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RECENT CLIMATE CHANGE IN THE HIGH ELEVATIONS OF THE SOUTHERN APPALACHIANS

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1. INTRODUCTION

Island species are often vulnerable to environmental change because the ecosystems are small and isolated. In a similar way, mountain peak ecosystems are isolated and may be referred to as “sky islands” (Heald, 1967; Kupfer et al., 2005). The southern Appalachian range provides an interesting case study with deciduous broadleaf tree species at elevations below 1500 meters above sea level, evergreen boreal species becoming common at elevations higher than 1500 meters above sea level, and other rare ecosystems known as grassy balds that include alpine tundra species. The Intergovernmental Panel on Climate Change (IPCC) and others suggest that the southeastern United States, which includes the southern Appalachians, is one region on the planet that experienced cooling since the beginning of the twentieth century (IPCC, 2013; Melillo et al., 2014). However, because many weather stations are located in low-elevation sites, a closer look at the region’s high-elevation observations is valuable.

The temporal trends of temperature highlighted here for the southern Appalachians give a more thorough description of the region’s high-elevation 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). Past research has focused on mean, minimum, and maximum temperature. However, trends and impacts of temperature extremes are gaining increased research attention (e.g., Peterson et al., 2012; 2013; Herring et al., 2014; 2015). A first look at temperature extremes for high-elevation sites of the southern Appalachians is provided here. Model projections of the region’s temperature will now have an extensive baseline of various temperature values for comparison.

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2. DATA AND METHODS

The southern Appalachian study site includes portions of Tennessee, Georgia, North Carolina, and South Carolina within the southeastern United States (Figure 1). Up to 18 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 19th century.

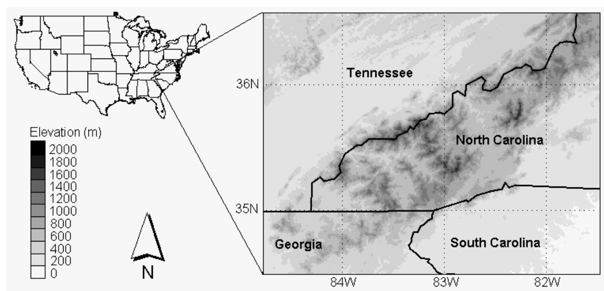

FIG. 1. Study site bounded by 34.50 to 36.55 °N and 81.50 to 84.75 °W. Elevation in meters above sea level is included in gray tones.

For the study that follows, six monthly variables were considered: mean temperature, minimum temperature, maximum temperature, extreme minimum temperature, extreme maximum temperature, and total snowfall. Monthly values were determined from stations’ daily observations. Total snowfall is the summation of all daily observations taken during a given month for a station. Mean, minimum, and maximum temperature values for a station are determined by calculating the mean value of the variable from all daily observations collected during the month. In addition, the coldest reported minimum temperature in the month becomes the extreme minimum temperature and the warmest maximum temperature reported in the month becomes the extreme maximum temperature.

Missing daily observations were common and would likely impact monthly values. For example, if observations from the first half of March were missing from a station, there would be a greater probability that the monthly temperature values would be warmer than what actually occurred given that early March is often colder than late March for the region. To minimize the impact of missing observations, stations needed to report at least 90% of the daily observations in a month for the monthly value to be included in the climatology.

In order to consider the effect of elevation on temperature, stations were subdivided into two categories: 1000-1499 m and ≥ 1500 m above sea level. For each month and year the number of stations reporting a value was determined for the two elevation categories above. A complete period of record was necessary to make conclusions about temporal trends of temperature so at least one station in each elevation category was necessary for a month and year to be included. Given the above criteria, the period of record for stations at 1000-1499 m extends from the present back to 1948; however, at elevations ≥ 1500 m no stations reported during December 1975. To allow for direct comparisons between the two elevation categories, the beginning month was selected as January 1976 and the most recent complete year at the time of analysis was 2014, making the complete period of record 1976-2014.

Beginning with January 1976, all reporting stations for each elevation category were used to determine the mean value of each variable. The same process was repeated for each subsequent year in order to create a temporal trend of each variable. Next, a Spearman's rank correlation was computed for each variable at each elevation category, as well as the two-sided deviation. Deviation values of ≤ 0.05, ≤ 0.01, and ≤ 0.001 were deemed as statistically significant. A linear fitted line was calculated for each time series. The difference between the ending (2014) and starting (1976) values of the linear fit was determined to express the linear temporal trend of each variable over the 39-year period.

