Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Environment International 29 (2003) 263–275
ENVIRONMENT INTERNATIONAL
www.elsevier.com/locate/envint

Analysis of climate trends in North Carolina (1949–1998)

Ryan P. Boyles*, Sethu Raman

State Climate Office of North Carolina, Department of Marine, Earth, and Atmospheric Sciences, North Carolina State University, Raleigh, NC 27695-7236, USA

Abstract

North Carolina has one of the most complex climates in the United States (U.S.). Analysis of the climate in this state is critical for agricultural and planning purposes. Climate patterns and trends in North Carolina are analyzed for the period 1949–1998. Precipitation, minimum temperature, and maximum temperature are analyzed on seasonal and annual time scales using data collected from the National Weather Service Cooperative Observer Network. Additionally, changes in patterns of occurrence of the last spring freeze and first fall freeze are investigated. Linear time series slopes are analyzed to investigate the spatial and temporal trends of climate variability in North Carolina. Spatial analysis of climate variability across North Carolina is performed using a geographic information system.

While most trends are local in nature, there are general statewide patterns. Precipitation in North Carolina has increased over the past 50 years during the fall and winter seasons, but decreased during the summer. Temperatures during the last 10 years are warmer than average, but are not warmer than those experienced during the 1950s. The warm season has become longer, as measured by the dates of the last spring freeze and first fall freeze. Generally, the last 10 years were the wettest of the study period.

These conclusions are consistent with earlier studies that show that the difference between the maximum and minimum temperatures is decreasing, possibly due to increased cloud cover and precipitation. Similarly, these results show that temperature patterns are in phase with the North Atlantic Oscillation and precipitation patterns appear to be correlated with the Pacific Decadal Oscillation.

Keywords: North Carolina; Climate change; Spatial analysis; Precipitation; Temperature

1. Introduction

North Carolina has one of the most complex climates in the U.S. Factors such as complex topography in the west and warm waters off the east coast combine with weather patterns to produce a region with locally variable weather and climate. Historically, climate analysis has been performed on continental and global scales (Pielke et al., 2000). However, with such local complexities, there is need to define local climate patterns. Local scale climate analysis can more accurately represent the complex climate that exists in North Carolina, and offers new insights into precipitation and temperature patterns. Epperson et al. (1988) documented historical climate patterns in North Carolina. However, there has been no investigation into climate change on a local scale. Such research is especially needed given the debate over the past decade about global and local climate change and the world's efforts to mitigate human influences on climate through the 1997 Kyoto Protocol.

Traditionally, climate patterns have been investigated using trend analysis on a point-by-point basis. Temperature and precipitation trends from one location would be compared with surrounding locations. This is appropriate when large distances separate monitoring locations. However, advanced spatial analysis is possible when monitoring locations are clustered in a local region. Spatially analyzing climate variables on a local scale provides improved insight into local patterns over both space and time.

In the 1980s, several studies were published that investigated climate change on a national and global scale, using surface observations and remote sensing platforms (Diaz and Quayle, 1980). However, there were few studies that investigated climate on a local scale, using the full suite of observing locations. Historically, climate researchers have used observations from a single location to represent the climate for a large area, sometimes even an entire state (Pielke et al., 2000).

Generally, a single station, especially in complex climatic regions, cannot accurately represent a large region. A good

* Corresponding author. Tel.: +1-919-515-3056; fax: +1-919-515-1441.
E-mail address: ryan_boyles@ncsu.edu (R.P. Boyles).

0160-4120/02/$ - see front matter © 2002 Elsevier Science Ltd. All rights reserved.
doi:10.1016/S0160-4120(02)00185-X

example is the Asheville, NC recording station. This station in downtown Asheville is one of the driest stations in North Carolina, receiving less than 40 in. of precipitation annually; the 30-year normal precipitation from 1961 to 1990 is 37.97 in. (Owenby and Ezell, 1992). The Asheville station is often used in climate studies due to its long period of record. The Asheville station is at the base of the French Broad river valley, and is surrounded by mountains. Twenty-five miles away, the wettest region in North Carolina is in Transylvania County. This region is considered a temperate rain forest, and some areas receive nearly 100 in. of precipitation annually; the 30-year normal from 1961 to 1990 for Coweeta (Macon County) is 93.2 in. (Owenby and Ezell, 1992). However, since there are few long-term stations in this region, the climate signal from Asheville is used to represent the entire western part of North Carolina in many climate studies. Use of Asheville data suggests that western NC is dry, when in fact the region as a whole is rather wet.

2. Statistical methods of analysis

The traditional method for defining local climate is to analyze climatic data records for the specific area. Generally, temperature and precipitation measuring instruments have been sited so that data would be as representative as possible for the surrounding region. In 1949, there were 57 stations in North Carolina that measured and recorded temperature and precipitation and 18 that recorded precipitation only.

Trend analysis of time series from single point observations has often been used to define local climate trends. Advanced statistics, such as signal-to-noise ratios and optimal signal detection, have been used to investigate the changes that occur on different time scales for each point. Use of these statistics often proves insightful for single points, but must be adjusted to optimize the signal for all other location. Simple statistical methods, such as

