North Carolina
Climate Science Report

Report Findings and Executive Summary

NCICS

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NCICS

Foreword

The North Carolina Climate Science Report is a scientific assessment of historical climate trends and potential future climate change in North Carolina under increased greenhouse gas concentrations. It supports Governor Cooper's Executive Order 80 (EO80), "North Carolina's Commitment to Address Climate Change and Transition to a Clean Energy Economy," by providing an independent peer-reviewed scientific contribution to the EO80.

The report was prepared independently by North Carolina–based climate experts informed by (i) the scientific consensus on climate change represented in the United States Fourth National Climate Assessment and the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, (ii) the latest research published in credible scientific journals, and (iii) information in the North Carolina State Climate Summary.

An advisory panel ("Climate Science Advisory Panel") was formed to provide oversight and review of the report. This panel consisted of North Carolina university and federal research scientists with national and international reputations in their specialty areas of climate science.

The report underwent several rounds of review and revision, including an anonymous peer review organized by NOAA's National Centers for Environmental Information (NCEI). The report is available via ncics.org/nccsr.

Report Findings

These findings present key conclusions of this report about observed and projected changes in the climate of the state of North Carolina.

Quantitative projections for temperature, precipitation, and sea level rise are provided for two future scenarios: a higher scenario (RCP8.5), in which greenhouse gas emissions continue to increase through the end of this century, and a lower scenario (RCP4.5), in which emissions increase at a slower rate, peak around the middle of this century, and then begin to decrease. Future increases in temperature are dependent on greenhouse gas emissions, with higher emissions resulting in greater warming. Qualitative projections are based on expert judgment and assessment of the relevant scientific literature and draw on multiple lines of scientific evidence as well as model simulations.

Global average temperature has increased about 1.8°F since 1895. Scientists have ***very high confidence*** that this warming is largely due to human activities that have significantly increased atmospheric concentrations of carbon dioxide (CO_2) and other greenhouse gases. It is ***virtually certain*** that global warming will continue, assuming greenhouse gas concentrations continue to increase. By the end of this century (2080–2099), global average temperature is projected to increase by about 4°–8°F compared to the recent climate (1996–2015) under the higher scenario (RCP8.5) and by about 1°–4°F under the lower scenario (RCP4.5).

Global average sea level has increased by about 7–8 inches since 1900, with almost half of this increase occurring since 1993. It is ***virtually certain*** that global sea level will continue to rise due to expansion of ocean water from warming and melting of ice on land, such as the Greenland and Antarctic ice sheets.

Observed and Projected Changes for North Carolina

Except where noted, statements about future changes refer to projections through the end of this century.

- Our scientific understanding of the climate system strongly supports the conclusion that large changes in North Carolina's climate, much larger than at any time in the state's history, are ***very likely*** by the end of this century under both the lower and higher scenarios.

Temperature

- North Carolina annual average temperature has increased by about 1.0°F since 1895, somewhat less than the global average. The most recent 10 years (2009–2018), however, represent the warmest 10-year period on record in North Carolina, averaging about 0.6°F warmer than the warmest decade in the 20th century (1930–1939). Recently released data indicate that 2019 was the warmest year on record for North Carolina.

- Although regional changes in temperature can vary from global changes, it is ***very likely*** that North Carolina temperatures will also increase substantially in all seasons. Annual average temperature increases relative to the recent climate (1996–2015) for North Carolina are projected to be on the order of 2°–5°F under a higher scenario (RCP8.5) and 2°–4°F under a lower scenario (RCP4.5) by the middle of this century. By the end of this century, annual average temperature increases relative to the recent climate (1996–2015) for North Carolina are projected to be on the order of 6°–10°F under a higher scenario (RCP8.5) and 2°–6°F under a lower scenario (RCP4.5).
- North Carolina has not experienced an increase in the number of hot (daytime maximum temperature of 90°F or higher) and very hot (daytime maximum temperature of 95°F or higher) summer days since 1900. However, it has seen an increase in the number of warm (nighttime minimum temperature of 70°F or higher) and very warm nights (nighttime minimum temperature of 75°F or higher).
- It is ***very likely*** that the number of warm and very warm nights will increase.
- It is ***very likely*** that summer heat index values will increase because of increases in absolute humidity.
- It is ***likely*** that the number of hot and very hot days will increase.
- It is ***likely*** that the number of cold days (daytime maximum temperature of 32°F or lower) will decrease.

