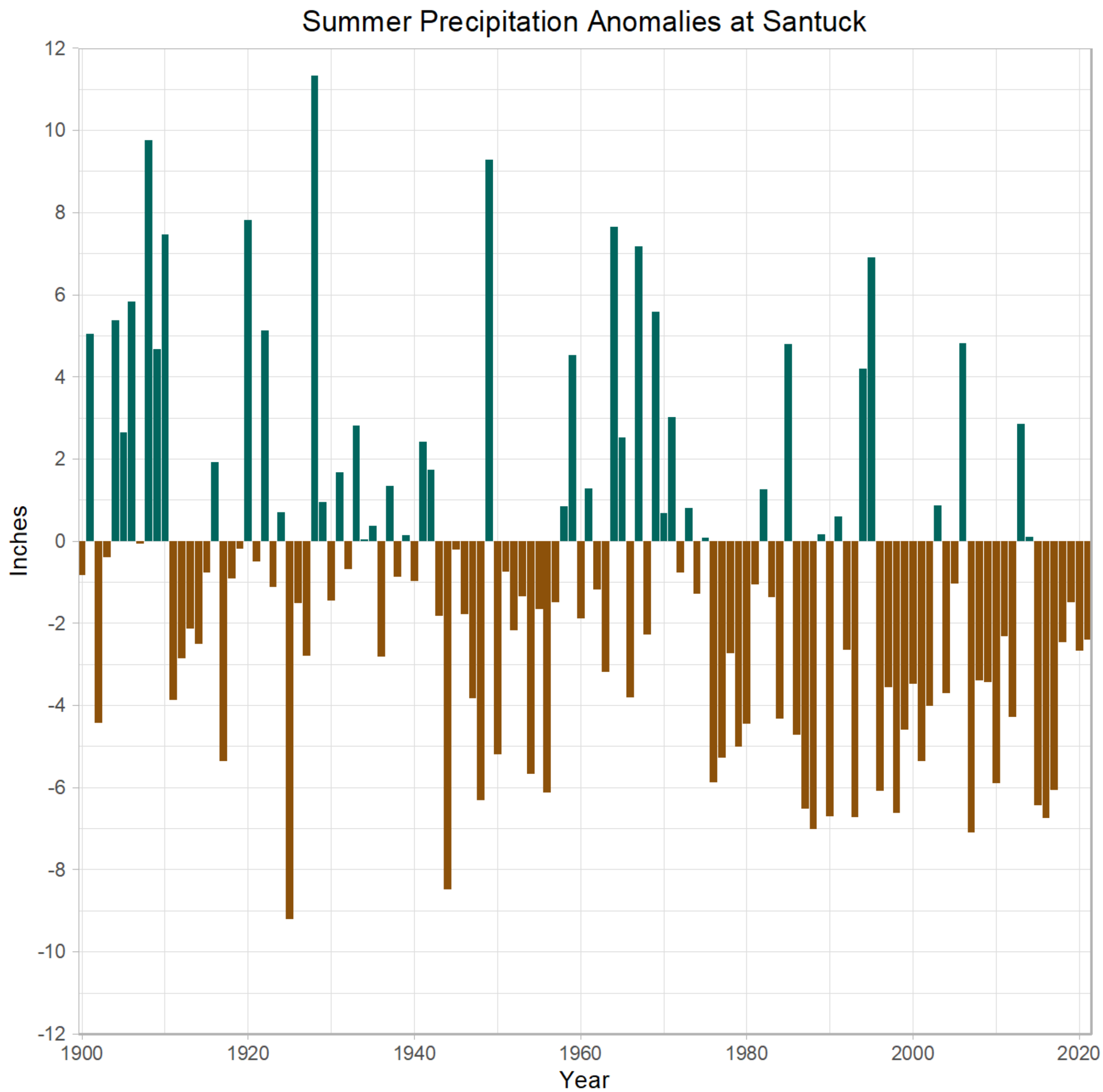

Figure 4.18: Santuck, SC summer precipitation anomalies from 1901-1960 mean

FUTURE PRECIPITATION PROJECTIONS

Most future precipitation projections show modest increases through the 21st century (Figure 4.20). There is a range among even those models with the best performance in the southeastern US during the historic period. One wetter model shows an average increase of about 10% with annual swings exceeding 40% of current average conditions. A drier model shows decreases of 10% and annual swings of 40% lower than current average conditions. The ensemble mean shows state-averaged precipitation increases of 5-10%. It is important to note that even if South Carolina's precipitation increases in the future, some of this increase would be offset by higher evaporation rates caused by warming. Under those conditions it is possible for precipitation to increase, but moisture availability in soils and watersheds to decrease because of higher evaporation rates. Moisture availability also depends on the nature of precipitation changes. If delivered in shorter, more intense bursts, precipitation runoff could increase, limiting soil moisture gains and increasing the risk of flooding.