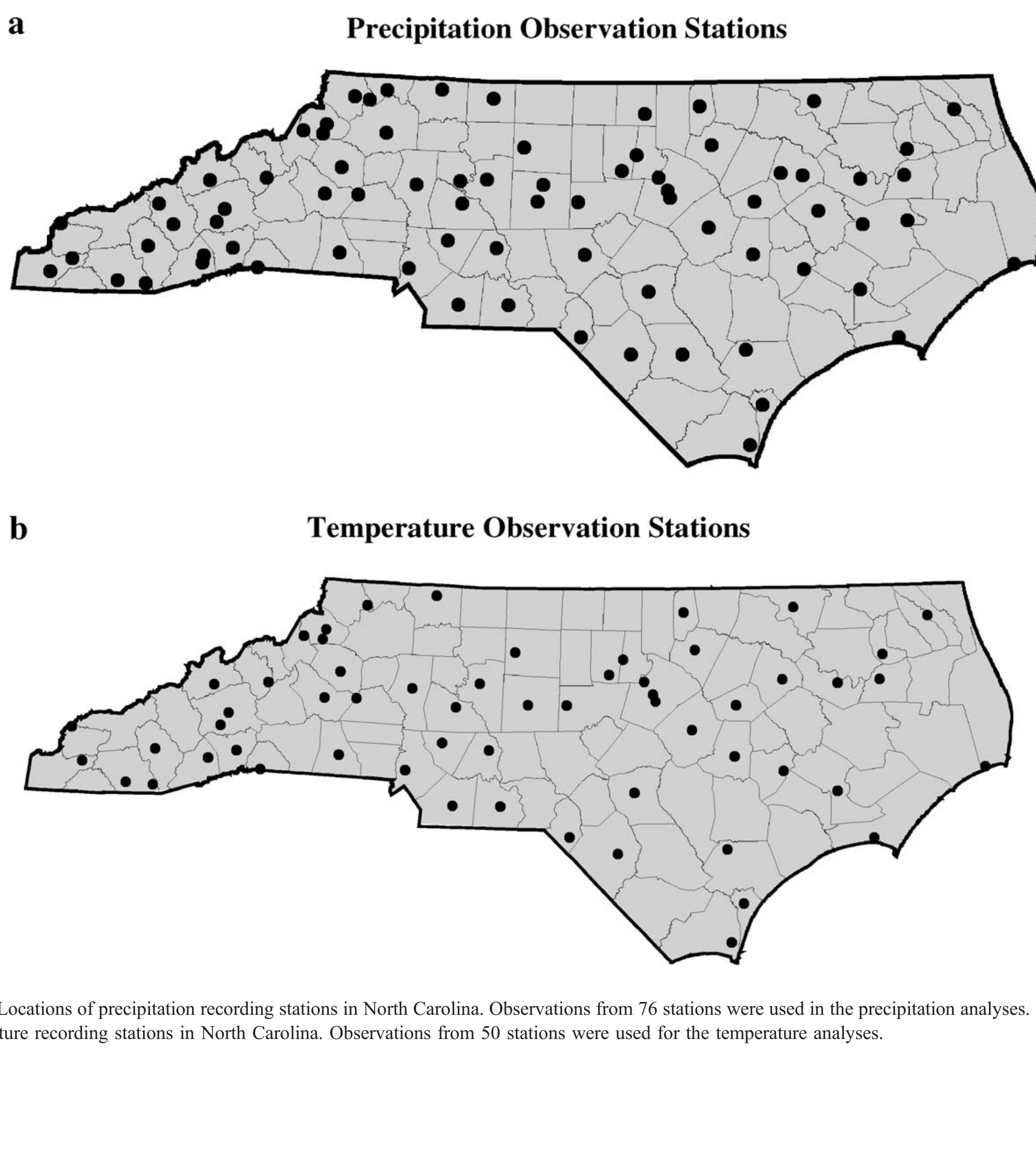


Fig. 1. (a) Locations of precipitation recording stations in North Carolina. Observations from 76 stations were used in the precipitation analyses. (b) Locations of temperature recording stations in North Carolina. Observations from 50 stations were used for the temperature analyses.

linear trends, are still useful for investigating changes in climatic patterns. Slopes of the linear fits to the time series of climatic data provide a simple picture of changes that have occurred at any location over an extended period of time.

To investigate the general trends in climatic conditions for locations in North Carolina, monthly temperature and precipitation observations were collected and analyzed for the 50-year period 1949–1998. Data for each station were obtained from the State Climate Office of North Carolina. Station instruments were maintained by the National Weather Service, as part of the Cooperative Weather Observer Program. Data are quality-controlled by the National, Climatic Data Center. No other quality control or data adjustment has been made.

Stations that were used had a complete record for the 50-year period. While each station that recorded temperature also recorded precipitation, there were 18 additional stations that recorded precipitation only. Station locations are shown in Fig. 1a and b.

Seasonal averages are calculated for each station based on the following astronomical seasonal breakdown:

Winter:	January, February, March
Spring:	April, May, June
Summer:	July, August, September
Fall:	October, November, December

While these are not the traditional time periods used for the listed seasons, this averaging strategy eliminates the problem December data cause when trying to average them with observations from the next year and still maintains representative climatic seasons. For example, most locations in North Carolina record more snowfall in March than in December, suggesting that March is more of a winter month than a spring month.

After seasonal and annual averages were calculated, a linear trend was fitted to each time series. While the equations for more advanced techniques of trend analysis change for each time series to optimize the fit of a curve to the data, the equations for linear trends are the same for all time series. Thus, although linear trends offer little insight into complex time series, the authors believe linear trends are currently the best choice for multistation spatial analysis of changes in climatic patterns. Only linear trends can be used to compare changes in the time series of multiple stations across a region. For example, multivariate analysis may provide a good curve fit to the wintertime series for the Raleigh, NC station in the Eastern Piedmont, but that same equation may be a poor fit to data from Asheville in the Western Mountains. With linear trends, the slopes calculated at each station can be spatially analyzed for regional changes.

For these analyses, a kriging analysis was used for spatial interpolation. This method, while computationally intensive, is a true interpolation technique and has been found to be the optimal scheme for irregularly spaced point climate data (Collins and Bolstad, 1996; Goodale et al., 1998). For temperature and precipitation analyses, a universal linear kriging interpolation scheme with a minimum sample of 12 points was used. This technique was used instead of other methods (e.g., circular, Gaussian, quadratic, exponential, spherical) because it allowed a good interpolation without the need to repeatedly analyze the structure of semivariograms.

Linear slopes from all observing stations were analyzed for each season using ArcView GIS 3.2. In addition to analysis of linear slopes, each parameter was analyzed over subsequent non-overlapping 10-year periods. For each 10-year period, average values and departures from the 50-year average were analyzed. Ten-year periods were selected to minimize the multiyear influences of El Niño/Southern Oscillation (ENSO), which has been shown to affect both temperature and precipitation patterns in the southeastern United States with a cycle of approximately 2 to 7 years (Roswintiarti et al., 1998).

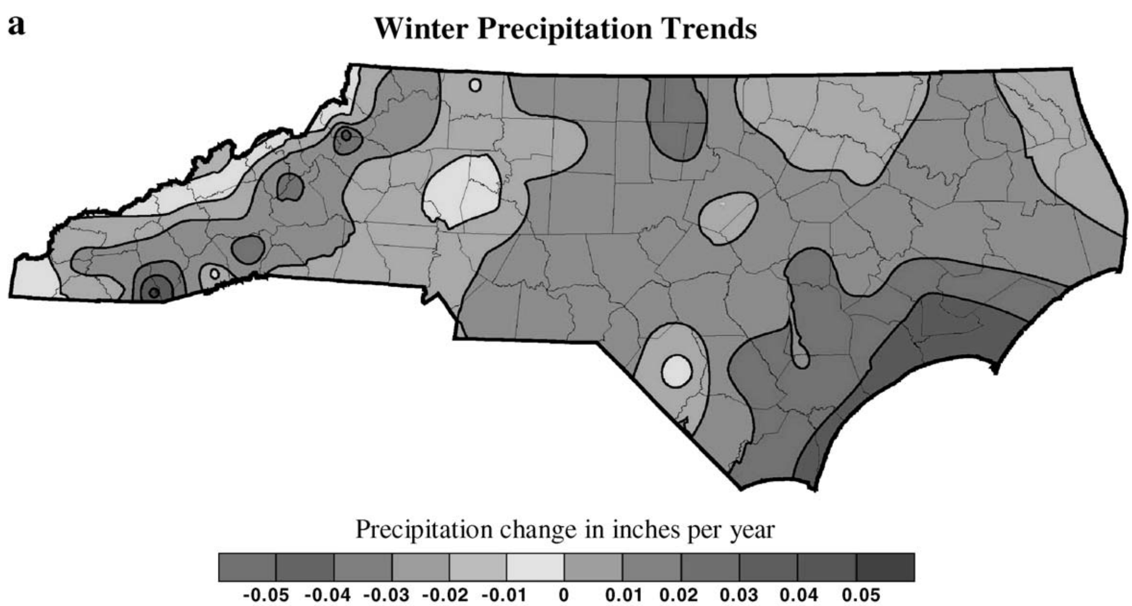
3. Precipitation

Precipitation is a unique climatic variable primarily because it does not occur every day or even every month. While there is always a nonzero temperature to be measured, this is not the case for precipitation. Furthermore, precipitation in North Carolina is often spotty and convective in nature, especially during the warm seasons. There can be large differences in precipitation amounts recorded over a relatively short distance, even on monthly time scales. However, since almost all locations receive some precipitation during the course of a season, it is possible and even valuable to analyze precipitation patterns on this time scale. Knowledge of seasonal precipitation patterns is crucial for a variety of governmental and industrial uses including agribusiness, construction, and natural resource management.

Monthly precipitation records from 75 recording stations in North Carolina were obtained from the State Climate Office of North Carolina. Monthly records were summed to provide seasonal and annual totals for each year. Seasonal and annual time series were then statistically analyzed and fitted with linear trends. While analysis of seasonal observations from each station provides insight into the climatic trends for those specific locations, a single station cannot be used to represent the entire climatic region. This is clearly shown in the earlier example of Asheville, which is very unrepresentative of the climate in the Southern Mountains of North Carolina. By using GIS, climatic trends from each station can be spatially analyzed, providing a more accurate picture of regional climatic trends. Using GIS, the linear trends from each station were spatially analyzed and are shown in Fig. 2a–e. A true interpolation scheme was used to insure accuracy between point slopes and the interpolated surfaces.

