

Spatial Variability of Temperature Trends in Urbanized and Urbanizing Areas of North Carolina

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This paper investigates the differences in temperature trends during a 40-year period in urbanized and urbanizing areas in North Carolina. Urbanized sites are in the urban cores of the selected regions; urbanizing sites are in outlying suburban locations characterized by lower development intensities than their respective urban cores. We examined maximum and minimum temperatures for four seasons represented by the months of March, June, September, and December. This study shows that the heavily urbanized downtown areas did not exhibit significant increasing trend in temperatures. Rather, the significant increases in temperatures occurred in suburban areas that experienced varying degrees of urbanization during the past 40 years. We conclude that although some urbanized areas may have higher temperatures than areas in their surrounding regions, urbanizing locations outside of central cities may be closing that gap, possibly due to the process of urbanization.

Introduction

The concept that humans may be contributing to an atypical warming of Earth's atmosphere—through emission of greenhouse gases and alteration of natural landscapes—has received increasing attention in the scientific community in recent decades. Because of its implications, the issue has pervaded a wide range of scientific fields. The impacts of climate change have been modeled or studied, for example, in relation to infectious diseases (Patz et al. 1996), wildlife (Anderson et al. 1993), coral reefs (Pittock 1999, Pandolfi, 1999), agriculture (Lewandrowski and Schimmelpfennig 1999), glaciation (Haeberli et al. 1999), hurricane intensity (Knutson 1998), and foreign policy (Ott 2001).

Climate is not constant; Earth's climatic history is characterized by fluctuations in atmospheric composition, temperature, and precipitation (Schneider 1994). It is widely accepted, however, that worldwide temperatures have exhibited a general increase in the last 40 years that is probably not due to natural climatic fluctuations. Concur-

rent increases in world population and atmospheric concentrations of greenhouse gases have fostered the assertion that humans are in large part responsible for current climatic change at both global and local scales (Schneider 1994). Some scientists disagree. For example, Michaels and Balling (2000) contend that Earth's climate *has* experienced distinct natural warming (and cooling) phases, even in relatively recent history. They specifically argue that not enough evidence exists to conclude that climate is changing abnormally. They also note that while many temperature readings admittedly indicate warming trends, most weather stations in the more developed countries are located in or near cities, which often exhibit distinct microclimates relative to surrounding rural areas. The issue, they claim, is warming at the regional, rather than the global scale.

Partially due to the increased focus on climate change or global warming, regional and urban climate change has also received attention. The urban heat island has been addressed empirically by, among others, Oke (1973), Karaca et al. (1995),

Bohm (1998), Klysik and Fortuniak (1999), and Tumanov et al. (1999). Further, it has been established that nationwide growth during roughly our period of study (1960-2000) has occurred largely outside of established urban cores, and that in most cases, communities and regions have consumed land for urbanization at a faster rate than their populations have grown, indicating that many communities outside of urban cores are urbanizing.

As regions become urbanized, the character of the natural landscape is altered in a variety of ways. Development for urban purposes (housing, factories, skyscrapers, roads) necessarily removes natural vegetation, replacing it with impervious surface materials. Common materials in urban construction such as asphalt, cement, and roofing tile have a higher heat capacity than the vegetation and other natural features being displaced (Rodgers and Stone 2001). Large quantities of thermal energy are absorbed by these materials during daylight hours, and re-emitted to the atmosphere at night. Loss of vegetation also limits evapotranspiration, a natural cooling method employed by plants using solar radiation to convert water to vapor. The energy trapped by vegetation is not available to heat urban structures or the ground surface, and the release of water vapor to the air serves to decrease the ambient air temperature (Mixon 1994, Rodgers and Stone 2001). Michaels and Balling (2000) contend that the primary cause of urban warming is the waterproofing of the urban land surface with impervious paving and construction materials. Aside from the removal of existing vegetation and the higher heat capacity of urban structures, impervious surfaces induce rapid rainfall runoff, allowing for little soil moisture and groundwater recharge. With less near-surface moisture, more solar energy is involved in directly heating the surface (Michaels and Balling 2000). Other factors contribute to urban heat retention as well. High traffic volume, energy consumption (especially fossil fuels used in heating and cooling), pollution concentration, and the lower reflectivity of many urban surfaces relative to the natural surfaces displaced, combine to enhance the urban heat island effect.

Due to these factors, urbanized regions may exhibit heat island intensities of 6-8 Fahrenheit (4-

6 Celsius) degrees, especially at night. (Oke 1973, Rodgers and Stone 2001). Like absorption of thermal energy, the heat island effect is cumulative; as urban regions absorb higher levels of energy during daylight hours, they emit more heat at night, increasing ambient surface temperature. (Fehr-Snyder 1999).