Precipitation

- There is no long-term trend in annual total precipitation averaged across the state. However, there is an upward trend in the number of heavy rainfall events (3 inches or more in a day), with the last four years (2015–2018) having seen the greatest number of events since 1900.
- It is ***likely*** that annual total precipitation for North Carolina will increase.
- It is ***very likely*** that extreme precipitation frequency and intensity in North Carolina will increase due to increases in atmospheric water vapor content.

Sea Level

- Sea level along the northeastern coast of North Carolina has risen about twice as fast as along the southeastern coast, averaging 1.8 inches per decade since 1978 at Duck, NC, and 0.9 inches per decade since 1935 at Wilmington, NC.
- It is ***virtually certain*** that sea level along the North Carolina coast will continue to rise due to expansion of ocean water from warming and melting of ice on land, such as the Greenland and Antarctic ice sheets. Under a higher scenario (RCP8.5), storm-driven water levels that have a 1% chance of occurring each year in the beginning of the 21st

century may have as much as a 30%–100% chance of occurring each year in the latter part of the century. High tide flooding, defined as water levels of 1.6–2.1 feet (0.5–0.65 m) above Mean Higher High Water, is projected to become a nearly daily occurrence by 2100 under both the lower and higher scenarios.

Hurricanes

- On a global scale, the intensity of the strongest hurricanes is ***likely*** to increase with warming. The confidence in this outcome is ***high***. For individual regions such as North Carolina, the confidence in this outcome is ***medium***. While confidence for North Carolina is lower than for the entire globe, there is no known reason that North Carolina would be protected from stronger hurricanes, and this potential risk should be considered in risk assessments.
- Heavy precipitation accompanying hurricanes that pass near or over North Carolina is ***very likely*** to increase, which would in turn increase the potential for freshwater flooding in the state.
- There is ***low confidence*** concerning future changes in the number of landfalling hurricanes in North Carolina.

Storms

- It is ***likely*** that the frequency of severe thunderstorms in North Carolina will increase.
- It is ***likely*** that total snowfall and the number of heavy snowstorms in North Carolina will decrease due to increasing winter temperatures.
- There is ***low confidence*** concerning future changes in the number of winter coastal storms.
- There is ***low confidence*** concerning future changes in the number of ice storms in North Carolina.

Floods, Droughts, and Wildfire

- It is ***virtually certain*** that rising sea level and increasing intensity of coastal storms, especially hurricanes, will lead to an increase in storm surge flooding in coastal North Carolina.
- It is ***likely*** that increases in extreme precipitation will lead to increases in inland flooding in North Carolina.
- It is ***likely*** that future severe droughts in their multiple forms in North Carolina will be more frequent and intense due to higher temperatures leading to increased evaporation. As a result, it is ***likely*** that the frequency of climate conditions conducive to wildfires in North Carolina will increase.

Other Compound Events

- It is ***likely*** that future urban growth will increase the magnitude of the urban heat island effect, with stronger warming in North Carolina urban centers.
- There is ***low confidence*** concerning future changes in conditions favorable for near-surface ozone formation in North Carolina because of counteracting influences from increases in both temperature and water vapor.

Engineering Design Standards

- It is ***very likely*** that some current climate design standards for North Carolina buildings and other infrastructure will change by the middle of the 21st century. This includes increases in design values for precipitation, temperature, and humidity. Several professional societies, however, are actively working on methods to incorporate climate change into national standards, and updated standards appropriate for use in a changing climate may be available in the near future.

Executive Summary

Our scientific understanding of the climate system strongly supports the conclusion that North Carolina's climate has changed in recent decades and the expectation that large changes—much larger than at any time in the state's history—will occur if current trends in greenhouse gas concentrations continue. Even under a scenario where emissions peak around 2050 and decline thereafter, North Carolina will experience substantial changes in climate. The projected changes with the highest level of scientific confidence include increases in temperature, increases in summer absolute humidity, increases in sea level, and increases in extreme precipitation. It is also ***likely*** that there will be increases in the intensity of the strongest hurricanes.