The interpolated linear slopes for the winter season (Fig. 2a) indicate a positive slope for most of the state. This relates to an increase in seasonal precipitation over the 50-year period. Only a small region in the Western Piedmont and extreme Western Mountains show slopes near zero or negative. Throughout the central and Eastern Piedmont, and the coastal plain, there is an extensive region of positive slopes that increase with proximity to the coast.

The interpolated surface slope for spring is shown in Fig. 2b. While no general trend appears, there are regions of very positive (Southern Mountains) and negative (Outer Banks) slopes. Most areas of the state, especially in the Piedmont and Coastal Plain, have slightly negative slopes. These slopes signify slight decreases in precipitation over the 50-year period for the months of April, May, and June.



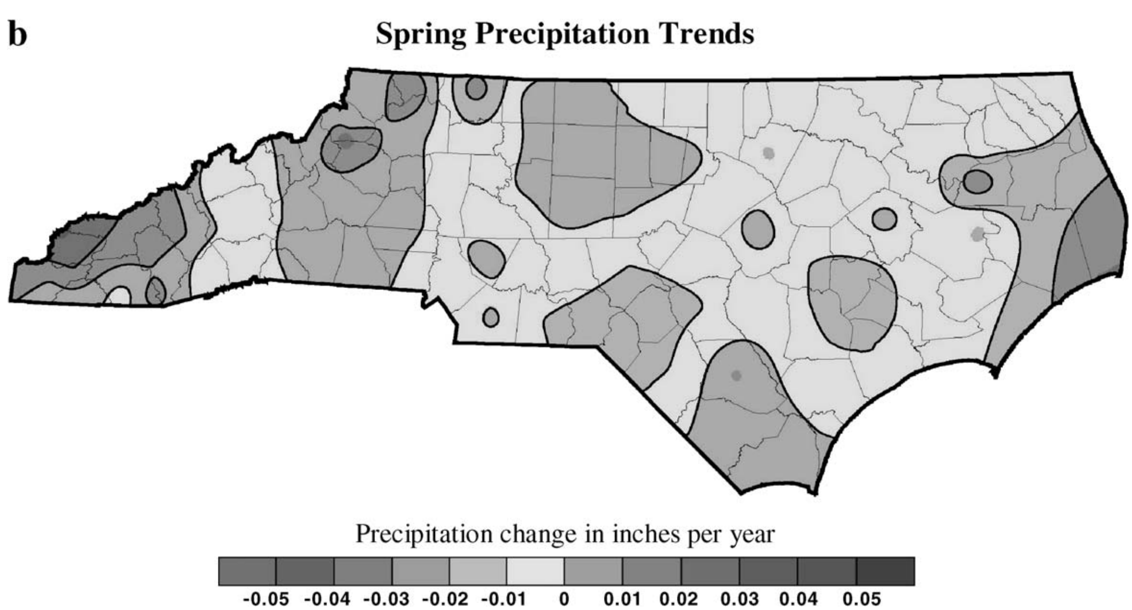


Fig. 2. (a) Precipitation trends for the winter season over the period 1949–1998. Linear slopes are in inches per year. Generally, there is an increase in precipitation across the state during the winter. (b) Precipitation trends for the spring season. Linear slopes across the state are slightly positive or negative, but generally are near zero. (c) Precipitation trends for the summer season. Slopes across North Carolina are generally negative. While the slopes in the Southern Coastal Plain are positive, there is a significant negative trend in the central and Northern Coastal Plain. (d) Precipitation trends for the fall season. Slopes are positive across most of North Carolina. Highest positive trends are in the southern mountains. (e) Annual precipitation slopes. The scale of precipitation trends is increased since the annual precipitation is the sum of all four seasons. Precipitation across all season is increasing across most of the state, with decreases in the Northern Coastal Plain.

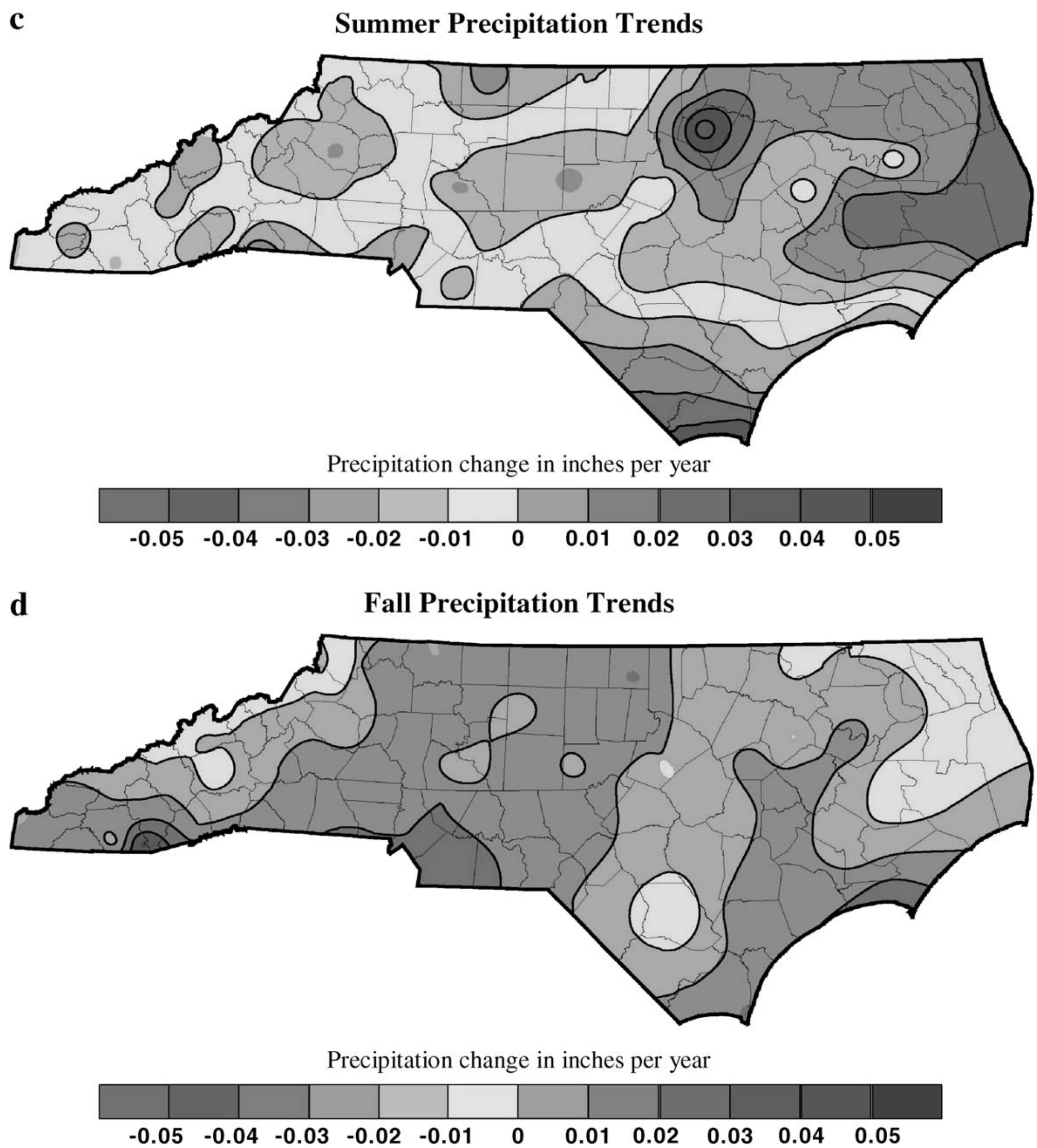


Fig. 2 (*continued*).

The interpolated linear slopes for summer (Fig. 2c) show widespread negative slopes covering most of the state, except for the Southern Coastal Plain. Negative slopes are prevalent in the central and northern Coastal Plain. During the summer months, these regions have seen significant linear decreases in precipitation over the period 1949–1998.