The effects of urbanization on urban and regional climate are complex and difficult to quantify. Early attempts to verify and analyze the urban heat excess did so by calculating the difference between urban and rural temperatures. This became the standard formula for heat island intensity (Oke 1973). Others have examined urban cross-sections by collecting temperature measurements along transects through urbanized areas. This method provides greater evidence of the distribution and "shape" of the heat island (Tumanov et al. 1999, Unger et al. 2001). More recently, long term (>30 years) temperature data from fixed stations have been used to describe heat islands, particularly in Europe and the Middle East. These studies have the distinct advantage of exhibiting specific seasonal and/or diurnal patterns of urban heat island development. Goldreich (1995) reviews a number of studies in Israel, some of which combine the transect and fixed-station collection methods. Separate studies have analyzed heat island intensity and form in the U.S. (Quattrochi et al. 2000, Rodgers and Stone 2001, Lo and Quattrochi 2003); as well as in Istanbul, Ankara (Karaca et al. 1995), Bucharest (Tumanov et al. 1999), Vienna (Bohm 1998), and Lodz, Poland (Klysik and Fortuniak 1999). In the cases of Vienna and Bucharest, the authors examine temperature time series from multiple urban and rural stations. This approach seems to offer the most information about the spatial distribution and intensity of urban heat excess.

These studies lead to certain conclusions. First, it seems that formation of an urban heat island depends more on the physical characteristics of the built landscapes than on demographic variables (Klysik and Fortuniak 1999). For example, in certain cases population growth and population density have been rejected as meaningful indicators of urban warming (Bohm 1998). Second, heat island intensity is generally greatest during the high-sun

season, when urban structures and materials absorb the greatest amounts of solar radiation. Finally, heat island intensity tends to be greatest among minimum temperatures, usually at night or early in the morning. It is generally accepted that urban areas are warmer than their surrounding suburban and rural areas, especially at night.

The need for a larger inventory of empirical evidence regarding trends in regional and global climate is clear. Based on existing findings that worldwide temperatures may be increasing, and that urban temperatures are generally increasing at greater rates than those in suburban and rural locations, the purpose of this paper is to investigate the long-term urban heat island effect and its spatial variability in selected areas of North Carolina. The specific objectives are: 1) determine trends in air temperature over a 40-year period in urbanized and urbanizing areas; 2) analyze the differences in temperature trends between urbanized and urbanizing areas; and 3) examine the spatial, temporal, and diurnal variability of urban climatic change in different parts of metropolitan regions.

Study Area

Our study area includes the Asheville and Raleigh regions of North Carolina (Figure 1). These two regions represent certain physiographic segments of the state—Asheville the mountainous western portion, and Raleigh the piedmont/coastal plain transition of the east-central portion. The regions are far enough from each other to be independent in terms of temperature. Thus, localized warming in Asheville will have no direct impact on temperatures in Raleigh, and vice versa.

In each region, we selected weather stations and classified them either ‘urbanized’ or ‘urbanizing’ (Table 1). One location in the urban core of each region was classified ‘urbanized’. These stations are in established downtown areas, surrounded by significant development, including roads, commercial and residential structures, pavement, and other artificial surfaces. The sites lack dense or extensive vegetation. Three weather stations in each region were classified ‘urbanizing’. The ‘urbaniz-

ing’ sites are in outlying areas that have experienced some degree of urbanization during the last forty years, but are clearly distinct from the urbanized stations due to their lack of intensely urbanized landscapes. Natural surfaces are more abundant in the immediate surroundings of these sites than the ‘urbanized’ ones. For example, the weather stations at the airports in the respective regions are in the proximity of the terminals, the runways are paved, and the surroundings are less rural than they were in 1960, but in neither case is the landscape intensely urbanized. The distance between weather stations (> five miles in all cases) should be sufficient to isolate variations in trends between individual sites.

Asheville Region

Asheville is located in Buncombe County in western North Carolina, in the foothills of the Appalachian Mountains, near Great Smoky Mountains National Park. The region is approximately 2,100 feet above mean sea level, but exhibits significant relief. For purposes of this study, the Asheville region consists of three counties: Madison, Buncombe, and Henderson.

‘Asheville 1’ is the ‘urbanized’ station in the region, located in the northeast quadrant of downtown Asheville. The first ‘urbanizing’ station, ‘Hendersonville 1NE,’ is in a suburban setting in the town of Hendersonville, 19 miles south of Asheville. The second ‘urbanizing’ station, ‘Regional Airport,’ is located in the airfield of Asheville Regional Airport, surrounded in large part by open grassy and wooded areas. The ‘Marshall’ station is the third ‘urbanizing’ station in the Asheville region, in the rural community of Marshall, around 15 miles north of Asheville.

Raleigh Region

Raleigh is in Wake County near the center of the state, at an approximate elevation of 300 feet above mean sea level. The Raleigh region includes Wake and Johnston Counties. The Raleigh St. University station is the urbanized site in the Raleigh region, and is in a heavily urbanized setting near the campus of North Carolina State University in