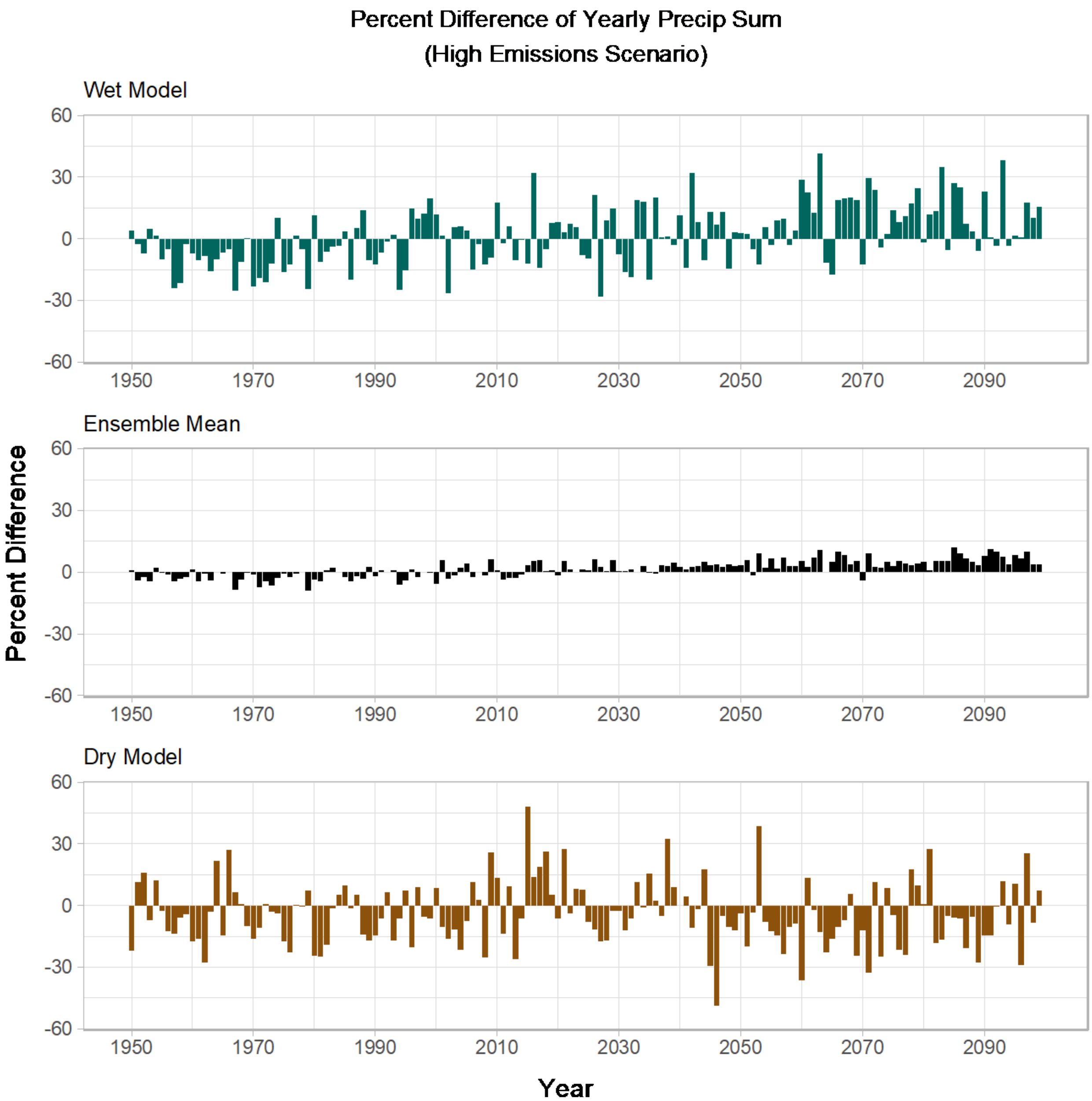

Figure 4.19 Model projected annual precipitation as percentage greater or less than 1991-2020 mean.

PRECIPITATION EXTREMES

Precipitation extremes potentially pose even greater social risks than changes in monthly, seasonal, or annual averages. South Carolina experiences many heavy precipitation events fueled by moisture delivery from the Gulf of Mexico and Atlantic, as well as lift from thunderstorms, tropical cyclones, and fronts. Changes in moisture supply or storm patterns can alter the frequency of heavy precipitation events and the intensity, or rate, at which precipitation falls during these events.

Analysis of South Carolina precipitation extremes reveals three fundamental points. First, most measures of heavy precipitation have large interannual and interdecadal variability, even greater than that seen in monthly, seasonal, or annual total precipitation. Second, while heavy precipitation has increased since the mid-1900s at many southeastern US stations (Easterling et al., 2017; Powell & Keim, 2015), the picture is less consistent in South Carolina, where most stations do not exhibit significant long term trends (Moraglia et al., 2022). Few stations in South Carolina, for example, have significant changes in the 1-day precipitation amounts expected with 50%, 10%, or 1% probability in any given year (often called 2-, 10-, and 100-year events, respectively).

The large interannual and interdecadal variability, combined with the infrequency of extreme precipitation events, makes finding statistically significant long-term trends difficult. Third, despite the lack of long term trends, extreme events during the past decade (including 2015, 2016, and 2018) are among the highest in the historic record and have resulted in extensive property damage and loss of life.

One South Carolina station that does show a long term, statistically significant increase in heavy precipitation is Conway. Analysis of 50-year periods for the station clearly shows how big events in recent decades have affected 1-day precipitation probabilities. For a given precipitation depth there is a higher probability of occurrence when considering 50-year periods after 1950 versus those earlier in the 20th century (Figure 4.20). For example, a 5-inch rainfall event has a one-in-ten chance of occurring in any given year (the so-called 10-year event) when using 1930-1979 precipitation data, but a one-in-five chance of occurring (a 5-year event) using 1970-2019 data. This has implications for infrastructure designed and built decades ago.

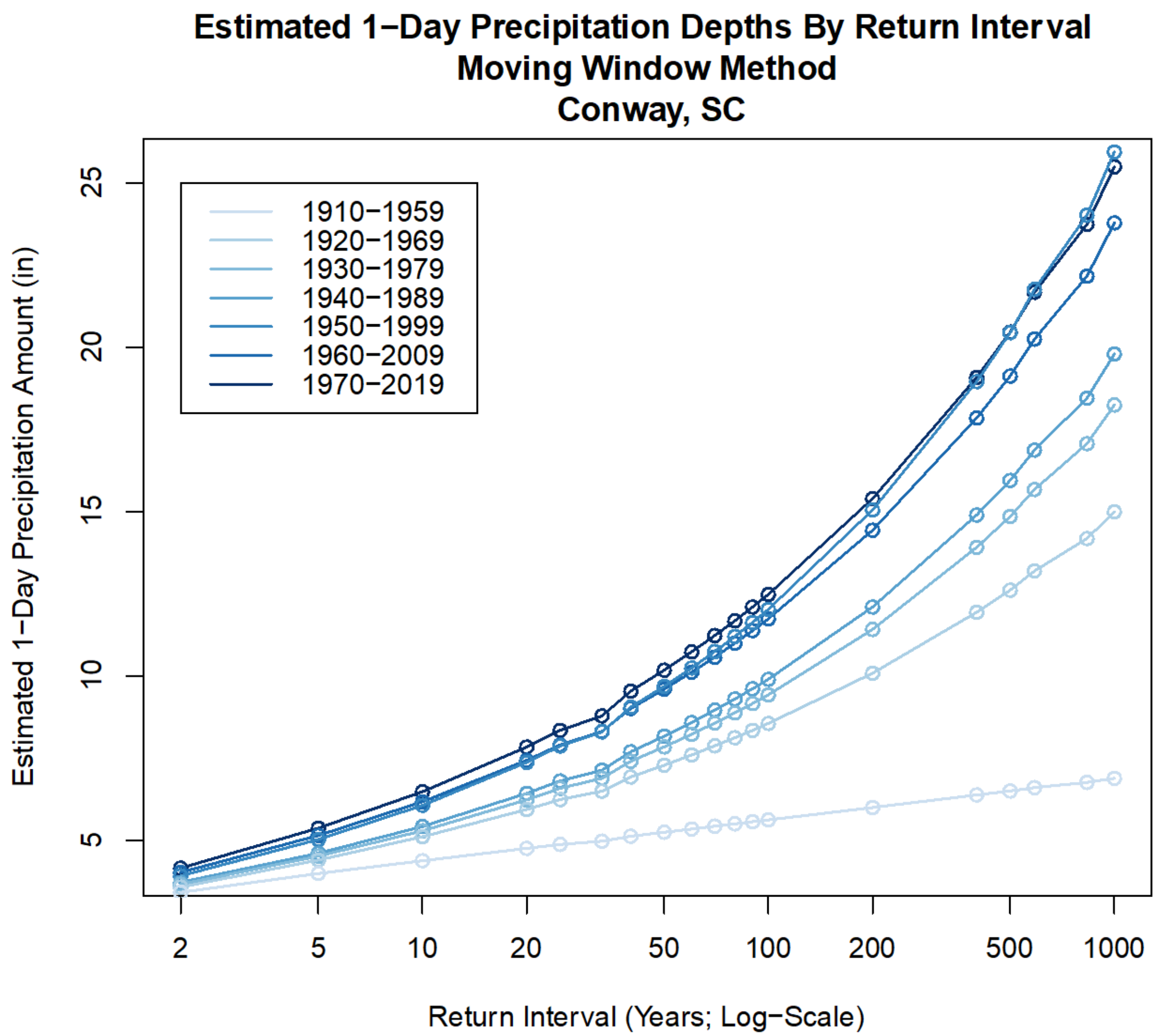

Figure 4.20: Average recurrence interval of 1-day precipitation depths calculated for separate 50-year periods. Shading is lightest for earliest period (1910-1959) and darkest for most recent period (1970-2019).