The statewide slope contours for the fall season (Fig. 2d), like the winter season, show widespread positive slopes. However, the overall magnitude is not as great. The Piedmont and Southern Mountains have seen the greatest linear increase in precipitation over the 50-year period.

Based on the interpolated surface of annual slopes, positive slopes are generally present statewide, except for the northeast corner (Fig. 2e). The most positive slopes are in the Southern Coastal Plain and the Southern Mountains.

Based on the spatial analysis of seasonal and annual slopes, a few general conclusions can be made about precipitation trends over the study period. The winter and fall seasons show increases in precipitation, while the summer season shows widespread decreases. The spring season shows no general spatial trend. As a whole, the annual precipitation slopes are positive across the state.

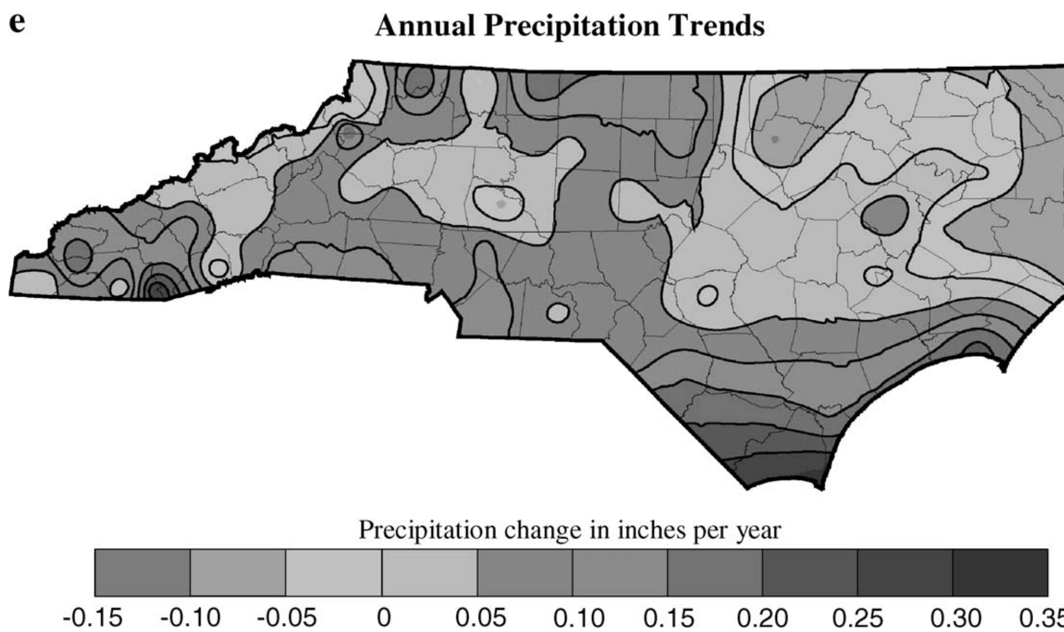


Fig. 2 (*continued*).

Generally, precipitation has increased statewide in the winter and fall seasons. These two seasons show the greatest statewide trend when compared to the spring and summer. This may be related to increased coastal storm activity that is greatest during the fall and winter seasons. During the summer, precipitation has significantly increased along the Southern Coast and decreased in the Northern Coastal Plain. For the rest of the state, there is a slight increase in precipitation during the summer. Precipitation during the spring season does not appear to significantly increase or decrease in any region of the state. This is consistent with other research that suggests that precipitation amount is increasing across the United States (Karl and Knight, 1998). However, Karl and Knight (1998) suggest that the proportion of total precipitation derived from heavy events is increasing. In North Carolina, heavy precipitation events are generally associated with local thunderstorms during the spring and summer months, while precipitation during the fall and winter is more steady and widespread in nature. The analyses here suggest that the increase in precipitation in North Carolina is not due to increasing extreme or heavy precipitation events, since increases are strongest in the fall and winter.

4. Minimum temperature

Detection and prediction of long-term changes in temperature patterns are often the driving force in climate change analysis. While averages and means are often the focus of analysis, the use of mean temperature alone can hide significant patterns in temperature change. Mean temperature is the average of maximum and minimum temperature, and therefore averages any trends in the minimums and maximums. Instead of mean temperature, spatial and temporal patterns of minimum and maximum temperature were analyzed and are discussed here. Similarly, the importance of seasonal temperatures is stressed in this discussion. Opposite trends in the seasonal signals may negate each other, resulting in little or no change in the annual trends.

As with precipitation, it is difficult to analyze regional minimum temperature patterns by examining only the time series and trends from individual stations. Using GIS, complex spatial analyses of climatic patterns can be developed, providing more insight into local and regional trends. Minimum temperature trends are shown in Fig. 3a–e for each season and for the annual period. For these analyses, temperature observations from 57 Cooperative observer stations in North Carolina were used. Positive slopes represent a linear increase in minimum temperatures over the period, while negative slopes represent a linear decrease in minimum temperatures.

Fig. 3a shows the spatially analyzed linear slopes of minimum temperature for the winter season. Positive slopes are generally seen in the Southern Mountains, although a region of negative slopes lays along the Southern border. Negative slopes are also evident in the Southern Coastal Plain and in the Northern Piedmont.

Minimum temperature trends for the spring season are given in Fig. 3b. Similar to the winter season, negative slopes are seen in the Northwestern Piedmont and in the Southern Coastal Plain. In these regions, minimum temperatures seem to be decreasing over the period 1949–1998.

Fig. 3c shows the minimum temperature trends for the summer season. During this season, more widespread positive slopes are seen, dominating the Southern Mountain and Piedmont regions. However, the Southern Coast shows negative trends similar to the winter and spring seasons.

Minimum temperature trends for the fall season, shown in Fig. 3d, are similar to the pattern for the summer season. Here, stronger positive slopes are seen along the southwestern border and along the northeast coastline. Positive slopes are evident along the Southern Coast and Northern Piedmont, similar to the patterns in the other three seasons.

Generally, minimum temperatures are increasing in the Southern Mountains and parts of the Central Piedmont, as shown in the annual minimum temperature trends (Fig. 3e). However, minimum temperatures are decreasing along the Southern Coast and parts of the Northeastern Pied-