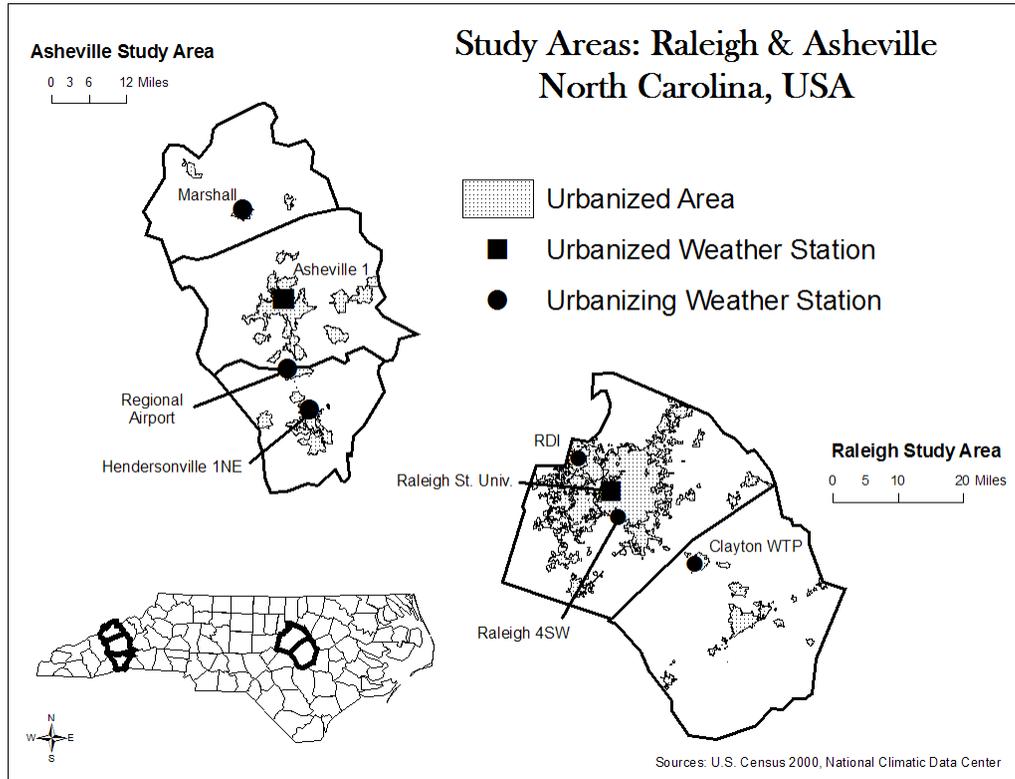


Figure 1. Location of weather stations analyzed in this study.

the western portion of the city of Raleigh. The first of three urbanizing sites in the region is Raleigh 4SW, on the North Carolina State University farms approximately 6 miles south of Raleigh. The second urbanizing site is RDI, located in the airfield at Raleigh-Durham International Airport. The Clayton WTP station is the third urbanizing station, located in an urbanizing area on the outskirts of the community of Clayton, approximately 15 miles southeast of Raleigh.

Data

We acquired temperature data for eight weather stations, four in each region (Table 1, Figure 1), from online records of the National Climatic Data Center (2004). Daily maximum and minimum temperatures from each station were collected for March, June, September, and December (to repre-

sent seasonality) over the period 1960–2000. From these data, we calculated means of maximum and minimum temperature for each of the four months at each weather station. In the case of small discontinuities (no more than one year), values were interpolated using the data from the previous year and the following year (less than one percent of data values). The resulting 41-year time series of mean maximum and minimum temperature at each location for each of the four months were analyzed for trends. These trends were also compared with raw temperature values to clarify the relationship between the Kendall Coefficient and actual temperature change.

Methods

There are various methods of trend analysis available for long-term temperature data. In this

Table 1. Weather station names and locations analyzed in this study as identified by the National Climatic Data Center (2004).

Station Name	Lat. / Lon.	Station Type*	Elevation (ft)	Period of Record **
Asheville 1	35°36' N/82°32' W	Urbanized	2,240	1960-2000
Asheville Regional Airport	35°26' N/82°32' W	Urbanizing	2,140	1965-2000
Marshall	35°48' N/82°40' W	Urbanizing	2,000	1960-2000
Hendersonville 1NE	35°20' N/82°27' W	Urbanizing	2,160	1960-2000
Raleigh St. Univ.	35°48' N/78°42' W	Urbanized	400	1960-2000
Raleigh-Durham Intl. Airport	35°52' N/78°47' W	Urbanizing	416	1960-2000
Raleigh 4SW	35°44' N/78°41' W	Urbanizing	420	1960-2000
Clayton WTP	35°38' N/78°28' W	Urbanizing	300	1960-2000

* Urbanized sites are in the urban cores of the regions. Urbanizing sites are in outlying suburban areas with less intense urban development characteristics.

** In some cases, one or two years were missing from the beginning of the study period; these values could not be interpolated. Thus, the period of record varies slightly at certain locations.

study, we used a sequential version of the Mann-Kendall rank statistic because this method allows detection of abrupt climatic change (Goosens and Berger 1986, Karaca et al. 1995). In this study, we applied the test to both daytime (maximum) and nighttime (minimum) temperature values. Examining monthly mean temperatures rather than annual means also allows for discussion of seasonal variation during the period of study.

