1000 DIFFERENTIAL TEMPERATURE TRENDS ACROSS ELEVATION WITHIN THE "WARMING HOLE" OF THE SOUTHEAST UNITED STATES

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1. INTRODUCTION

The area of insignificant or negative temperature trends across the central and southeastern United States, or "warming hole," has received much attention in recent years (Robinson et al., 2002; Pan et al., 2004; 2013; 2017; Kunkel et al., 2006; Meehl et al., 2012; 2015; Intergovernmental Panel on Climate Change, 2013; Kumar et al., 2013; Melillo et al., 2014; Yu et al., 2014; Tanner et al., 2015; Shadbolt, 2016; 2017; Banerjee et al., 2017; Grose et al., 2017). With many meteorological stations sited at low elevations and within urban settings, a closer examination of temperature changes across elevation within the southern Appalachian Mountains is a useful contribution to better understanding the warming hole.

The temporal trends spanning 1967-2016 of mean monthly maximum and minimum air temperature highlighted here for the southern Appalachians give a more thorough description of the region's climate compared to previous studies that were limited to only a few years or a few stations (Shanks, 1954; Mark 1958; Hicks 1979; Bolstad et al., 1998). As a result, regional and global model projections of the southeast U.S. will now have the context of an extensive and updated baseline.

2. DATA AND METHODS

The southern Appalachian study area includes portions of Tennessee, Georgia, North Carolina, and South Carolina within the southeastern United States. Monthly land-surface variables are available for download from the Global Historical Climatology Network (GHCN). The dataset is monitored by the National Centers for Environmental Information (NCEI) with some stations reporting as far back as the nineteenth century.

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For the study that follows, mean monthly maximum and minimum air temperature data were analyzed for 20 stations spanning the 50-year period of 1967-2016 (Figure 1). Missing daily observations were common and impact reported monthly values. Following Stooksbury et al. (1999), in order to minimize the impact of missing observations a station needed to report greater than 90 percent of the daily observations (i.e., 2-day data gap or less) in a month for a mean monthly value to be included in the climatology. Resulting stations with continuous coverage varied in elevation from 200-1200 m above sea level. To consider the effect of elevation on temperature, stations were subdivided into two categories: 200-600 m and 600-1200 m above sea level.

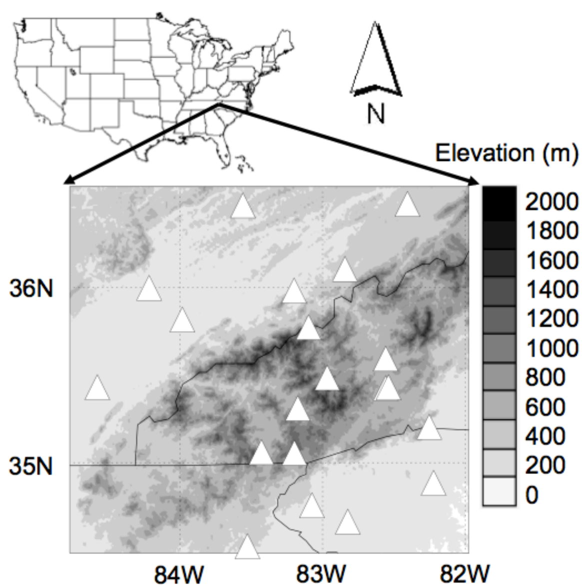

FIG. 1. Study site bounded by 34.50 to 36.55 °N and 82.00 to 84.75 °W. Elevation in meters above sea level is included in gray tones. White triangles indicate 20 station locations.

A Pearson's correlation and p-value were computed for mean monthly maximum and minimum temperature versus year for each available station and month. A simple linear regression (temperature-year) was calculated for each time series and decadal linear temperature trends recorded. Decadal trends for the stations were also correlated with station elevation. As recommended by Benjamin et al. (2018), any trends with a "statistically suggestive" p-value level of ≤ 0.05 or statistically significant p-value level of ≤ 0.005 were noted.