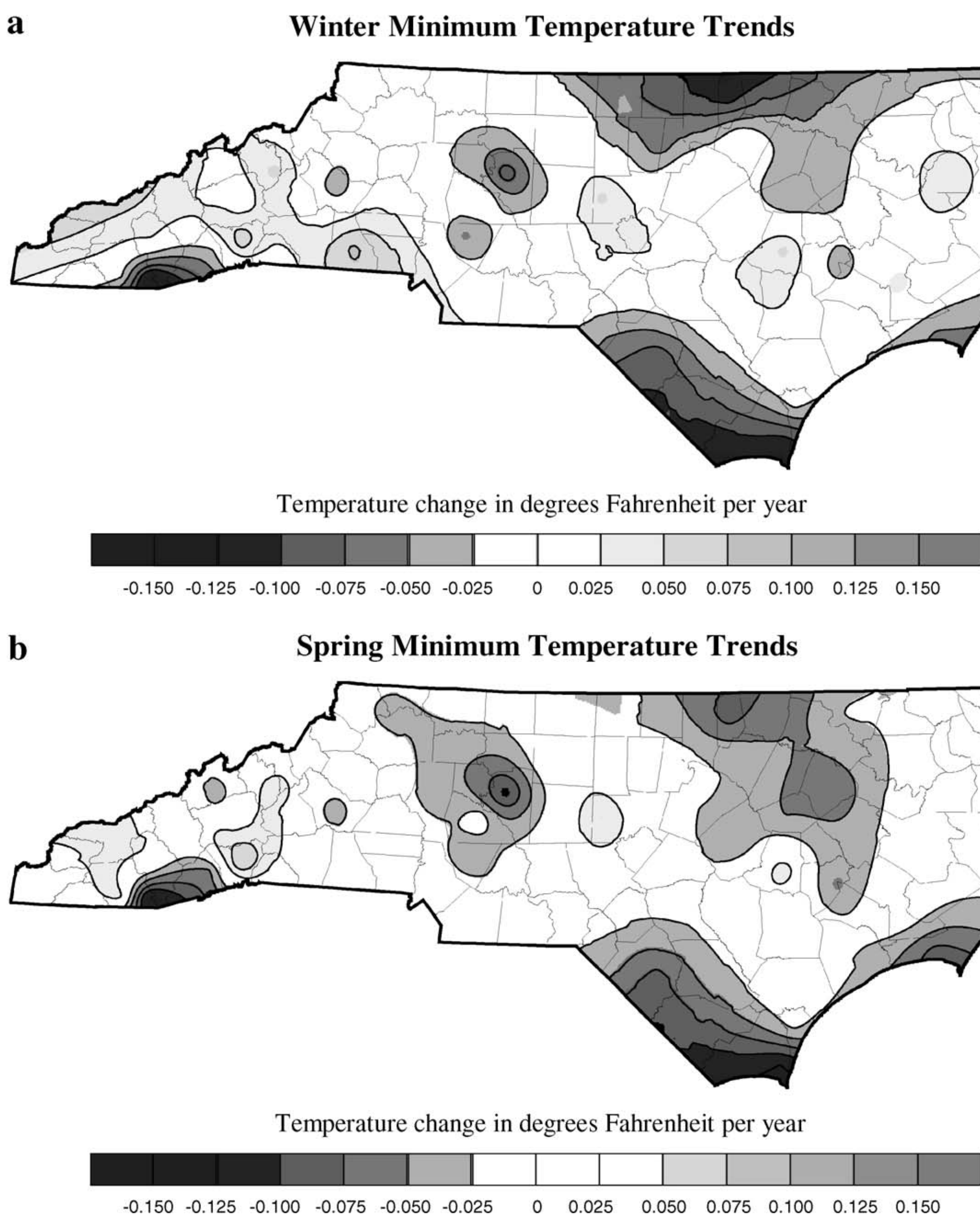


Fig. 3. (a) Minimum temperature trends for the winter season over the period 1949–1998. Trends along the Southern Coast and Northern Piedmont are negative, while positive trends are in parts of the southern mountains. (b) Minimum temperature trends for the spring season over the 50-year study period. The greatest negative slopes are in the Southern Coastal Plain and the Northern Coastal Plain. Most of the state has trends near zero. (c) Minimum temperature trends for the summer season over the period 1949–1998. The mountains and Piedmont generally have experienced an increase in minimum temperatures. (d) Minimum temperature trends over the 50-year period for the fall season. Positive linear trends are evident in the mountains, central, and southern Piedmont, and the central and Northern Coastal Plain. (e) Annual minimum temperature trends for the period 1949–1998. Generally, warming of minimum temperatures has been experienced in the southern mountains and parts of the Piedmont. Cooling is most evident along the southern coast and the Northern Piedmont.

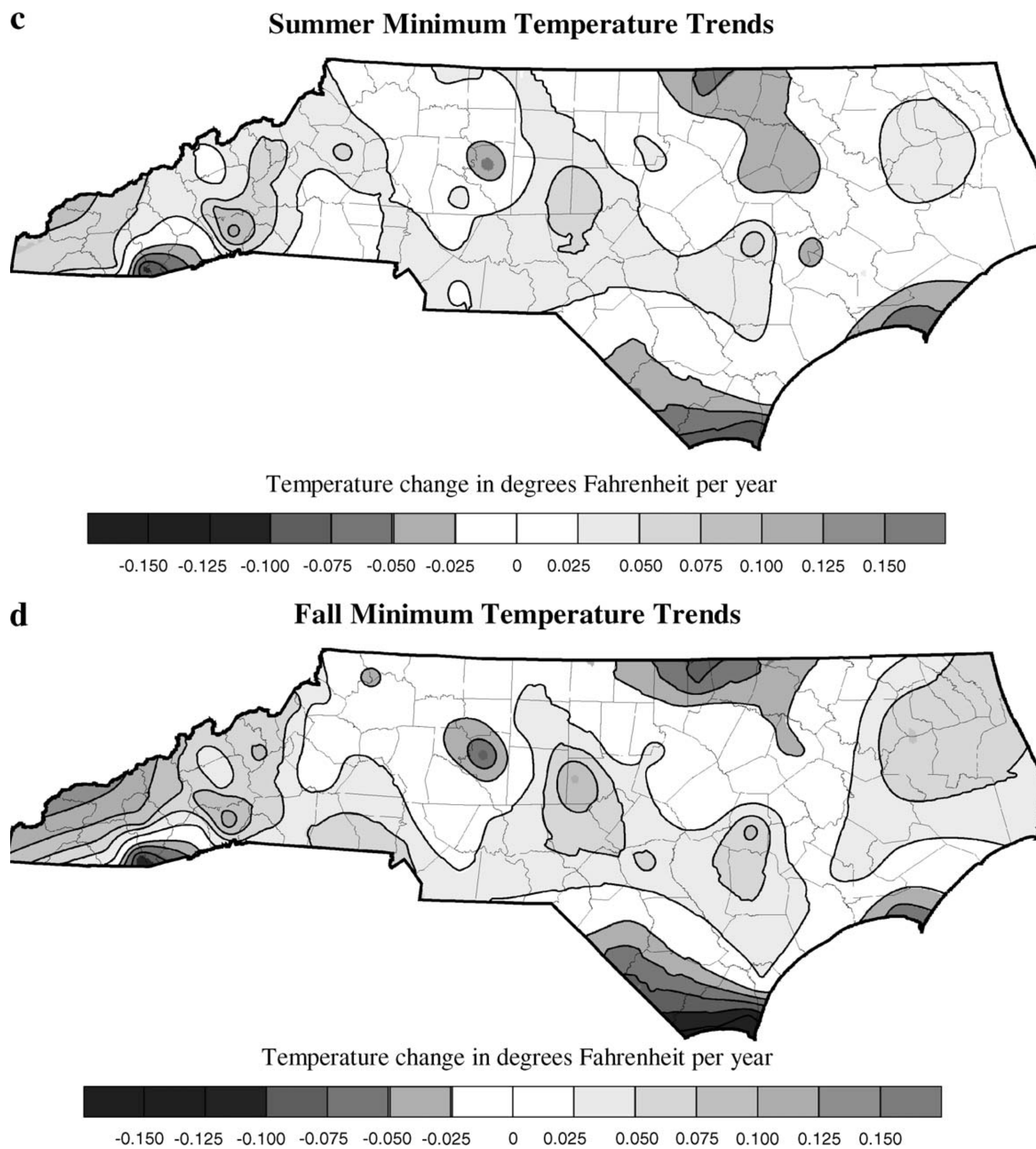


Fig. 3 (*continued*).

mont. The linear trend signals from local stations tend to dominate, and there is no widespread pattern across North Carolina.