The Mann-Kendall test is a non-parametric test that is applicable under the hypothesis of a stable climate, in which a series of values are independent and exhibit a constant probability distribution (Goosens and Berger 1986). For each term x_i in a

series of N terms, y_i is the number of terms (x_j) preceding x_i ($i > j$), where $x_i > x_j$. The sum of these values, denoted z_N , is calculated:

$$(1) \quad z_N = \text{Sum } (y_i)$$

For large N (> 30), under the hypothesis of no change, z_N will be normally distributed with an expected value (E) of:

$$(2) \quad E(z_N) = N(N-1)/4$$

and a variance of:

$$(3) \quad V(z_N) = N(N-1)(2N+5)/72$$

The standard deviation s_z of each population is given as:

$$(4) \quad s_z = [V(z_N)]^{1/2}$$

The Kendall Coefficient m_z is obtained by:

$$(5) \quad m_z = [z_N - E(z_N)] / s_z$$

The Kendall Coefficient (m_z) has a standard normal distribution with a mean of zero ($E(z_N) = 0$) and a variance of one ($V(z_N) = 1$). The graphical representation of this series of values along the time axis is analyzed for trends. For purposes of analysis, a 95% confidence level was selected so that the series exhibits a significant trend when m_z falls outside the interval -1.96 to 1.96 (the pair of dotted lines on Figure 2a). The sign of m_z indicates the direction of trend, in this case towards warming (+) or cooling (-). In addition, we examined raw temperature values for trend by plotting the time series of each data set and fitting a regression line by least squares to each time series plot (the dotted line on Figure 2b).

In some cases a data set exhibited a Kendall Coefficient that only achieved statistical significance for a year or two. Due to the nature of the Mann-Kendall test, in which the Kendall Coefficient (m_z) is calculated based on previous values in the series, a few warm (or cool) years can produce high (or low) values of m_z . In the context of climate change, trends that reach statistical significance for only one or two years do not indicate a meaningful trend in temperature. However, for trends to remain significant for several years, actual temperature values must exhibit more consistent change in the direction of trend, and must be warmer (or cooler) than a significant portion of the temperatures from prior years in the series. The greater the number of years that the Kendall Coefficient falls outside the selected confidence interval, the stronger is the indication of a persistent and meaningful trend in temperature. Comparison of the test statistic re-

sults with time series plots of real temperature values confirms this relationship.

For example, certain time series indicated trends that achieved statistical significance for less than four years. While these short-term trends are of interest at a different spatial scale (i.e. community rather than regional scale), we focused instead on the occurrence of persistent trends indicative of more than random fluctuations in order to highlight variations in temperature change across different parts of the selected metro regions. Unless persistent trends were observed at all of the stations in a selected region, we could conclude that localized instances of trends were not the result of a broader regional trend in temperature. Next, we present those data sets in which persistent trends were identified.

Results - Asheville Region

No significant trend was observed for any time series of maximum temperatures in the Asheville region. Among a total of 32 data sets for the Asheville region (maximum and minimum temperature for each of four months at each of four weather stations), only five exhibited trends of long-term significance; each of the five occurred among minimum temperature data. These five data sets are examined below in detail.

Substantial significant trends existed at the Regional Airport station for June minimum temperature and at the Hendersonville station for minimum temperatures in March, June, September, and December. June minima clearly showed a warming trend at Asheville Regional Airport, beginning around 1966, achieving significance at different points in the time series, but remaining strongly positive and fluctuating near significance from 1980-2000. Raw values of June mean minimum temperature at Regional Airport support the indication of a warming trend (Figure 2).

March minima at Hendersonville exhibited a sharp increase from 1971-2000, becoming significant around 1990 (Figure 3). The data fluctuations around the significance line from 1990-2000 indicate that mean minimum temperatures were nearly constant during the period, and warmer than

at the beginning of the time series. June minima at Hendersonville exhibited a drastic warming trend beginning around 1974, following a period of no discernible change. The trend increased from the early 1980s through the year 2000. This indicates substantial warming for the data set. The graph of September minima indicates significant warming beginning around 1969, following some 10 years of significant cooling. The warming trend remained significant from 1987-2000.

December minima at Hendersonville also exhibited significant warming, but not at the magnitude observed for March, June, or September. The fluctuation of the data values indicates less drastic warming than the Hendersonville minimum temperature observations for the other three months. However, because the Kendall Coefficient remains strongly positive throughout, and is significant at several points in the series, we may conclude that minimum temperatures exhibited meaningful increase for the period of analysis. Again, raw mean minimum temperature values for each of the four months at Hendersonville reinforce the evidence of a warming trend (Figure 3).

The urbanized downtown station, Asheville 1, exhibited no significant trends among any data sets. A representative plot of temperatures from the Asheville 1 station is indicative of the absence of significant temperature change during the period of study (Figure 4). The urbanizing Marshall station also showed no persistent trends in any data set. Thus, warming trends in the Asheville region during the last 40 years appear to have been confined to outlying, urbanizing areas in the southern portion of the study area.

Results - Raleigh Region

Only four data sets from the Raleigh region indicated significant, relatively long-term temperature change; each exhibited significant warming. Two of the four occurred among maximum temperature data. June mean maxima exhibited persistent positive trends only at the RDI and Clayton stations. At RDI, the trend was significant for much of the final decade of study, and raw temperature values indicate slight warming during the period

of record (Figure 5). The warming trend among June maxima at Clayton was also significant for much of the final ten years of study, and raw temperatures indicate slight warming, similar to the change observed among the RDI June maxima (Figure 6).