Next, the 50-year period was divided into two 30-year overlapping periods of 1967-1996 and 1987-2016. Decadal trends were determined for both periods in order to highlight differences by time period and by station elevation.

3. RESULTS

Linear trends by individual station illustrate that southern Appalachian stations experienced increasing mean monthly maximum and minimum air temperatures over 1967-2016. While twenty different stations were considered, the number of stations with continuous coverage varied by month and elevation category, as indicated in column two of Tables 1-4 to follow.

Table 1 provides a summary of results for mean monthly maximum air temperature at stations sited in the 200-600 m elevation range. All 12 months are characterized by an overall positive trend when considering all stations, with the annual mean station trend being +0.19 °C per decade. Three months have trends of ≥ 0.20 °C per decade (January, May, and, August) and two months have trends reaching ≥ 0.30 °C per decade (June and November). Of the 80 station time series considered, 20 have p-values of ≤ 0.05, and of those, five are significant at ≤ 0.005. Out of the trends with p-values ≤ 0.05, 17 trends out of 20 are positive.

In the 600-1200 m elevation range, 42 station time series were analyzed for mean monthly maximum air temperature. Table 2 shows that the annual mean station trend is +0.15 °C per decade. While March and April each revealed no trend, the other 10 months have positive decadal trend values. The two months with the largest positive trends are August (+0.24 °C per decade) and June (+0.30 °C per decade). Of the 42 trends, seven have p-values ≤ 0.05, three of which are significant at ≤ 0.005. All trends with p-values ≤ 0.05 are positive and occurred during the warm season months of May through August.

Month	Number of 200-600 m stations for T_{max}	Mean decadal trend (°C/decade)	Number of stations with negative trend significant at ≤ 0.05	Number of stations with negative trend significant at ≤ 0.005	Number of stations with positive trend significant at ≤ 0.05	Number of stations with positive trend significant at ≤ 0.005
January	7	+0.24	0	0	0	0
February	7	+0.17	0	0	0	0
March	5	+0.14	0	0	1	0
April	10	+0.04	1	1	0	0
May	8	+0.20	1	0	5	0
June	6	+0.35	0	0	2	3
July	9	+0.18	0	0	0	0
August	6	+0.29	0	0	4	0
September	6	+0.15	0	0	1	0
October	4	+0.15	0	0	0	0
November	6	+0.31	0	0	0	1
December	6	+0.18	0	0	0	0
All Months	**80**	**+0.19**	**2**	**1**	**13**	**4**

Table 1: Temporal trends in maximum temperature (T_{max}) over 1967-2016 for stations located at 200-600 m elevation above sea level in the southern Appalachians. Number of available stations is listed for each month (column 2). Mean decadal trend from all available stations is provided in °C per decade (column 3). Of those, the numbers of positive or negative station trends with p-values of ≤ 0.05 or ≤ 0.005 are indicated (columns 4-7).

Month	Number of 600-1200 m stations for T_{max}	Mean decadal trend (°C/decade)	Number of stations with positive trend significant at ≤ 0.05	Number of stations with positive trend significant at ≤ 0.005
January	2	+0.11	0	0
February	4	+0.06	0	0
March	2	0.00	0	0
April	3	0.00	0	0
May	4	+0.18	1	0
June	5	+0.30	2	1
July	6	+0.17	0	1
August	5	+0.24	1	1
September	4	+0.17	0	0
October	3	+0.07	0	0
November	2	+0.16	0	0
December	2	+0.06	0	0
All Months	**42**	**+0.15**	**4**	**3**

Table 2: Temporal trends in maximum temperature (T_{max}) over 1967-2016 for stations located at 600-1200 m elevation above sea level in the southern Appalachians. Number of available stations is listed for each month (column 2). Mean decadal trend from all available stations is provided in °C per decade (column 3). Of those, the numbers of positive station trends with p-values of ≤ 0.05 or ≤ 0.005 are indicated (columns 4-5).