5. Maximum temperature

Annual and seasonal average maximum temperature trends were analyzed, following the methods used for precipitation and minimum temperatures. Since the linear slopes from a few stations do not provide sufficient information on maximum temperature patterns and trends statewide, spatial interpolation of the linear slopes for the annual and seasonal time series is given in Fig. 4a–e. Maximum temperature trends for the winter are shown in Fig. 4a. Generally, maximum temperature slopes are negative through most of the Piedmont and the Northern Mountains. Slopes are near zero for most of the Coastal Plain and Southern Mountains. Maximum temperature trends for the spring season (Fig. 4b) are negative for the Piedmont and mountain regions. Slopes for the Coastal Plain are generally near zero during the spring. Fig. 4c shows the spatially analyzed linear trends for the summer season. Statewide, the trends are near zero, with linear increases along the coast and some small regions with negative trends. During the summer season

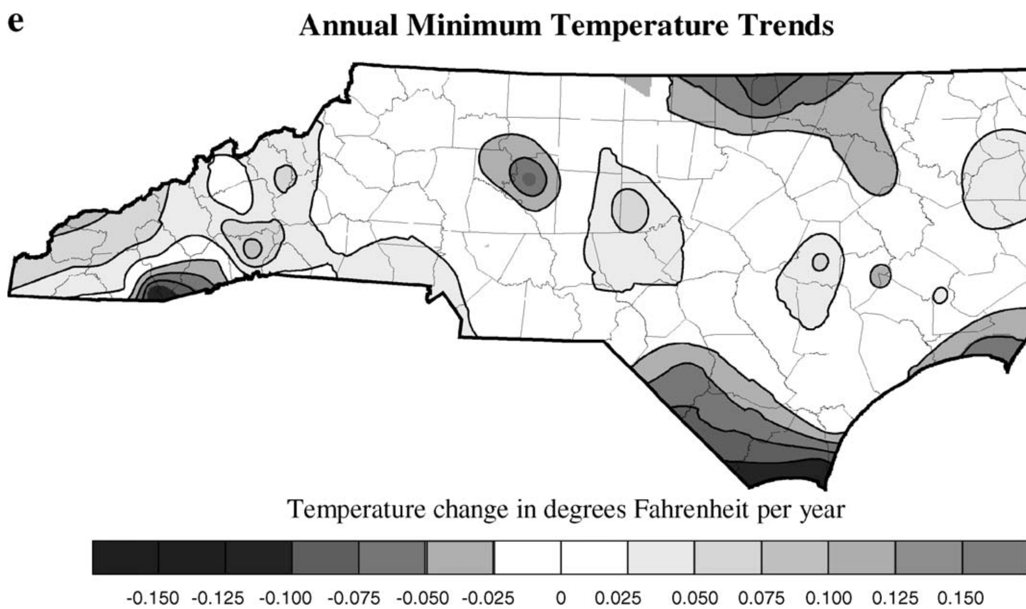


Fig. 3 (*continued*).

(Fig. 4d), maximum temperature trends are positive along the coast and negative through the Eastern Piedmont. Generally, maximum temperatures decreased in the Piedmont and Northern Mountains over the 50-year period (1949–1998) as shown in Fig. 4e. However, increases in maximum temperatures are seen along the Coast. The spatial analysis of maximum temperature trends suggests that there have been little changes in maximum temperatures in the Western Coastal Plain and Southern Mountains.

6. Summary and conclusions

Based on the analysis of precipitation and temperature (both minimum and maximum) over the 50-year period (1949–1998), a few general, but important, conclusions can be made. First, precipitation in North Carolina seems to have increased, especially during the fall and winter seasons. Second, minimum temperatures have increased over the period, especially in the summer and fall, but are not much warmer than during the 1950s. Third, maximum temperatures have changed little over the last 30 years of the study period, although analysis of the linear slopes suggests a cooling in the Piedmont and Northern Mountains. Finally, the number of days between the last spring freeze and first fall freeze increased during the last 10-year period. Combined, these individual analyses suggest that the last 10 years were the warmest and wettest in half a century. However, it is unclear as to whether these trends are part of a longer-period oscillation or the result of long-term climate change.

Easterling et al. (1997) and Dai et al. (1999) documented the decreasing difference between maximum and minimum temperatures. The temperature analyses for North Carolina are evidence of this pattern. While maximum temperatures have been consistent over the past 30 years, minimum temperatures have been warming. Easterling et al. (1997) and Dai et al. (1999) suggest that this decrease in the diurnal temperature range may be due to increased cloud cover and precipitation. Given the increase in precipitation during the fall and winter seasons, shown in these analyses, increased cloud cover and precipitation are possible factors for the observed temperature trends. The hypotheses presented by Easterling et al. (1997) and Dai et al. (1999) appear to hold true in North Carolina.

Hurrell (1996) suggests that the North Atlantic Oscillation (NAO) accounts for a significant amount of the climate variability in the Northern Hemisphere. The North Atlantic Oscillation is a quasi-decadal oscillation measured by the pressure difference between the Icelandic Low and the Azores high-pressure systems. Specifically, the NAO index is the difference in normalized pressure between Stykkisholmur, Iceland and Lisbon, Portugal. Generally, positive NAO indices are associated with warmer temperatures over the eastern United States (Hurrell, 1995). NAO indices during the 1950s and 1990s are positive. These two decades were also the warmest periods in the temperature study discussed above. Temperature variations in North Carolina thus appear to be in phase with the North Atlantic Oscillation. However, the NAO does not seem to be in phase with the precipitation trend seen in North Carolina, as precipitation amounts are increasing over the entire 50-year period.

Similarly, Mantua (2000) suggests that the Pacific Decadal Oscillation (PDO) is related to climate variability in the United States. The PDO is a 20- to 30-year cycle of anomalous sea surface temperatures in the Northern Pacific

Basin. The PDO index accounts for the strength and frequency of both El Niño (warm) and La Niña (cool) events in the Pacific Ocean. According to Mantua (2000), warm PDO phases are associated with cool, wet conditions in the southeastern United States, while cool phases are associated with warm, dry conditions. However, evidence of this relationship is only seen in North Carolina with regard to precipitation. For the period 1949–1979, the PDO is in a cool phase. In North Carolina, while the period from 1949 to 1958 was warmer than average, the period 1959–1968 was cooler than average; this does not agree with the relationship proposed by Mantua (2000). Similarly the warm phase of PDO, since the 1980s, is not in agreement with the warmer temperatures in North Carolina. However, precipitation in the period from 1949 to 1958 was below normal, as indicated by the PDO cool phase. Similarly, the precipitation in North Carolina is above normal from 1989 to 1998, which is a PDO warm phase. While the North Atlantic Oscillation is related to temperature variability in North Carolina, the Pacific Decadal Oscillation appears to be better correlated with precipitation trends in North Carolina.