A full appreciation for past and future changes in North Carolina's climate requires a global perspective. Earth's climate has warmed substantially since the late 19th century, with most of that warming occurring in the last 50 years. This warming trend is clear from global temperature records and many other indicators, including rising global sea levels and rapid decreases in arctic sea ice cover. Scientists have ***very high confidence*** that this warming is largely due to human activities that have significantly increased atmospheric concentrations of carbon dioxide (CO_2) and other greenhouse gases. Extensive research has examined other potential causes of this warming, and the increase in greenhouse gas concentrations is the only plausible cause that is consistent with the observed data and the physics that govern the climate system.

Observed Changes

In North Carolina, annual average temperature has increased about 1°F since 1895, compared to the global average increase of about 1.8°F during that period. Annual average temperatures have been consistently above normal since the 1990s, with the most recent 10 years (2009–2018) representing the warmest 10-year period on record—about 0.6°F warmer than the warmest decade of the 1900s (1930–1939). Data for 2019, which were released during the review of this report, indicate that 2019 was the warmest year on record for North Carolina.

Most other temperature indicators also show warming. Average temperatures have increased in all four seasons. There has been an increase in the number of very warm nights. The length of the growing season has increased and is now about 1.5 weeks longer than the long-term average. There is an upward trend in the number of cooling degree days (a temperature indicator related to air conditioning demand) and a downward trend in the number of heating degree days (an indicator of heating demand)—both changes are consistent with a warming climate. However, a few indicators that would be expected to change with warmer conditions have not. For example, the number of very hot days has not increased, and there is no overall trend in the number of cold days and cold nights.

There is no long-term trend in annual total precipitation averaged across the state; however, 2018 was the wettest year on record, in part due to the torrential rainfall from Hurricane Florence. There has been an upward trend in the number of heavy rainfall events (days with more than 3 inches of rain), indicating that a larger portion of the annual total precipitation is occurring in heavy events. Temperature and precipitation trends in the three regions of the state (Coastal Plain, Piedmont, and Western Mountains) are generally similar to statewide trends.

Most observing stations outside of the mountains have experienced a downward trend in snowfall. In the Western Mountains, there is no century-long trend in snowfall, although stations in the southern mountains have seen decreasing trends over the last 50 years. Conditions favorable for snow-cover maintenance and snowmaking in the Western Mountains have been highly variable since 1981, but recent years have seen below average percentages of time when conditions are favorable.

Global average sea level has increased by about 7–8 inches since 1900, with almost half of this increase occurring since 1993—a rate of about 1.2 inches per decade. Sea level along the northeastern coast of North Carolina is rising about twice as fast as along the southeastern coast, averaging 1.8 inches per decade since 1978 at Duck, NC, and 0.9 inches per decade at Wilmington, NC, mainly due to different rates of land subsidence.

Projected Changes

The projections of North Carolina climate conditions presented in this report are based on the ***virtual certainty*** that greenhouse gas concentrations, particularly CO_2, will continue to rise. It may take decades for non-carbon-based sources of energy to replace most of the production based on fossil fuels. The basic principles of physics dictate that increases in greenhouse gas concentrations will have a warming effect, with ***virtual certainty***, due to the increase in atmospheric absorption of infrared energy.

Quantitative projections for temperature, precipitation, and sea level rise are provided for two future scenarios: a higher scenario (RCP8.5), in which greenhouse gas emissions continue to increase through the end of this century, and a lower scenario (RCP4.5), in which emissions increase at a slower rate, peak around the middle of this century, and then begin to decrease. RCP8.5 and RCP4.5 are Representative Concentration Pathways—scenarios used in climate model simulations to examine how Earth's climate would respond to differing levels of greenhouse gas concentrations. The numbers 8.5 and 4.5 refer to the magnitude of the energy imbalance in the climate system (in units of watts per square meter) that would result in the year 2100 from the increases in greenhouse gas concentrations specified by the respective scenarios. By comparison, the increase in concentrations since the initiation of the Industrial Revolution has resulted in an imbalance of approximately 2.3 watts per square meter.