Trends in mean monthly minimum air temperature for stations in the 200-600 m elevation range are shown in Table 3. Across all months and the 80 station trends, the annual mean trend is +0.30 °C per decade. The mean trend for November is -0.03 °C per decade, while the mean trends from all other 11 months are positive. Months exceeding +0.20 °C per decade include October and December. March, April, July, August, and September each exceed +0.30 °C per decade. February, May, and June exceed +0.40 °C per decade. Of the 80 trends analyzed, exactly half have positive trends with p-values ≤ 0.05, and out of those, 24 are significant at ≤ 0.005. P-values reaching ≤ 0.005 favor warm season months. There are no negative trends with p-values of ≤ 0.05.

Table 4 shows mean monthly minimum air temperature results for stations in the 600-1200 m range. All 12 months are characterized by positive mean decadal trends. The overall annual mean from the 42 trends is +0.23 °C per decade. Six months exceed +0.20 °C per decade (January, February, April, May, August, and December), while March and June each exceed +0.30 °C per decade. Out of the 42 trends, 17 have p-values of ≤ 0.05 and of those 11 trends have p-values of ≤ 0.005. All trends with p-values of ≤ 0.05 are positive and generally stem from warm season months.

Month	Number of 200-600 m stations for T_{min}	Mean decadal trend (°C/decade)	Number of stations with positive trend significant at ≤ 0.05	Number of stations with positive trend significant at ≤ 0.005
January	7	+0.19	0	0
February	7	+0.40	3	1
March	5	+0.31	3	0
April	10	+0.32	4	2
May	8	+0.41	1	4
June	6	+0.47	0	5
July	9	+0.31	1	6
August	6	+0.32	0	4
September	6	+0.32	2	2
October	4	+0.22	1	0
November	6	-0.03	0	0
December	6	+0.28	1	0
ALL	**80**	**+0.30**	**16**	**24**

Table 3: Same as Table 2, but for minimum temperature (T_{min}) at the 200-600 m elevation range.

Month	Number of 600-1200 m stations for T_{min}	Mean decadal trend (°C/decade)	Number of stations with positive trend significant at ≤ 0.05	Number of stations with positive trend significant at ≤ 0.005
January	2	+0.22	0	0
February	4	+0.26	2	0
March	2	+0.30	0	0
April	3	+0.22	1	0
May	4	+0.29	2	0
June	5	+0.39	0	5
July	6	+0.19	1	3
August	5	+0.26	0	3
September	4	+0.08	0	0
October	3	+0.11	0	0
November	2	+0.08	0	0
December	2	+0.29	0	0
ALL	**42**	**+0.23**	**6**	**11**

Table 4: Same as Table 2, but for minimum temperature (T_{min}) at the 600-1200 m elevation range.

Results from Tables 1-4 indicate that warming occurred across the region during the period 1967-2016 when considering both mean monthly maximum and minimum air temperature. Not surprisingly, warming was generally greater when considering minimum temperature compared to maximum temperature. When considering elevation influences, stations positioned at 200-600 m elevation, on average, experienced more warming compared to stations positioned at an elevation of 600-1200 m.

With maximum temperature during September and minimum temperature during January as the only exceptions, all other months illustrated a negative relationship between station decadal trend versus station elevation for both maximum and minimum temperature. That being said, none of the relationships between decadal trends and elevation for maximum temperature had p-values of ≤ 0.05. For minimum temperature, July and September were the only two months where the relationship between decadal trends of minimum temperature versus station elevation had a p-value of ≤ 0.05.

Decadal trend results from Tables 1-4 summarize linear trends over the full 50-year time period. Given the possibility that warming trends have changed over 1967-2016, decadal trends of mean monthly maximum and minimum air temperature were compared for two overlapping 30-year periods of 1967-1996 and 1987-2016. The mean of the 30-year trends in maximum temperature for stations located at 200-600 m elevation decreased from +0.19 to +0.12 °C per decade from the early to the latter of the 30-year time periods. In contrast, the mean of the 30-year trends in maximum temperature for stations sited within 600-1200 m elevation increased from +0.08 to +0.18 °C per decade. For minimum temperature, the mean trend for stations in the 200-600 m elevation range increased from +0.18 to +0.35 °C per decade while the mean trend in minimum temperature for stations at 600-1200 m elevation increased from +0.20 to +0.31 °C per decade between the overlapping time periods.