Interestingly, persistent trends among minimum temperatures in the Raleigh region were observed for June at the same locations as trends in maximum temperatures. June mean minima at RDI showed a significant cooling trend early in the time series, followed by significant warming towards the end. Slight warming at RDI for the period of record is also indicated by June minimum raw temperature values (Figure 5). Kendall Coefficients for minimum temperatures for June at Clayton exhibited a warming trend late in the time series, which is supported by slight warming in raw temperature values (Figure 6).

The urbanized downtown station, Raleigh St. University, exhibited no persistent trends among any data sets. A plot of temperatures from Raleigh St. University (Figure 4) provides representative evidence that temperature change in downtown Raleigh was insignificant during the period of study, much like in downtown Asheville. Likewise, data from the urbanizing Raleigh 4SW station registered no persistent trends. Thus, in the Raleigh region during the period 1960 - 2000, the month of June experienced a warming trend among both maximum and minimum temperatures in outlying, urbanizing areas on opposite sides of the study area (RDI to the west, Clayton to the east).

The Clayton and RDI June data sets exhibited a striking temporal similarity. Each of the four sets showed negative values early in the series, followed by steady increase to positive significance within the last ten years of study. While the trend for each series was clearly positive, the true magnitude of change may be questionable. Although each plot line achieved significance late in the series, none remained significant for a large number of consecutive years. They tended to fluctuate around the significance line through the end of the period of the study. This indicates that actual temperatures in the last decade of the series were generally

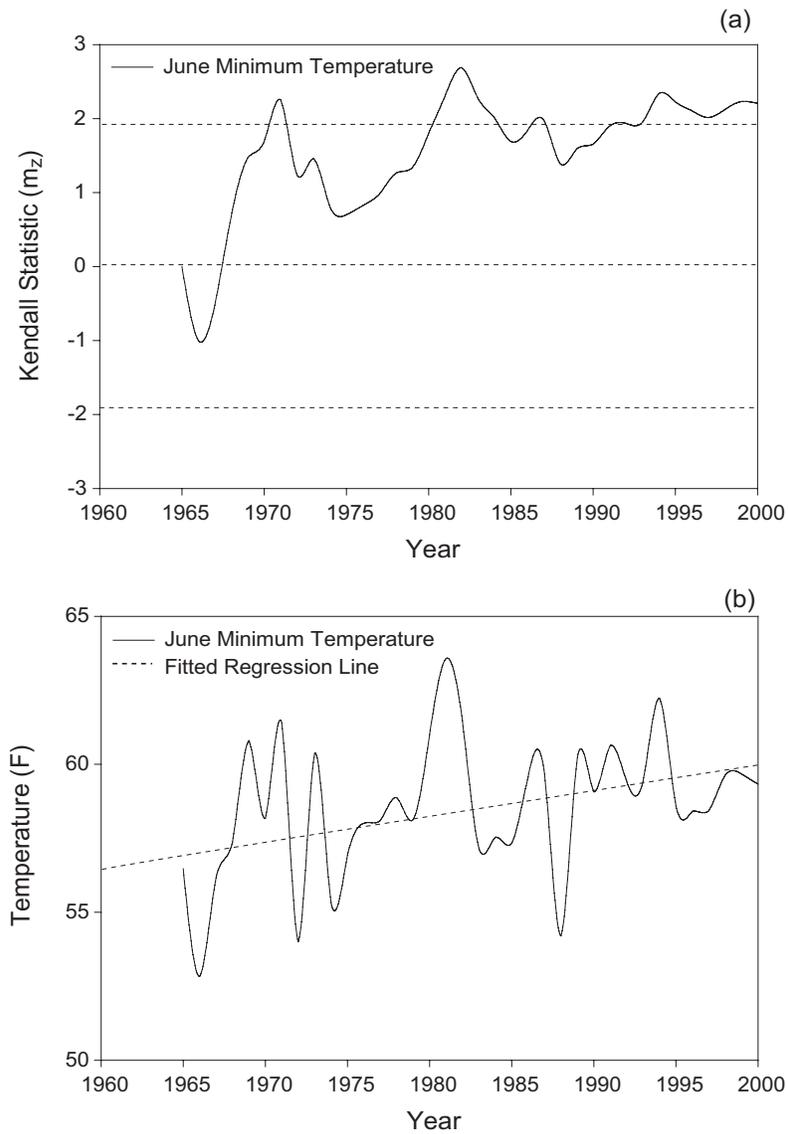


Figure 2. Data for Asheville Regional Airport. (a) Time series plot of the Kendall Coefficient (m_z); parallel dotted lines indicate 95% confidence interval. Trends are significant when values of m_z are greater than 1.96 or less than -1.96. (b) Time series plot of monthly mean temperatures.