In Conway's case, there is a need to understand how recent events altered the precipitation probability of the full record. Specifically, how do probabilities of 1-day precipitation maxima during the period 1910-2000 (used in the widely-referenced Atlas-14) differ from those using data from 1910-2020? Such differences, it turns out, are relatively modest (Figure 4.21). The likely reason is that the 1910-2000 record includes 11.35 inches of precipitation from 1999's Hurricane Floyd, which already shifted the tails of the distribution. Large shifts in probability require unprecedented events, and big events after 1999 have not yielded higher 1-day precipitation at Conway. Because heavy rainfall frequently occurs for only short durations across small areas, it is often undetected, particularly by the few weather stations with the long, consistent records necessary for evaluating change. Even fewer stations measure hourly precipitation, which may be more important for capturing intensity as highest hourly precipitation can contribute more than 40% of a day's total (Barbero et al., 2019). A recent study of 1960-2015 trends in hourly precipitation at National Weather Service stations in Greenville, Columbia, and Charleston, as well as Wilmington and Charlotte, NC, and Savannah and Augusta, GA (Brown et al., 2019), found significant shortening of storm duration at all stations (90% confidence) and increasing hourly totals at Charleston (95% confidence), and Savannah, Charlotte, and Wilmington (90% confidence). By contrast, the frequency of events exceeding the station-specific average hourly accumulation dropped significantly at three stations — Greenville, Columbia, and Savannah (90% confidence). These mixed results warrant more investigation of sub-daily precipitation records.

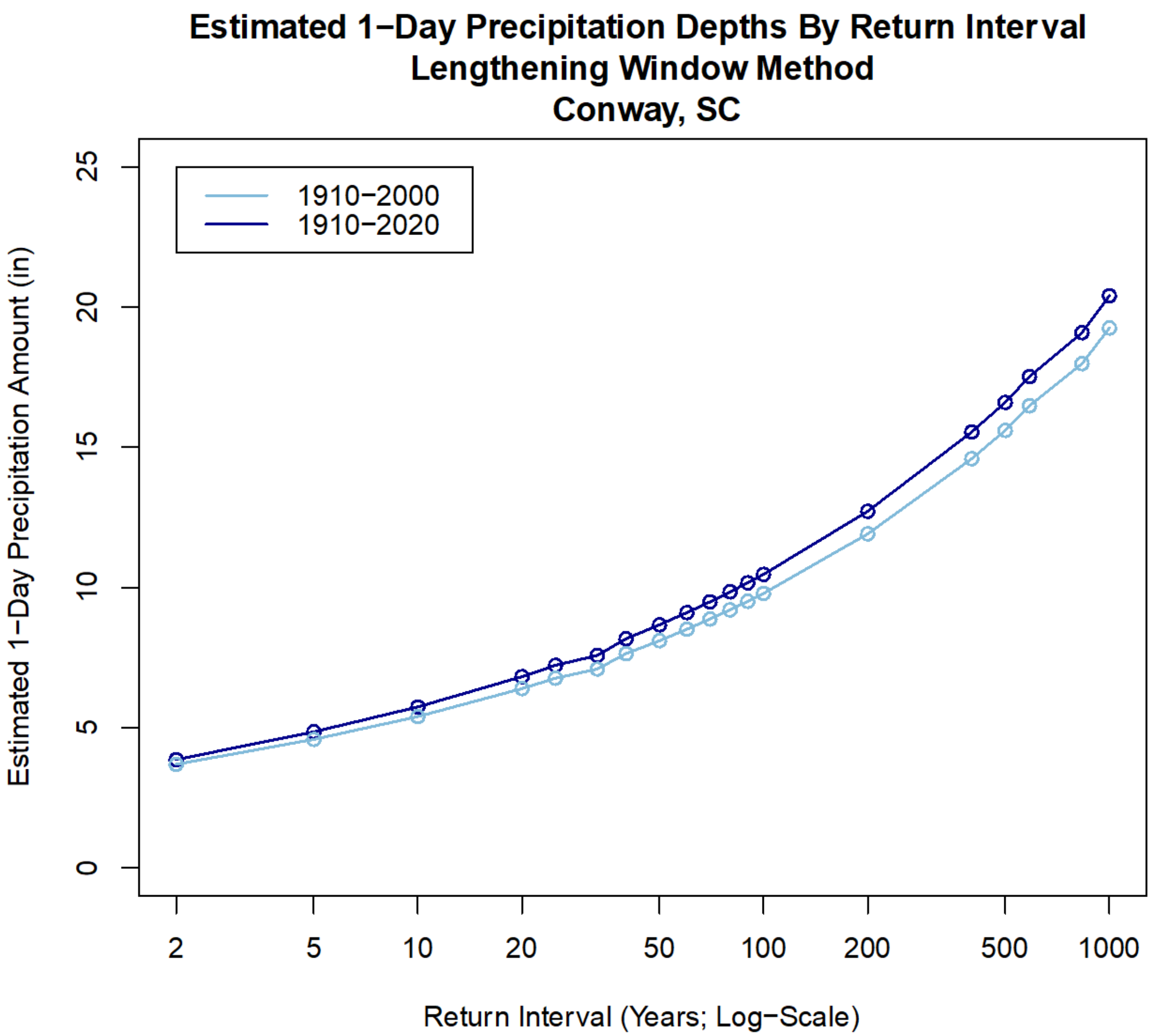

Figure 4.21: Average recurrence interval of 1-day precipitation depths calculated separately for 1910-2000, and for 1910-2020.

Changes in global climate could alter moisture availability and storm systems in ways that affect precipitation intensity. Globally, water vapor increases by approximately 7% for each 1.8°F (1°C) temperature increase (Trenberth et al., 2003). While this relationship does not translate directly to heavier precipitation events, research has documented connections between moisture availability and increases in observed and modeled precipitation intensity at global, continental, and regional scales (Fischer & Knutti, 2016; Forestieri et al., 2018; Grabowski & Prein, 2019; Huang et al., 2017; Kunkel et al., 2020a; Lehmann et al., 2015; O’Gorman & Schneider, 2009; Tabari, 2020). Heavy precipitation events in the southeastern US are strongly driven by precipitable water availability (Kunkel et al., 2020b; Kunkel et al., 2020c). As temperature increases cause higher evaporation rates from the Gulf and Atlantic, delivery of precipitable water to South Carolina should increase in the 21st century. Only significant changes in storm frequency and dynamics would curtail heavier precipitation in the future. Projections from climate models show consistent increases in atmospheric moisture delivery to the Southeast with consequent increases in heavy precipitation at daily to hourly scales (Easterling et al., 2017; Prein et al., 2017).

Current climate models generate plausible global scenarios, but their ability to project daily or hourly precipitation for a specific region is limited. Recent application of statistical methods and high resolution climate models has helped to quantify the degree to which individual heavy precipitation events can be blamed on global scale climate trends. Examples of such attribution studies exist for a heavy rainfall event due to a stationary low-pressure system near Louisiana (van der Wiel et al., 2017) and for tropical cyclones, including Hurricane Harvey (Patricola and Wehner, 2018; Risser and Wehner, 2018; van Oldenborgh et al., 2017). While many uncertainties remain, new initiatives for more detailed precipitation monitoring and for climate modeling that incorporates convective cloud dynamics should further improve our understanding of how global scale climate trends can affect heavy, short duration rainfall (Blenkinsop et al., 2018; Fowler et al., 2021).