A very low scenario (RCP2.6) is also used occasionally in this report, but this scenario is very unlikely because there has been no slowdown in the annual growth rate of CO_2. Qualitative projections are based on expert judgment and assessment of the relevant scientific literature and draw on multiple lines of scientific evidence as well as model simulations. Except where noted, statements below about future changes refer to projections through the end of this century.

By the end of this century (2080–2099), global average temperature is projected to increase by about 4°–8°F compared to the current climate (1996–2015) under the higher scenario (RCP8.5) and by about 1°–4°F under the lower scenario (RCP4.5). The warming is projected to be greater in the middle and high latitudes and less at tropical latitudes.

Regional changes in temperature can differ from global changes, at least temporarily, as shown by the historical lower rate of warming in North Carolina compared to the global average. Seasonal and annual average temperatures, however, have been rising in North Carolina in recent decades, and it is ***very likely*** that North Carolina temperatures will continue to increase substantially in all seasons.

- By the middle of this century, annual average temperature increases relative to the current climate (1996–2015) for North Carolina are projected to be on the order of 2°–5°F under the higher scenario (RCP8.5) and 2°–4°F under the lower scenario (RCP4.5).
- By the end of this century, annual average temperature increases relative to the current climate (1996–2015) for North Carolina are projected to be on the order of 6°–10°F under the higher scenario (RCP8.5) and 2°–6°F under the lower scenario (RCP4.5).

Temperature extremes are also projected to change:

- It is ***very likely*** that the number of very warm nights will increase, continuing recent trends.
- It is ***likely*** that the number of very hot days will increase, although the level of confidence is lower than for very warm nights because of the lack of recent trends.
- It is ***likely*** that the number of cold days and very cold nights will decrease, but again the level of confidence is lower than for very warm nights because of the lack of recent trends.

Several additional climate features directly tied to temperature are also projected to change, with a high level of certainty:

- It is ***very likely*** that extreme precipitation frequency and intensity will increase because global ocean surface temperatures will continue to increase gradually. In turn, near-surface air temperature and absolute humidity will increase over the oceans because maximum water vapor content is strongly related to temperature, increasing by about 3.5% per °F.
- It is ***virtually certain*** that global sea level will continue to rise due to both the expansion of ocean water from warming and from the melting of ice on land, including the Greenland and Antarctic ice sheets. It is ***virtually certain*** that sea level along the North Carolina coast will also continue to rise. Under the higher scenario (RCP8.5), storm-driven water levels having a 1% chance of occurring each year in the beginning of the 21st century may have as much as a 30%–100% chance of occurring each year in the

latter part of the century. High tide flooding is projected to become nearly a daily occurrence by 2100 under both the lower and higher scenarios.

- It is ***very likely*** that summer heat index values will increase because of increases in absolute humidity.
- It is ***likely*** that the probability of snowfall and snow cover will decrease nearly everywhere in North Carolina because of warmer temperatures.

For climate variables where the temperature dependence is more complex, projected changes are less certain:

- Inland flooding depends not only on extreme precipitation but also on characteristics of the land surface, including land use, land cover, and soil moisture conditions. It also depends on whether deliberate adaptive measures are implemented proactively. It is ***likely*** that the frequency and severity of inland flooding will increase because of increases in the frequency and intensity of extreme precipitation. This lower level of certainty compared to projections for changes in extreme precipitation stems from the additional factors that determine flooding.
- It is ***likely*** that annual total precipitation in the state will increase, but there is less certainty for annual total precipitation than for projected increases in extreme precipitation because total precipitation is a function of both atmospheric water vapor and the frequency and intensity of weather systems that cause precipitation. Future changes in the intensity and frequency of such weather systems are more uncertain.

Hurricanes have some of the most important impacts on the state, often catastrophic (storm surge, wind, and flooding damage) but sometimes beneficial (rainfall recharging soil moisture and groundwater aquifers). An understanding of future changes in hurricanes has been the subject of extensive research by climate scientists. While that understanding continues to evolve, a recent assessment of the science leads to the conclusion that the intensity of the strongest hurricanes is ***likely*** to increase with warming, and this could result in stronger hurricanes impacting North Carolina. Confidence in this result is ***high*** for tropical cyclone changes on a global scale. For individual regions such as North Carolina, the confidence in this outcome is ***medium***. While confidence for North Carolina is lower than for the entire globe, there is no known reason that North Carolina would be protected from stronger hurricanes, and this potential risk should be considered in risk assessments.