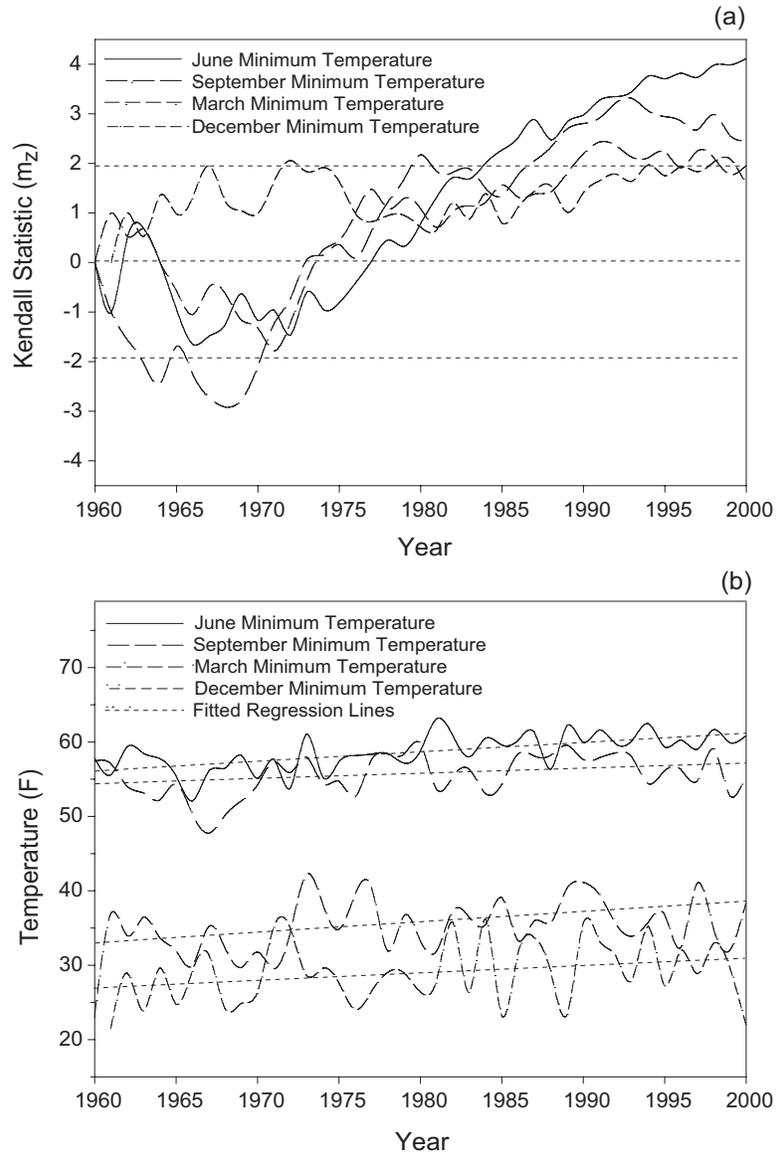


Figure 3. Data for Hendersonville 1NE. (a) Time series plots of the Kendall Coefficient. (b) Time series plots of monthly mean temperatures.

warmer than early in the series, but were not increasing at such a rate as to exhibit a strongly significant trend. These findings are supported by examination of the related raw temperature observations.

Discussion and Conclusions

The downtown weather station in the Asheville region (Asheville 1) exhibited no meaningful trend over the past forty years. The first urbanizing station (Hendersonville) exhibited significant warming among minimum temperature data sets for all four months of study. The only other instance of persistent warming at an urbanizing collection station occurred at Asheville Regional Airport, and only for mean minimum June temperatures.

The observed warming trend at the Hendersonville station may have been influenced by urbanization. It is possible that both the rate and magnitude of urbanization are greater over the last forty years in the Hendersonville area than in other parts of the Asheville region, including the central city of Asheville. The lack of a warming trend in downtown Asheville indicates the possibility that the city itself was highly urbanized at the beginning of the period of record, but did not experience a significant increase in urban characteristics during the forty-year period of study. A comparison of raw December mean minimum temperatures between the Asheville 1 and Hendersonville stations (Figures 3 and 4) indicates that December low temperatures were slightly higher in downtown Asheville than in Hendersonville during the study