The recent record of heavy precipitation in the Carolinas provides a tangible example of precipitation extremes, their spatial extent, and the potential for loss of life and property. Precipitation in October 2015, October 2016, and September 2018 produced record rainfall in large parts of eastern and central South Carolina, demonstrating how rare events can happen in quick succession — a compounding hazard that produced repetitive losses across the Pee Dee Basin. In just a few years, events with a 1% annual probability or less occurred multiple times in some locations (Figure 4.22). As reported elsewhere (Jalowska et al., 2021), the three extraordinary events are at the high end of future projections for precipitation intensity. Similar repetitive events have affected North Carolina during the past two decades (Paerl et al., 2019). These events are consistent with expectations of a warmer world with higher evaporation rates and atmospheric moisture and provide tangible examples of the state’s vulnerability to heavy precipitation.

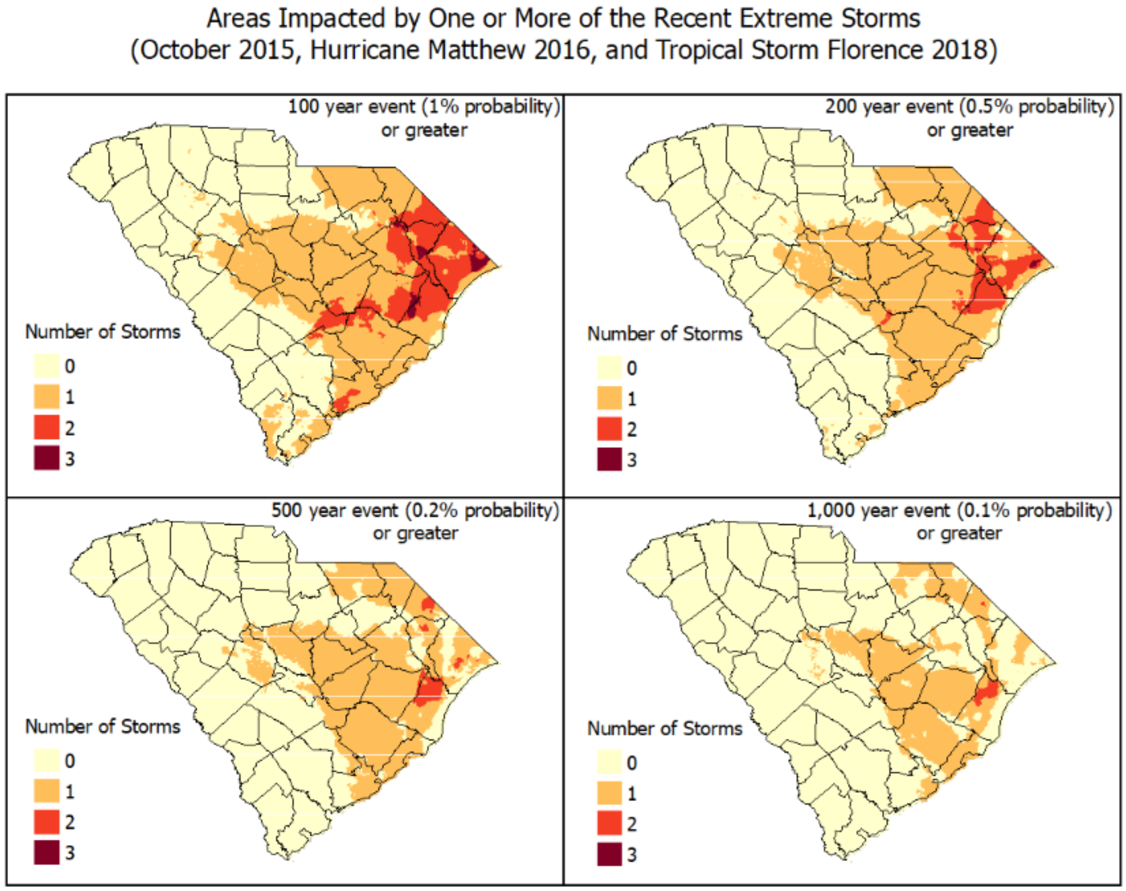

Figure 4.22: Areas experiencing 100-, 200-, 500-, and 1000-year rainfall events due to one or more of the recent extreme storms. (Data provided by SC Department of Natural Resources.)

Aside from observed or modelled changes in precipitation intensity, changes to the surface on which precipitation falls can alter the impacts of heavy rainfall events. Most of South Carolina has experienced increases in impervious surfaces in recent decades, a trend that is likely to continue through the 21st century (Terando et al., 2014). For example, urbanization around Charleston has resulted in land use and land cover change five times larger than the rate of population growth since 1990 (Allen & Lu, 2003). This land use change accelerates the delivery of water to rivers, lakes, and wetlands, increasing the likelihood that a given amount of precipitation will lead to flooding.

DROUGHT

South Carolina has endured extensive periods of meteorological, agricultural, and hydrologic drought as well as anomalously wet periods. The Standardized Precipitation Index (SPI) measures the intensity of wet or dry spells by comparing a fixed period against all such periods in the historic record. Historic records of this meteorological drought index show regular cycles of wet and dry periods during the past 125 years. By incorporating estimates of evapotranspiration, infiltration, and runoff, however, the Palmer Hydrological Drought Index (PHDI) provides a more complete measure of moisture deficit and surplus and is more commonly used when considering impacts on water resources (Figure 4.23). Both measures qualitatively show interannual and interdecadal variability in dry and wet periods, but no obvious historical trends in either. This echoes other recent research showing little statistically significant evidence for changing drought length or intensity in North Carolina (Soulé, 2022). South Carolina has also historically experienced rapid drought onset (i.e., “flash droughts”), and considerable variability across the state (Figure 4.24).