It is ***virtually certain*** that rising sea level and increasing intensity of coastal storms, especially hurricanes, will lead to increases in storm surge flooding in coastal North Carolina. There is ***low confidence*** concerning future changes in the total number of hurricanes. The total number of hurricanes depends on a variety of meteorological factors, such as vertical wind shear (changes in wind speed or direction with height in the atmosphere), and not just ocean surface temperatures, and there is considerable uncertainty about changes in these other factors. Heavy precipitation accompanying hurricanes is ***very likely*** to increase, increasing the potential for freshwater floods.

Severe thunderstorms (hail, tornadoes, and strong winds) are a regular occurrence in North Carolina, particularly in the spring. Severe thunderstorms require two primary atmospheric conditions: an unstable atmosphere and high vertical wind shear. It is ***very likely*** that vertical instability will increase, but it is also ***likely*** that vertical wind shear will decrease. These may counteract one another. Recent research suggests that the increases in atmospheric instability will dominate. While this remains an active area of research, it is ***likely*** that there will be increases in the frequency of severe thunderstorms.

Other important weather systems include snowstorms, winter coastal storms, and ice storms. There is considerable uncertainty about future changes in the number and severity of extratropical cyclones—the weather phenomenon that causes each of these winter storm types. In the case of snow, temperature is an important factor, and it is ***likely*** that total snowfall and the number of heavy snowstorms will decrease because of increasing temperatures. There is ***low confidence*** concerning future changes in the number of ice storms and winter coastal storms.

Drought can have major impacts on the state, including agricultural production, water availability in rivers, lakes, and aquifers, and wildfires. The impacts on these different sectors and systems vary depending on the duration and spatial scale of the precipitation deficits. Although overall precipitation is projected to increase, this is principally a result of larger amounts during heavy rain events. Intervening dry periods are projected to become more frequent, and higher temperatures during those dry periods will more rapidly deplete soil moisture. Thus, it is ***likely*** that major droughts in their multiple forms will become more frequent and severe because of higher temperatures that will increase evaporation rates. As a result, it is ***likely*** that the climate conditions conducive to wildfires in North Carolina will increase in the future.

The major urban areas of the state have expanded substantially over the past few decades, and this trend shows no signs of abating. The urban heat island effect results from the conversion of vegetated surfaces (such as forests and farmland) to urban and suburban landscapes with substantial percentages of impervious, non-vegetated surfaces, reducing the amount of natural cooling from evapotranspiration (the combination of evaporation of water from the surface and transpiration of water vapor from vegetation) and increasing the amount of heat retained in darker, paved surfaces as compared to natural land cover. It is ***likely*** that future warming in urban areas will be enhanced by future growth of those areas.

Near-surface ozone is a major component of air pollution, and harmful levels of near-surface ozone result from a combination of climate conditions and human-caused emissions of compounds necessary for the formation of ozone, including nitrogen oxides, carbon monoxide, and volatile organic compounds (referred to as ozone precursor compounds). Near-surface ozone concentrations tend to increase with temperature. However, changes in other climate conditions, such as increased precipitation, can counteract the temperature effect. Overall, it is uncertain what the net effect will be. Thus, there is ***low confidence*** concerning future changes in the conditions favorable for near-surface ozone concentrations.

Climate design values, which provide information on the average and extreme climate conditions experienced in a given location, are important for planning and designing many types of infrastructure. Many climate design values are projected to change because of warming. Because of the high level of confidence in increased temperature and extreme precipitation, it is ***very likely*** that some current climate design standards for building and other infrastructure will change by the middle of this century. This includes increases in design values for precipitation, temperature, and humidity. In fact, current design values are based on historical data and do not incorporate recent trends; thus, some standards may already be out of date. Several professional societies, however, are actively working on methods to incorporate climate change into national standards, and updated standards appropriate for use in a changing climate may be available in the near future.