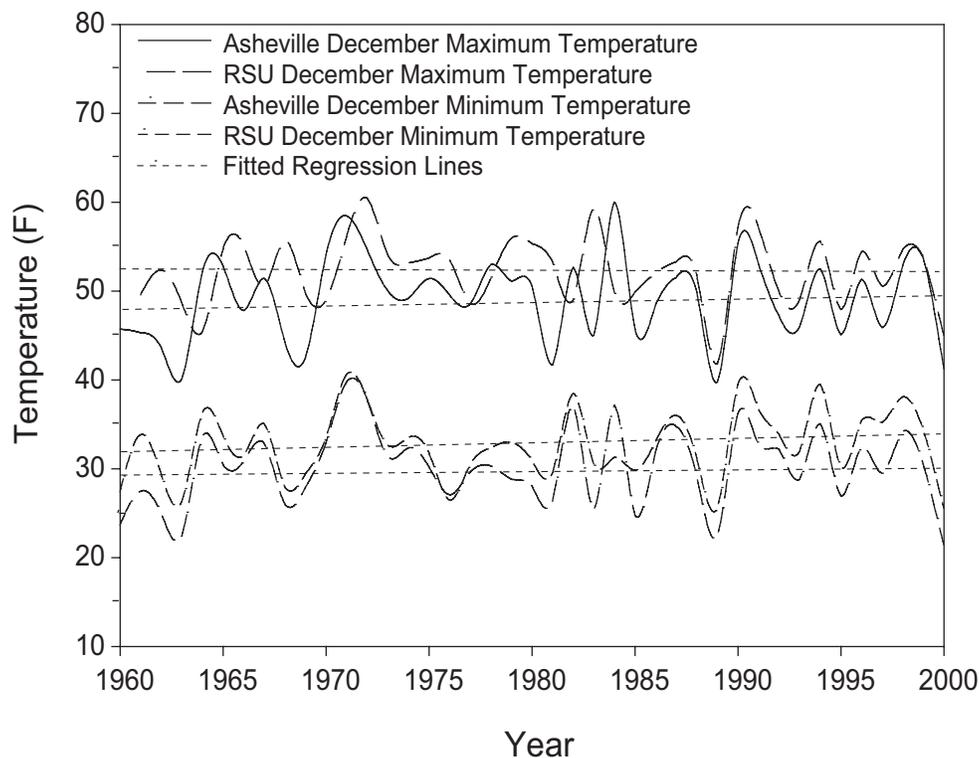


Figure 4. Sample time series plots of monthly mean temperatures for the two urbanized sites, Asheville 1 and Raleigh St. University (RSU), showing no warming trends.

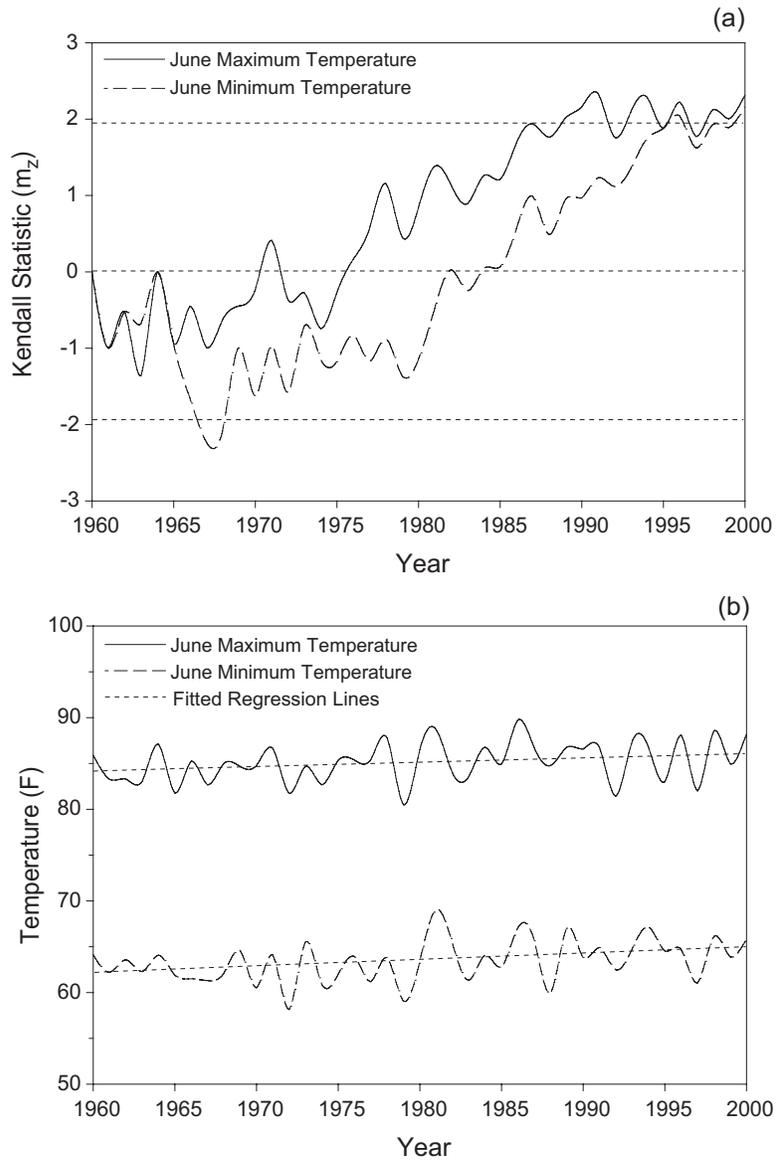


Figure 5. Data for Raleigh Durham International Airport. (a) Time series plots of the Kendall Coefficient. (b) Time series plots of monthly mean temperatures.