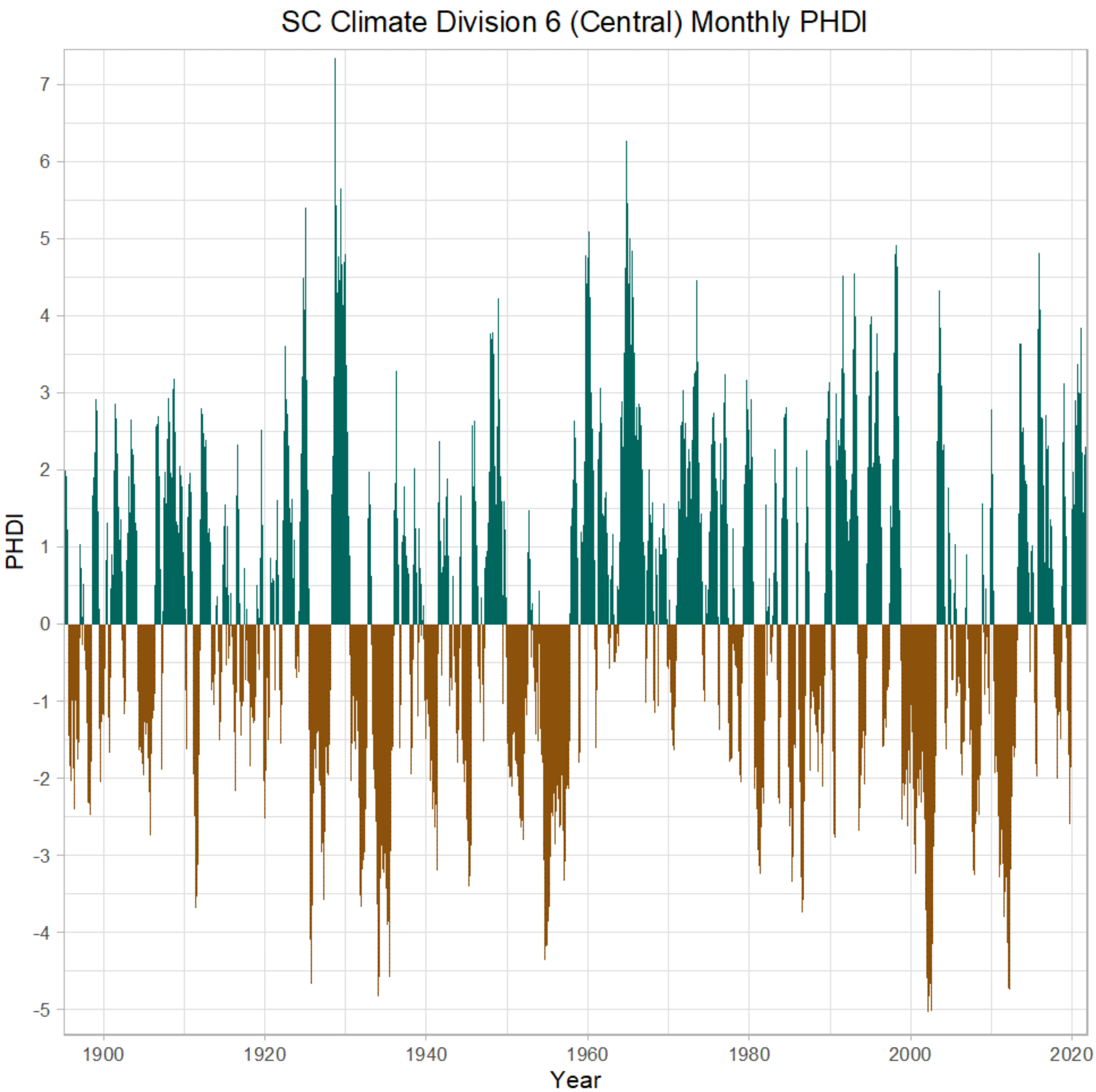

Figure 4.23: Palmer Hydrological Drought Index 1895-2020.

The 3-month SPI for November 2016 across North Carolina and South Carolina is represented in Figure 4.24. The legend shows areas of the index that indicate dry or wet conditions. The visual pattern is a swath of extremely dry areas in the western regions of the Carolinas and a swath of extremely wet areas on the Coastal Plain of the Carolinas. In the area between these two swaths, conditions are near normal.

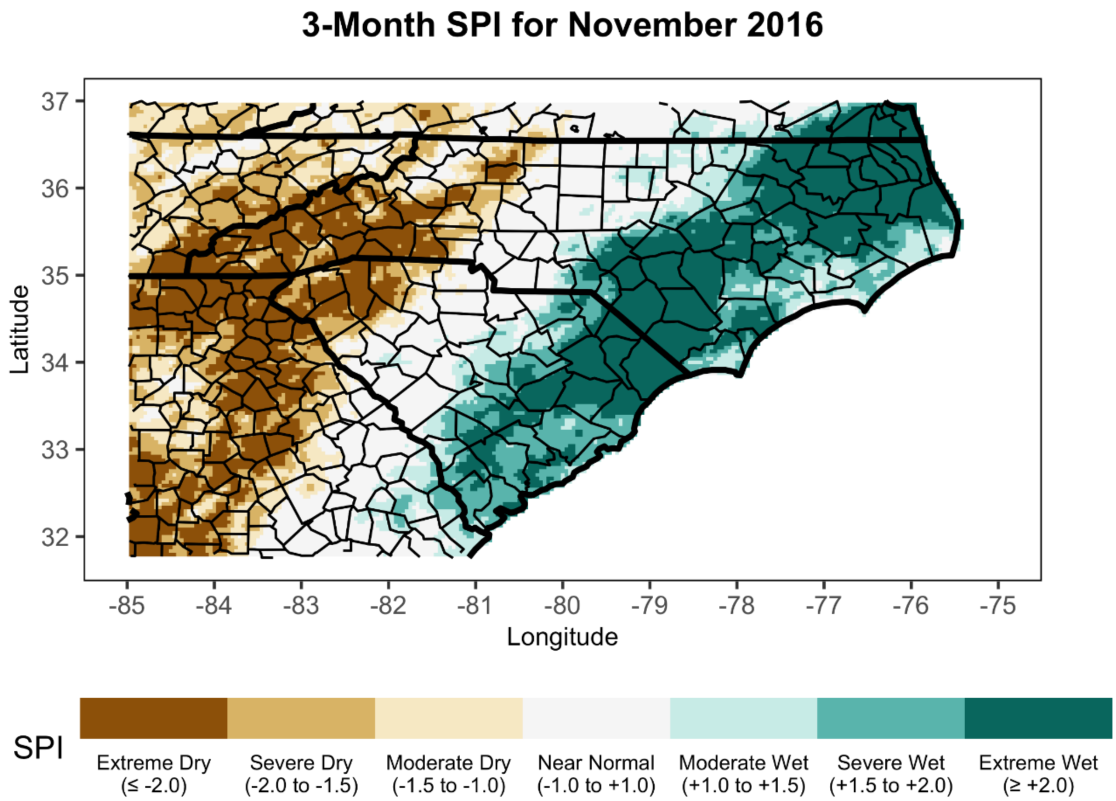

Figure 4.24: Variability of Drought across South Carolina (Fall 2016)

Projections of future meteorological drought in the state are mixed. Some recent work suggests very modest changes in projected consecutive dry days during the warm season and spatially mixed changes during the cool season (Keellings & Engström, 2019). More generally in the literature, there is relatively low confidence in human influence on meteorological drought because of uncertainties in precipitation projections. There is medium confidence that changes in the global climate could exacerbate agricultural and ecological drought, reflecting greater consensus on temperature increases that cause more evaporation from waterways and soil (Arias et al., 2021).

Projections of drought measures that incorporate an evaporation component show a trend towards drier conditions in the Southeast (Ahmadalipour et al., 2017).

TROPICAL CYCLONES

OBSERVED VARIABILITY

South Carolina's geographic position lends itself to periodic influences of tropical cyclones (i.e., tropical storms and hurricanes; Figure 4.25). Warm waters in the tropical Atlantic foster the development of these storms, that typically travel from east to west in the tropical trade wind belt. The Bermuda High pressure system in the subtropical Atlantic steers these storms when they drift north, sometimes towards South Carolina, bringing high winds, storm surge, and heavy precipitation. Some of these storms make direct strikes on the state from the Atlantic, others strike nearby states or brush the coast, still others enter as "backdoor" storms moving north from the Gulf of Mexico and ultimately affect South Carolina.

Tropical cyclone activity varies greatly from year to year and decade to decade, across the Atlantic Basin and the Gulf of Mexico. Activity depends on many variables, particularly sea surface temperature and wind shear across tropical and subtropical waters. In addition, conditions in the tropical Pacific (associated with El Niño/La Niña cycles) and thunderstorm activity in West Africa both influence the formation and development of Atlantic hurricanes.