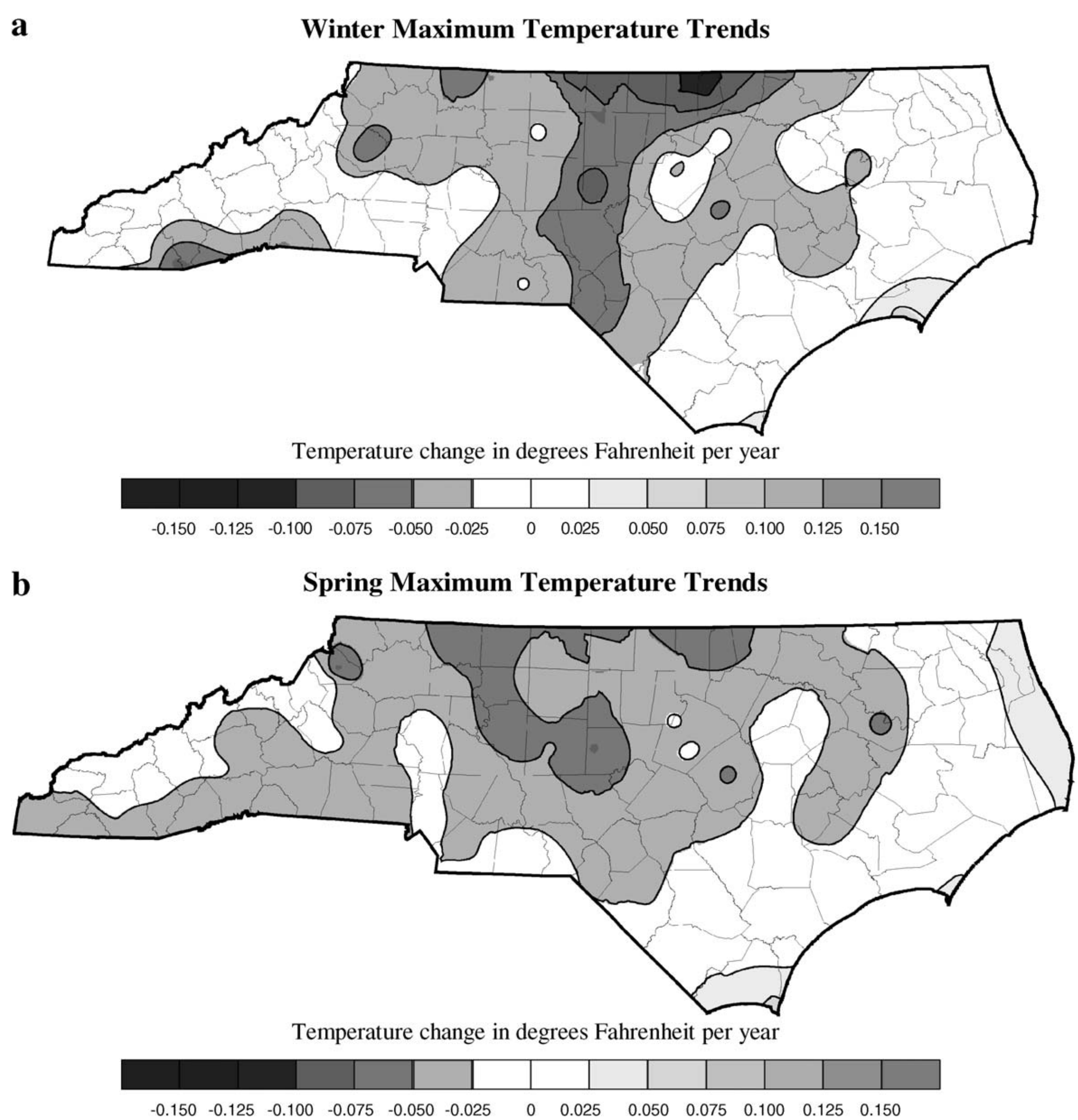
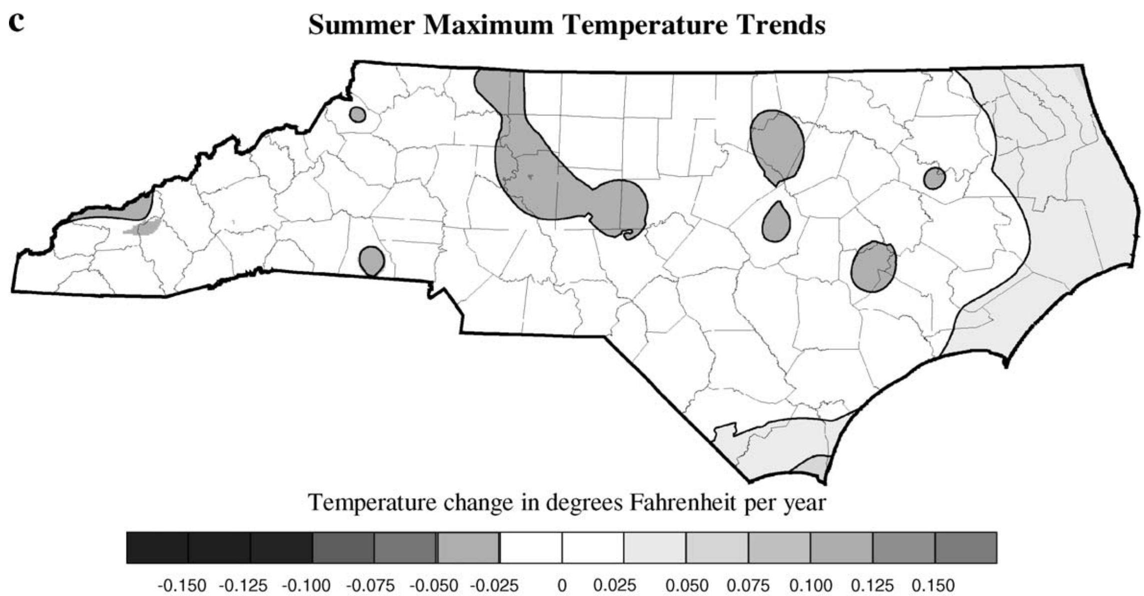


Fig. 4. (a) Maximum temperature trends for the winter season over the period 1949–1998. Negative trends dominate the piedmont and northern mountains. (b) Maximum temperature trends for the spring season over the 50-year study period. Negative linear trends are evident in most of the Piedmont and mountain regions. (c) Maximum temperature trends for the summer season over the period 1949–1998. Linear trends are generally near zero statewide. Positive trends are evident along the coast. (d) Maximum temperature trends over the 50-year period for the fall season. Negative slopes are seen in the Piedmont and positive linear trends along the coast. (e) Annual maximum temperature trends for the period 1949–1998. Generally, the Piedmont and Northern Mountains are seeing a cooling trend in maximum temperatures. Nominal warming trends are seen just along the coast.



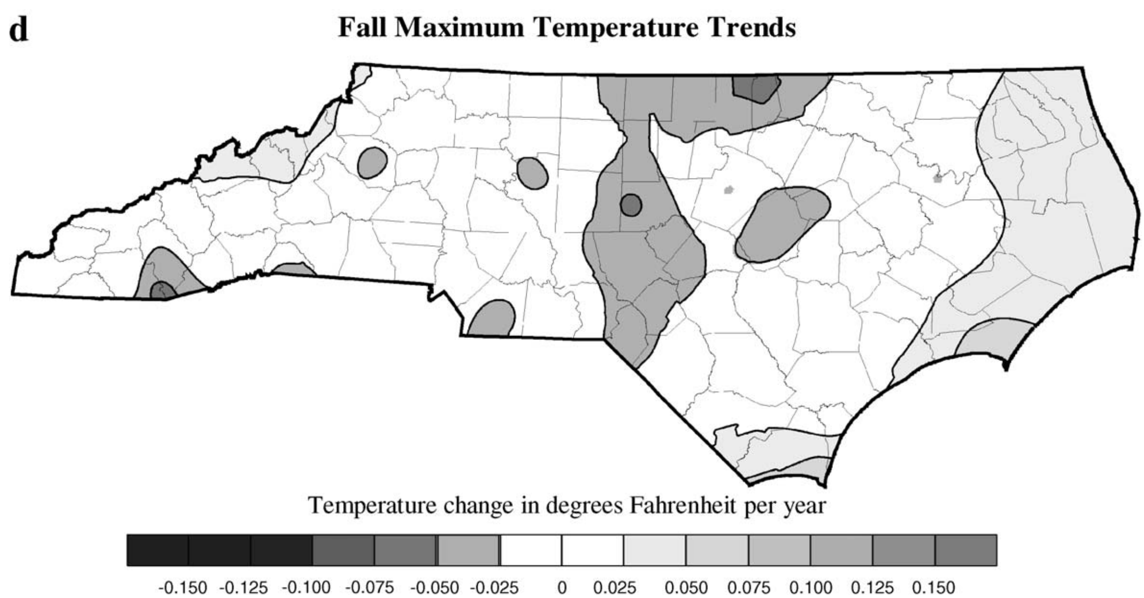


Fig. 4 (*continued*).

On time scales less than 10 years, the El Niño/Southern Oscillation (ENSO) plays a significant role in influencing climate in North Carolina. The ENSO has a cycle of 2 to 7 years, and Roswintiarti et al. (1998) show that precipitation increases in North Carolina in winter during warm (El Niño) events in the tropical Pacific Ocean. This statistical study also showed that summers during El Niño events are drier than normal. With La Niña episodes, opposite effects were seen. The number and strength of multiple ENSO events are incorporated in the Pacific Decadal Oscillation index.