While monthly variability in the degree of warming is present, the largest changes in decadal trends between the two overlapping 30-year periods generally occurred during the transitional months of spring and autumn. In particular, in February, temperatures at the stations studied generally increased during 1967-1996 and decreased during 1987-2016. Regardless of station elevation range or temperature variable the decadal trends for February changed from positive to negative trends with an overall change exceeding 1.00 °C per decade between the overlapping time periods. In contrast, the months of April, October, and December were characterized by some of the largest increases in decadal trends between the two time periods. For example, October minimum temperature trends at all elevations increased by more than 1.00 °C per decade during the latter period over the earlier period.

4. DISCUSSION AND CONCLUSIONS

Causation of cooling trends in the southeastern United States during the twentieth century was explored by Robinson et al. (2002). The authors uncovered a connection between high Pacific sea-surface temperatures during El Niño events and lower than normal temperatures in the southern states. Increased moisture and cloud cover were concluded to be responsible for decreasing mean temperature of the region.

More recently Meehl et al. (2012; 2015) also linked the warming hole to trends in the Pacific, but on decadal time scales, with cold-air advection in winter months and low-level moisture convergence in summer months. The authors also found that all though an east/west contrast across the United States did exist in the second half of the twentieth century, the "warming hole" appeared to weaken after the early 2000s. With the exception of low-elevation maximum temperature, the comparison of 30-year overlapping periods shown here generally agrees, especially when considering decadal trend increases of minimum air temperature.

Kunkel et al. (2009) and Kumar et al. (2013) found a stronger linkage between the warming hole with decadal trends of the North Atlantic. Meanwhile, Pan et al. (2013) conclude that linkages to trends of the Pacific or Atlantic were not always present and that land surface processes could be responsible. Banerjee et al. (2017) explored the theory that aerosol presence is responsible for cooling trends and the warming hole of the south central and southeast United States. The authors concluded that while aerosols did contribute, aerosols alone could not be solely responsible for the magnitude of the region's cooling.

Meehl et al. (2015) suggest that the region's warming hole may have disappeared with the recent transition of the Interdecadal Pacific Oscillation in the early 2000s. A possible local causative effect of recent warming in the southern Appalachian Mountains described here could be the recent die-off of hemlock forest, most of which has occurred since 2000. Several studies have looked at the impact of canopy gaps created by hemlock loss in the region. Despite observing increased stream light levels, Roberts et al. (2009) and Siderhurst et al. (2010) analyzed stream temperature values and found no significant difference between streams with primary over story of hemlock versus hardwood forest. All though it was not specific to hemlock forests, Clinton (2003) previously considered small canopy gaps of the region and concluded no relationship between canopy gaps with air or soil temperature. However, given the additional hemlock forest loss, as well as other disturbances in the region over recent years, such as the Chimney Tops 2 Fire of 2016, the increasing number and size of canopy gaps may be suitable sites for upcoming research.

Results here indicate general warming in the southern Appalachians with the largest increases favoring minimum temperature. Decadal trends of temperature were not clearly related to station elevation given that 1) most of the correlations between decadal trends and station elevation were not statistically significant, and 2) stations used in this study ranged in elevation from 200-1200 m. Peaks of the southern Appalachians often do exceed 1200 m. All though stations do exist for elevations greater than 1200 m, none of those stations met the criteria for continuous data coverage used here as suggested by Stooksbury et al. (1999). Thus, those high-elevation stations were not considered in this study. The results presented here do still highlight overall warming within the southern Appalachian Mountains in elevations extending up to 1200 m despite cooling trends previously described by other studies for the southeastern United States.

5. ACKNOWLEDGEMENTS

In-kind support was provided by Northland College.

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