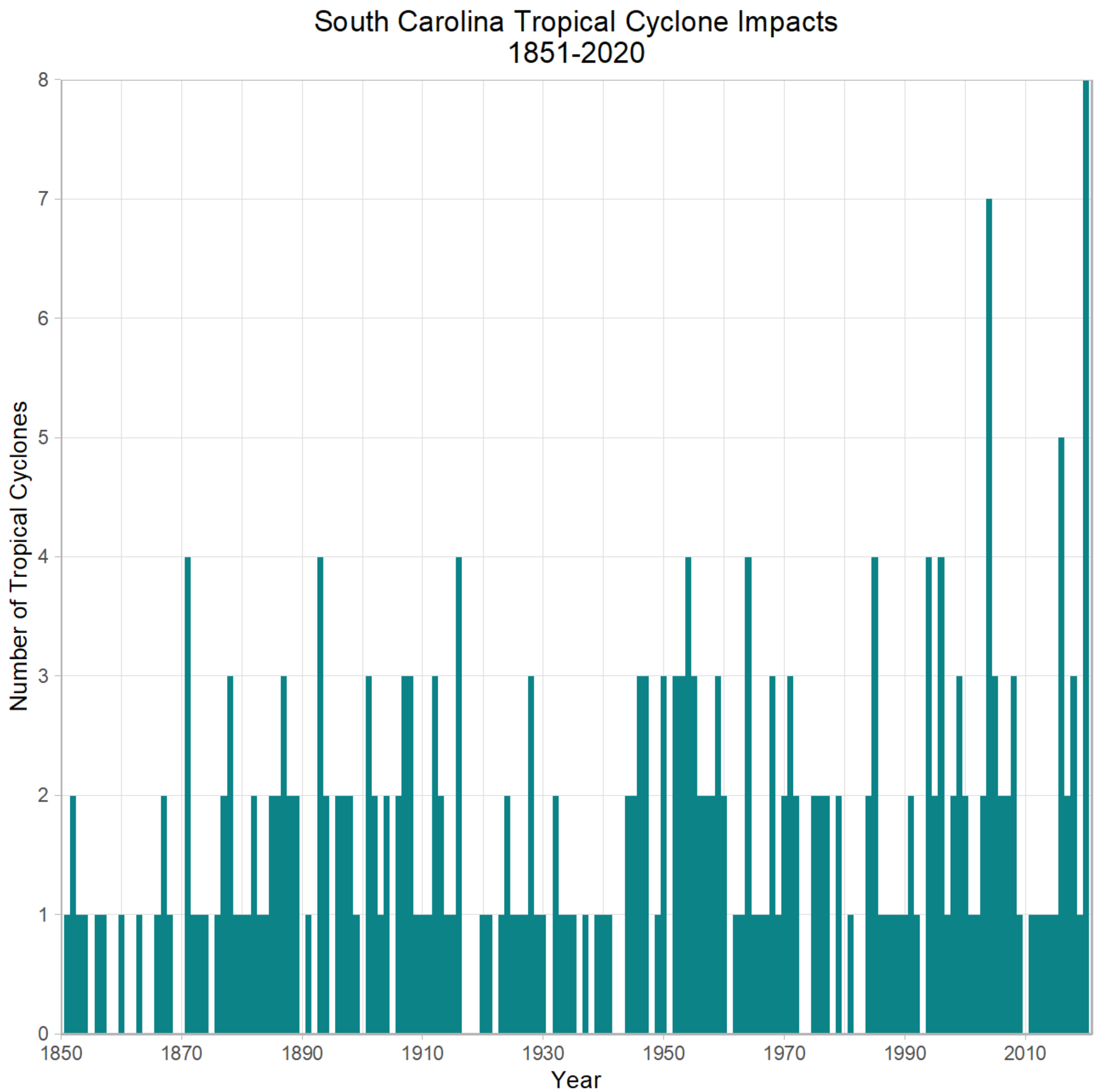

Figure 4.25: Tropical Cyclones affecting South Carolina, 1851-2020

FUTURE TROPICAL CYCLONE PROJECTIONS

Global climate trends could affect tropical cyclone frequency, intensity, and associated precipitation. Evidence for historic and projected changes come from observational analysis and climate model simulations, respectively. The observational record provides scant evidence for statistically significant changes in the number of North Atlantic hurricanes, though such investigations are hampered by a relatively short observational record (particularly over oceans), and high natural interannual and interdecadal variability. Likewise, future projections for 21st century North Atlantic hurricane frequency are mixed. While some modeling studies have indicated the possibility for fewer tropical cyclones (Mallard et al., 2013), others have shown no significant changes (Jing et al., 2021), or little basis for such decreases (Emanuel, 2021). Moreover, a panel of hurricane experts have expressed low to medium confidence in projections indicating a future decrease in the number of events (Knutson et al., 2020). The necessary conditions for hurricane formation are well known, but a more complete understanding of actual hurricane genesis is required for consistent and reliable estimates of future frequency (Sobel et al., 2021).

By contrast, observations and models show more consistency regarding recent and projected changes in hurricane intensity (Wu et al., 2022). Estimates during the satellite era (since 1979) show that category 3 and higher storms have increased in number by 8% per decade (Kossin et al., 2020). Models consistently link increasing tropical cyclone intensity to a warmer world where increasing sea surface temperatures provide more energy to the storm through increased condensation within its cumulonimbus and cumulus clouds (Emanuel, 2021; Jing & Lin, 2020; Lackman, 2015). Some future scenarios show decreased vertical wind shear near the southeastern US coast which could foster more formation and intensification of tropical cyclones (Ting et al., 2019; Vecchi & Soden, 2007). Models have also been used to estimate the effects of specific environmental changes on hurricane strength. For example, Hurricane Matthew was simulated with end-of-century-projected sea surface temperatures resulting in lower central pressure and consequent wind speed increases of 20 miles per hour (Jisan et al., 2018). There is further evidence that increased sea surface temperature has and will contribute to more rapid intensification of storms close to landfall (Emanuel, 2017).

Observations and models similarly provide a picture of increased precipitation associated with tropical cyclones (Stansfield et al., 2020). North Atlantic sea surface temperature increases of 0.75 to 1.6°F since 1850 have led to increased extreme 3-hourly rainfall rates and 3-day total precipitation of 10% and 5%, respectively, for tropical cyclone strength storms with wind speeds reaching 42 mph, and even higher for hurricane strength (74mph) storms (Reed et al., 2022). Models that incorporate convection show significantly enhanced precipitation rates and totals for simulations of Hurricanes Katrina, Irma, Maria, and Florence (Patricola & Wehner, 2018; Reed et al., 2020).

Finally, it is important to consider the impacts of compounding factors. Future changes in wind and consequent storm surge, atmospheric moisture increase and precipitation intensity, forward speed of tropical cyclones, and sea level rise could amplify impacts (Gori et al., 2022).

MARINE CLIMATE IMPACTS IN SOUTH CAROLINA

SEA LEVEL RISE

Globally, sea level rise has three main drivers — melting ice, warming ocean waters, and changes to water use on land. Melted ice adds water that was previously trapped in ice sheets and glaciers, water expands as it warms, and human uses of water either adds to (e.g., water previously trapped in an underground aquifer is taken out and used) or removes (e.g., a dam that slows the flow of a river into the ocean) water flowing into the ocean. Regionally, sea level rise can also be affected by ocean circulation and changes in land elevation.