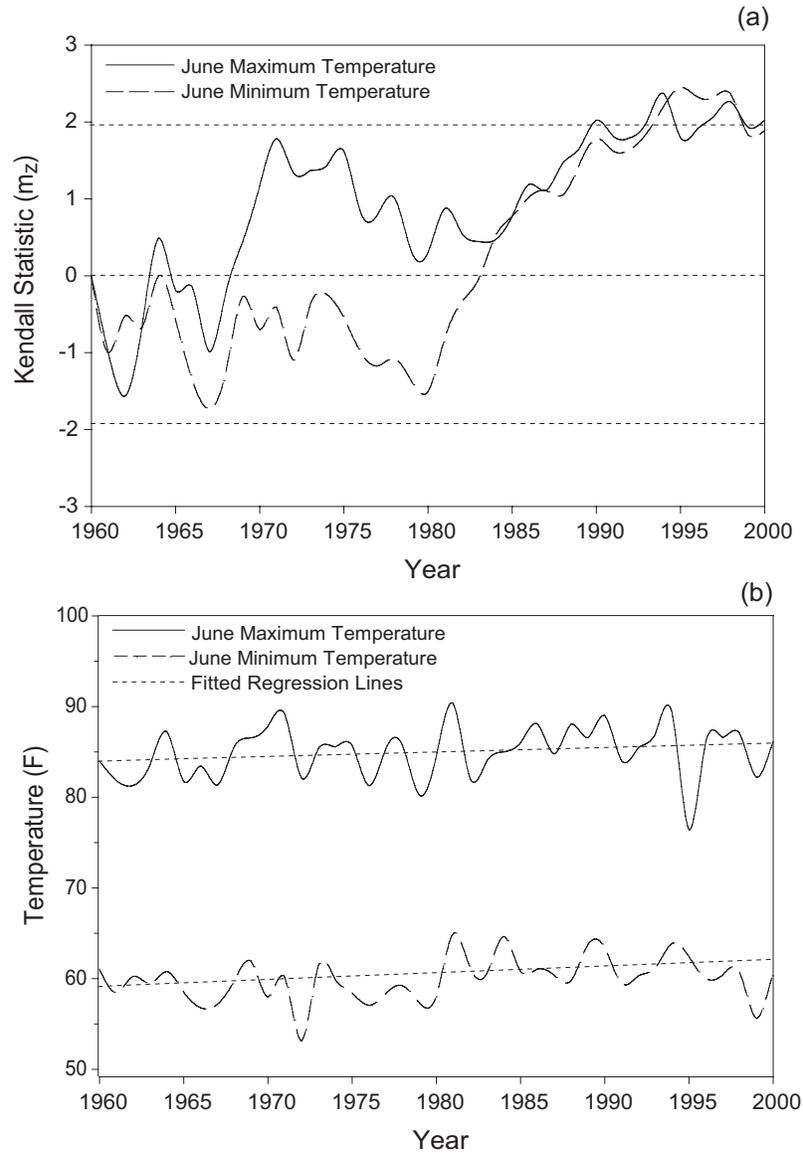


Figure 6. Data for Clayton WTP. (a) Time series plots of the Kendall Coefficient. (b) Time series plots of monthly mean temperatures.

period, but that temperatures in Hendersonville had narrowed that gap considerably by the last decade of study.

Meaningful trends in the Asheville region were found for minimum temperature data sets only. This indicates a trend toward increased overnight, as opposed to daytime, temperatures. These findings are in agreement with many studies of urban heat islands. Meaningful warming trends in the region reached significance around the mid-1980s, and generally remained significant through 2000. This indicates that temperature increases were more substantial during the past 10-15 years of the study period. Thus, future study might focus on the context of physical changes in the region during the stated period. It may be that the timing of the start of warming trends coincides with significant increases in urban development in the region, especially near the Hendersonville station. Because two weather stations still in less-urbanized settings, their surroundings likely underwent more development during the period of study than State University, the surroundings of which were constantly urban.

The absence of significant temperature change at the other two sites in the region (Raleigh 4SW and Raleigh St. University) again leads us to conclude that the observed warming trends are localized around RDI and Clayton, and are not the result of regional climate change.

Our study shows that increasing trends in temperature occurred in both study areas. Meaningful warming trends were observed outside of the heavily urbanized areas of the two regions. The most pronounced warming in the Asheville region occurred in suburban Hendersonville. Likewise in the Raleigh region—both instances of significant warming occurred at weather stations in less urbanized locations, while the more urbanized area exhibited no trends. Thus, urbanizing areas appear more likely to experience an increase in temperature through time than established urban areas. The implication is that the process of urbanization, rather than the existence of an urban landscape, may be responsible for urban temperature change. While urbanized areas may exhibit warmer temperatures on average, outlying urbanizing areas are more

likely to experience warming trends. The most significant trends in the two study areas occurred in places that were somewhat isolated from urban activity in 1960, but were approached more closely by urban development during the period of study. The trend toward warming in urbanizing areas could be a result of the overall expansion of the urbanized areas in the two regions.

This study may lead to a variety of future works. The direct results would be helpful in a more detailed analysis of urban temperature variability in the Asheville and Raleigh areas. Specifically, the relationship between the concentration of warming in suburban areas and the coincident patterns and rates of urbanization in those areas begs analysis, possibly incorporating remotely sensed imagery or other methods of quantifying urbanization in different parts of the study areas. Further, the results may inform future hypotheses of the spatial organization of the urban heat island, particularly by suggesting the need for increased focus on what may now be the issue of suburban – rather than urban – warming.

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