One possible limitation of the trend analysis should be noted. Although the station data used are continuous, there may be undocumented station moves and sensor changes that could cause spurious signals in the temperature and precipitation trends. The National Weather Service sometimes needs to move sensors from one location to another. When station moves are significant, a new station ID is assigned and a new station record begins. Whenever possible, stations are moved nearby where they are still considered representative of the area. In these cases, the station ID is maintained and the climate record continues. However, local station moves can still produce spurious signals that may affect the detected trends. While histories of all station and sensor changes are supposed to be documented, station histories are not readily available for reference. Station moves that are significant result in a new station name and ID, and are not used in these analyses.

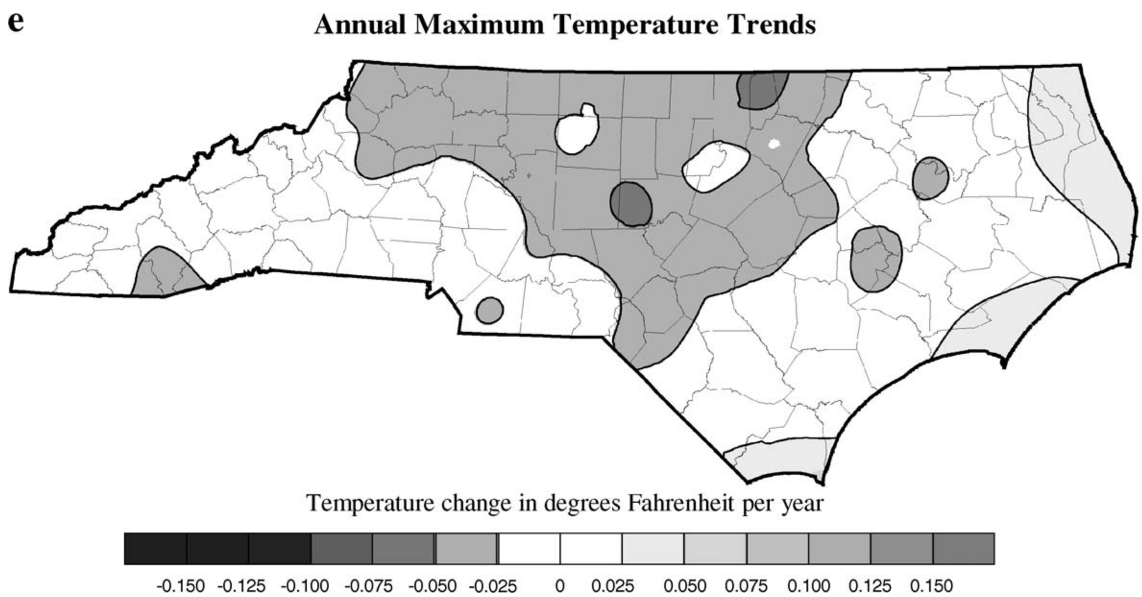


Fig. 4 (*continued*).

Station moves are assumed to be insignificant if they do not lead to new station IDs and the data are considered valid for the purposes of this research.

The primary problem associated with these climate analyses is the lack of good horizontal resolution of historic climate records for use in investigating changes in local climate (i.e., on a county scale). With the complex topography and weather patterns seen in North Carolina, there is a need for a higher station density in order to fully understand climate variability in North Carolina. While recent models, such as the PRISM model developed by Daly et al. (1994), have been able to better estimate precipitation and temperature in regions of complex topography, these models rely heavily on surface climate observations and simple relations to include topographic effects. Analyses such as those discussed in this study cannot accurately capture the climate patterns for each ridge and valley in the mountains of North Carolina. While remote sensing from satellites and radar offer large amounts of data for analysis, these platforms must be verified with surface observations. As climate variability and climate change at the local level become even more important as the century progresses, additional climate monitoring stations will need to be deployed to capture signals related to precipitation and temperature patterns. Two national efforts are currently underway to address this issue. The National Weather Service currently plans to enhance its Cooperative Observer Program to include additional stations and observations, and to improve data availability. In addition, the National Oceanic and Atmospheric Administration is developing a Climate Reference Network to provide high-quality climate observations that can be used to monitoring climate change.

Future research in this area should include the development of GIS-based models to investigate the direct relationship between environmental factors such as land use, soil, population density, and climate patterns. Since there is extensive spatial environmental data being developed by public and private agencies, it would be valuable to develop models that incorporate existing GIS data from various natural resource disciplines. Geographic Information Systems offers powerful methods for spatial analysis and should be better utilized in the field of atmospheric sciences and, in particular, climatology.

Acknowledgements

The authors wish to thank Peter Robinson, Department of Geography, University of North Carolina at Chapel Hill. Also, thanks are given to Dr. Hugh Devine, Center for Earth Observation, NC State University. This research was supported by the State Climate Office of North Carolina, the Department of Marine, Earth, and Atmospheric Sciences, and the College of Physical and Mathematical Sciences at North Carolina State University.

References

Collins FC, Bolstad PV. A comparison of spatial interpolation techniques in temperature estimation. National Center for Geographic Information and Analysis, CD-ROM and World Wide Webb, http://www.ncgia.ucsb.edu/conf/SANTA_FE_CD-ROM/main.html. Santa Barbara, CA; 1996.

Dai A, Trenberth KE, Karl TR. Effects of clouds, soil moisture, precipitation, and water vapor on diurnal temperature range. J Climate 1999; 12:2451–73.

Daly C, Neilson RP, Phillips DL. A statistical-topographic model for mapping climatological precipitation over mountainous terrain. J Appl Meteorol 1994;33:140–58.

Diaz HF, Quayle RG. The climate of the United States since 1985: spatial and temporal change. Mon Weather Rev 1980;108:249–66.

Easterling DR, Horton B, Jones PD, Peterson TC, Karl TR, Parker DE, et al. Maximum and minimum temperature trends for the globe. Science 1997;277:364–7.

Epperson DL, Johnson GL, Davis JM, Robinson PJ. Weather and climate. North Carolina. Agricultural Research Bulletin, vol 375. Raleigh, NC: Agricultural Extension Service, North Carolina State University; 1988. p. 1–48.

Goodale CL, Aber JD, Ollinger SV. Mapping monthly precipitation, temperature, and solar radiation for Ireland with polynomial regression and a digital elevation model. Clim Res 1998;10:35–49.

Hurrell JW. Decadal trends in the North Atlantic Oscillation—regional temperatures and precipitation. Science 1995;269:676–9.

Hurrell JW. Influence of variations in extra-topical wintertime tele-connections on Northern Hemisphere temperature. Geophys Res Lett 1996;23: 665–8.

Karl TR, Knight RW. Secular trends of precipitation amount, frequency, and intensity in the United States. Bull Am Meteorol Soc 1998;79: 231–41.

Mantua NJ. The Pacific Decadal Oscillation. Encycl. Global Environ Change. http://www.atmos.washington.edu/~mantua/REPORTS/PDO/PDO_egec.htm, accessed September; 2000.

Owenby JR, Ezell DS. Climatography of the United States No. 81: monthly station normals of temperature, precipitation, and heating and cooling degree days 1961–1990: North Carolina. Asheville, NC: National Climatic Data Center, National Oceanic and Atmospheric Administration, U.S. Department of Commerce; 1992.

Pielke Sr RA, Stohlgren T, Parton W, Doesken N, Money J, Schell L, et al. Spatial representativeness of temperature measurements from a single site. Bull Am Meteorol Soc 2000;81:826–30.

Roswintiarti O, Niyogi DS, Raman S. Tele-connections between tropical Pacific sea surface temperature anomalies and North Carolina precipitation anomalies during El Niño events. Geophys Res Lett 1998;25: 4201–4.