Measurements at tidal gauges provide direct evidence for sea level rise in South Carolina and around the world. For example, the tide gauge station in Charleston at the Cooper River has recorded data since September 13, 1899, showing a 1.1-foot rise during the past 100 years; the increase has accelerated since 2000 (NOAA, 2022c). In the past three decades satellites have supplemented gauge measurements with continuous monitoring of global sea level.

Based on current greenhouse gas concentrations, sea levels in South Carolina will rise an additional 10 to 14 inches by 2050 (Sweet et al., 2022). While the core mechanics of sea level rise are not debated, projections of it beyond 2050 vary because scientists continually improve understanding of complex interactions between multiple systems (ocean, land, and ice) and because of uncertainty associated with future emissions and the timing of certain physical processes, especially abrupt changes like when an ice sheet collapses. By 2150, it is almost certain to see approximately 2 feet of sea level rise, and likely to see 3.5 to 7 feet if greenhouse gas emissions do not rapidly decrease (Figure 4.26; Sweet et al., 2022).

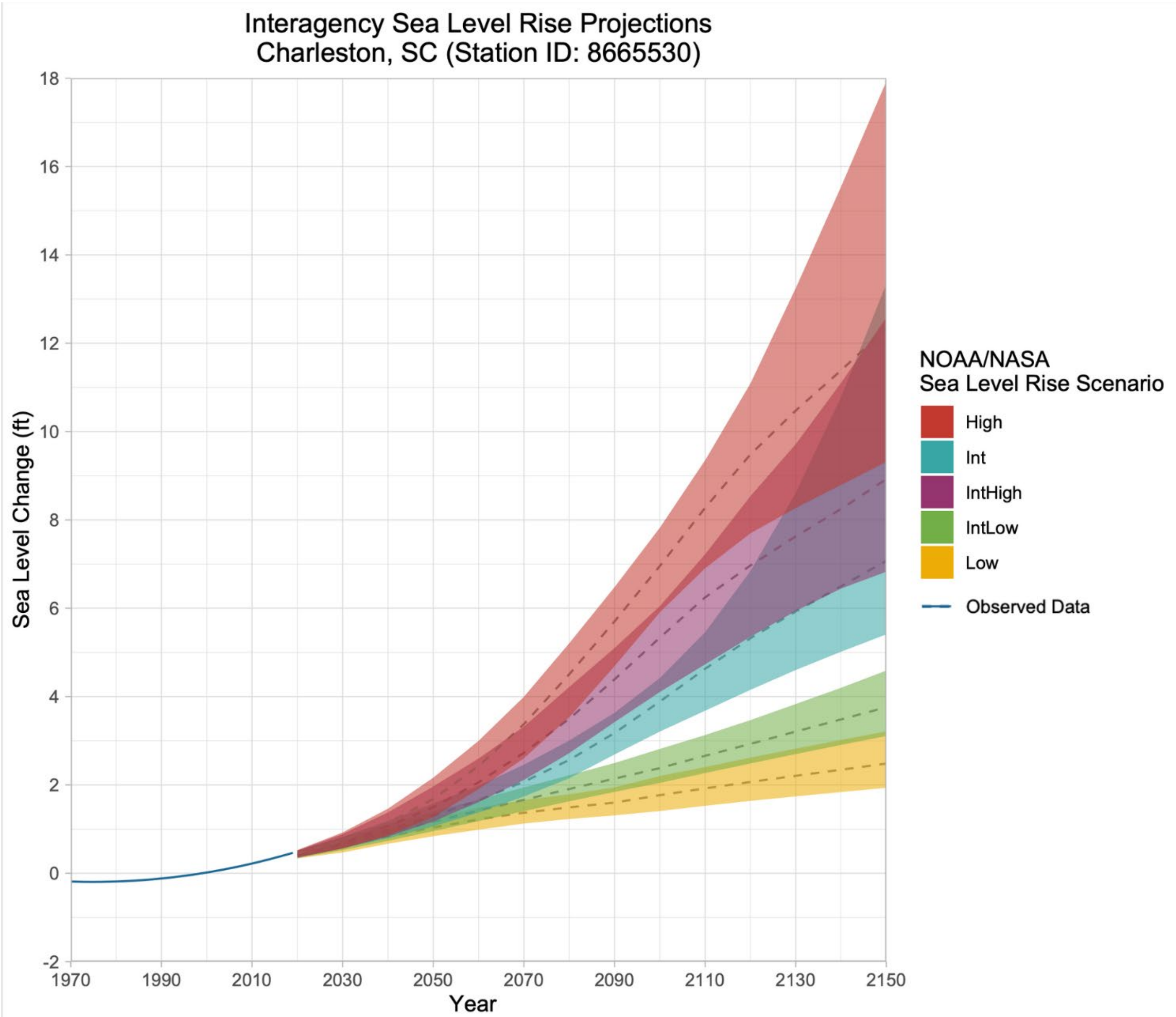

Figure 4.26: Sea level change projections at Charleston (Adapted from Sweet et al., 2022).

INCREASING FREQUENCY OF COASTAL FLOOD EXTREMES

Sea level rise can combine with storm surges, tides, or heavy rainfall to produce compound flood events (Figure 4.27; NOAA, 2022a, 2022c). Minor recurrent events cause disruptions and delays, while an additional 2 to 3 feet cause additional impacts, including damage to homes and businesses. These are sometimes referred to as extreme (sea level) events. In Charleston, extreme events are projected to occur 20 times as often by 2050 (Sweet et al., 2022).

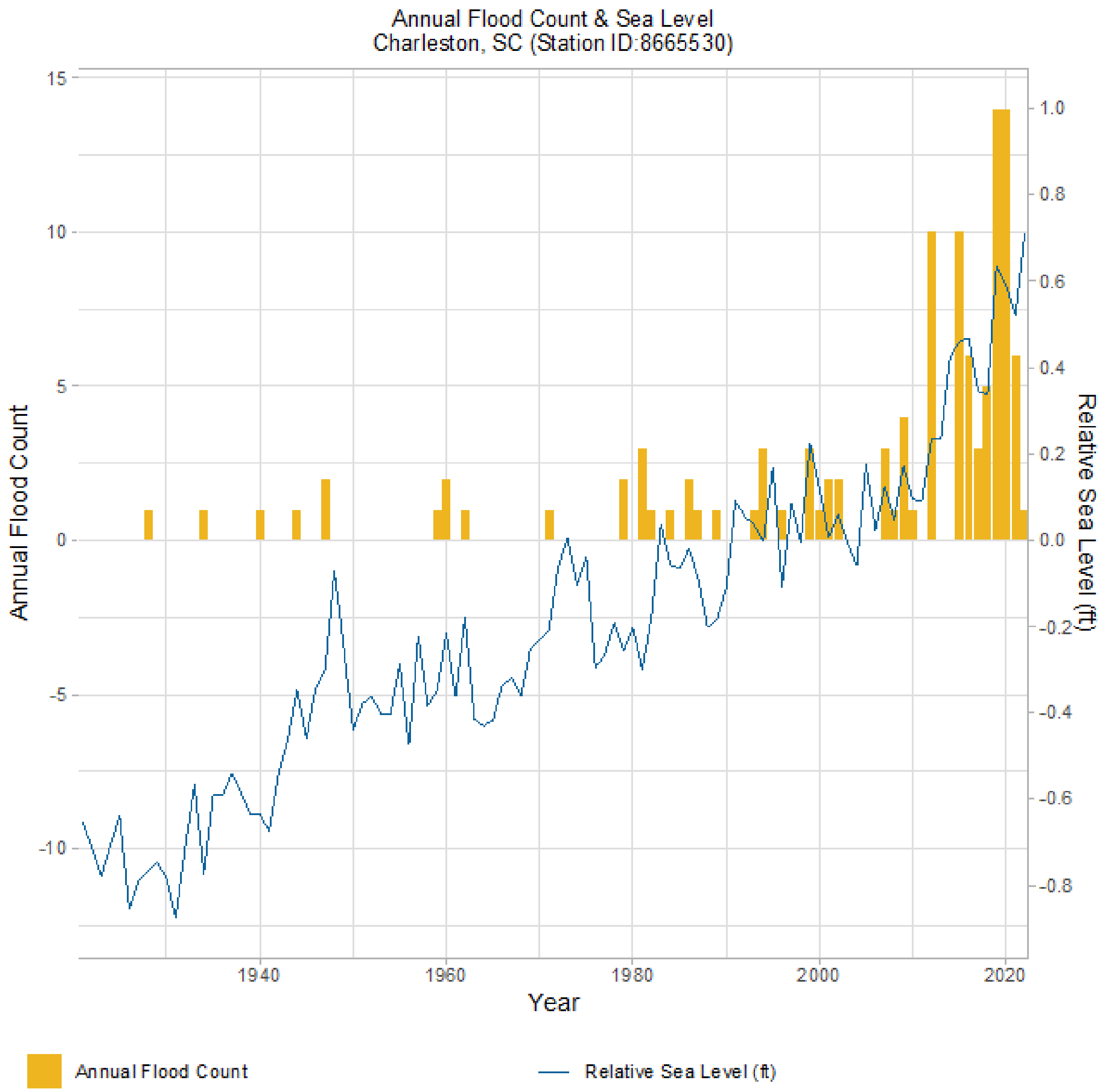

Figure 4.27: Annual Flood Count and Sea Level at Charleston Gauge. Sea level is relative to the current National Tidal Datum Epoch, 1983-2001.

OCEAN WARMING

The overwhelming majority (approximately 90%) of the warming from greenhouse gases has been absorbed by the ocean, which has warmed by about 1.6°F this century (Fox-Kemper et al., 2021). The global oceans cover approximately 71% of the Earth's surface area, and water is a highly efficient absorber of heat compared to the atmosphere. Most of the increase in sea surface temperature has been in the past 50 years, and current rates of ocean heat content increase are the highest in over 10,000 years (Fox-Kemper et al., 2021). Waters off the southeastern US coast have warmed slightly faster than the global average due to proximity to the Gulf Stream, which draws from a warming tropical Atlantic (Fox-Kemper et al., 2021). Projections from the most recent generation of (CMIP6) climate models indicate a hotspot off the U.S. Atlantic coastline, with an increase of approximately 7 to 9°F by 2100 (Table 4.1: MIP6 ensemble, Eastern North America Oceanic Region. Values in table are median projections, values in parenthetical are 5th and 95th percentiles, respectively. Future projections are in reference to baseline data from 1850 – 1900 (IPCC, 2022).Table 4.1; Intergovernmental Panel on Climate Change [IPCC], 2022; Ranasinghe et al., 2021). Coastal waters will warm faster than deep water, an effect of the gentle continental shelf slope and shallower water depths.

Warming ocean waters worsen other climate impacts, such as increasing the intensity of tropical hurricanes moving over them, as well as negatively affecting marine wildlife (Bindoff et al., 2019; Seneviratne et al., 2021). In addition to an increase in mean ocean temperature, temperatures can further spike within shorter periods; this is called a marine heatwave. If changes in global temperature exceed 3.6°F (2°C), the southeast U.S. Atlantic coast is projected to experience severe marine impacts, with marine heatwaves 20 times more often than present (Ranasinghe et al., 2021). NOAA is combining climate models with oceanographic station data to forecast marine heatwaves in our region up to 12 months in advance (Jacox et al., 2022).

OCEAN ACIDIFICATION

About a quarter (approximately 20 to 30%) of CO_2 emissions enter the ocean; there is robust evidence that this uptake has caused ocean acidification (Canadell et al., 2021). At the regional level, ocean acidification is additionally affected by biological processes and runoff from land (Canadell et al., 2021). The surface ocean pH (a measure of acidity / alkalinity) has decreased at a rate of 0.017 to 0.027 units per decade since the late 1980s (indicating greater acidity), and estimates place the total pH decrease from human activities around 0.1 (Canadell et al., 2021; Tanhua et al., 2015). Since pH is a logarithmic scale, a decline from 8.2 to 8.1 represents a 26% increase in acidity. The rate of ocean acidification is predicted to accelerate in the southeast region in the next 20 to 30 years, and projections of ocean acidification off the eastern coast of the U.S. under a high emissions scenario would approach pH levels not seen in the past 65 million years by the end of the century (Table 4.1; Canadell et al., 2021).

Table 4.1: MIP6 ensemble, Eastern North America Oceanic Region. Values in table are median projections, values in parenthetical are 5th and 95th percentiles, respectively. Future projections are in reference to baseline data from 1850 – 1900 (IPCC, 2022).

Variable	RCP 4.5 (2081 – 2100)	RCP 8.5 (2081 – 2100)
Sea Surface Temperature	+ 4.7°F (2.7 | 6.7)	+ 7.6°F (4.7 | 9.7)
pH at Surface	- 0.3 (-0.3 | -0.2)	- 0.5 (-0.5 | -0.4)

INCREASED SALINITY

The Atlantic has become saltier in the past 60 years, due to change in evaporation/precipitation balances over the ocean surface (Fox-Kemper et al., 2021). The link between anthropogenic CO_2 and salinity changes is robust (Eyring et al., 2021).

Observed changes off the Carolinas coast are highly significant when analyzed alongside climate model projections (Friedman et al., 2017).

DECREASED DISSOLVED OXYGEN

Ocean heating can reduce mixing and inhibit the process by which gasses dissolve in water. In the past 50 years, dissolved oxygen has decreased in the ocean's upper 1000 meters by 0.5 to 3.3% (Canadell et al., 2021). The link between anthropogenic CO_2 and changes in dissolved oxygen is highly robust (Canadell et al., 2021; Garcia-Soto et al., 2021). Deoxygenation serves as an indicator of changing ocean climate conditions with implications for biological habitats; it is projected to accelerate globally (Canadell et al., 2021).

CHANGING OCEAN CURRENTS

The Atlantic Meridional Overturning Circulation (a series of interconnected ocean currents, including the Gulf Stream) has slowed during the past 20 years and scientists are uncertain whether it could collapse under a high emissions scenario (Fox-Kemper et al., 2021). A combination of changes in water temperature and salinity, strongly affected by melting ice in Greenland, has affected the rate of deep water formation which drives this system of currents (Fox-Kemper et al., 2021). Climate models have underestimated observed rates of slowing, and scientists are actively researching the potential of a larger slowing or collapse (Fox-Kemper et al., 2021).

Significant decreases in the Gulf Stream would further increase sea levels along the southeast US coast.

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