3. RESULTS

A total of 94 stations were identified at elevations 1000-1499 m (Figure 2) and 20 stations were identified at elevations ≥ 1500 m (Figure 3). Statistically significant results from the temporal analysis were common. All significant results will be expressed in Tables 1-2 to follow. However, figures showing the time series of all statistically significant results are not included. Figures will be limited to one example for each variable. In each case, the figure shown will be the month with the largest temporal change.

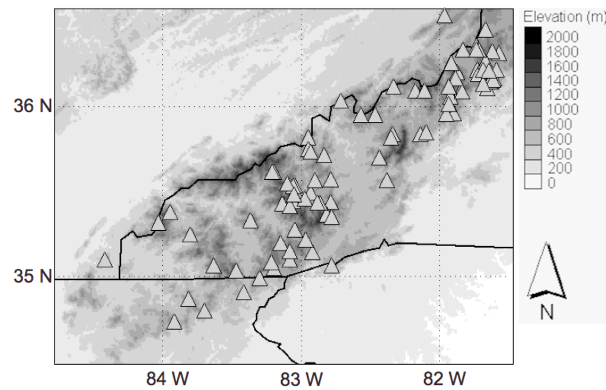

FIG. 2. Study site bounded by 34.50 to 36.55 °N and 81.50 to 84.75 °W. Elevation in meters above sea level is included in gray tones. Small gray triangles indicate 94 station locations at an elevation of 1000-1499 m.

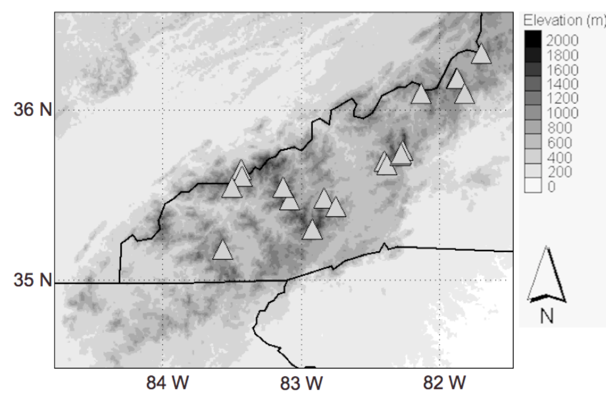

FIG. 3. Study site bounded by 34.50 to 36.55 °N and 81.50 to 84.75 °W. Elevation in meters above sea level is included in gray tones. Large gray triangles indicate 20 station locations at an elevation ≥ 1500 m.

3.1 *Trends of Temperature and Snowfall at 1000-1499 m Elevation*

All temporal trend values for minimum temperature, maximum temperature, mean temperature, extreme minimum temperature, extreme maximum temperature, and total snowfall are included in Table 1. The presence or absence of statistically significant values highlights two initial noteworthy results. First, all temperature variables generally increased over the 1976-2014 period. Second, no significant trends were found in the total snowfall data. It is well documented that warming at high latitudes impacts ice and snow amounts (IPCC, 2013), so total snowfall was included here. With no significant values found we cannot conclude that snowfall amount is the leading factor contributing to the region's warming trends.

Month	Extreme T_{min}	T_{min}	T_{mean}	T_{max}	Extreme T_{max}	Total Snowfall
January	**+7.91 °C***	**+5.20 °C****	**+4.93 °C****	**+4.70 °C****	**+7.29 °C*****	-225.70 mm
February	**+7.81 °C*****	+3.31 °C	**+2.77 °C***	**+2.23 °C***	+0.82 °C	-205.85 mm
March	+2.80 °C	+0.97 °C	+0.53 °C	+0.15 °C	+0.20 °C	+7.45 mm
April	+2.28 °C	**+1.89 °C***	**+1.84 °C***	+1.75 °C	+1.57 °C	-52.49 mm
May	**+2.67 °C****	**+1.93 °C***	**+1.78 °C***	**+1.64 °C***	+1.27 °C	-3.40 mm
June	**+5.81 °C*****	**+2.30 °C*****	**+1.92 °C*****	**+1.47 °C***	**+1.79 °C***	0.00 mm
July	**+2.15 °C***	**+1.47 °C****	+0.90 °C	+0.30 °C	+0.34 °C	0.00 mm
August	**+3.04 °C***	**+1.71 °C****	**+1.37 °C***	+1.00 °C	+0.29 °C	0.00 mm
September	**+2.69 °C***	**+1.60 °C***	**+1.37 °C***	+1.16 °C	+0.41 °C	0.00 mm
October	+1.95 °C	**+2.30 °C***	**+1.94 °C***	**+1.60 °C***	**+2.53 °C****	+12.79 mm
November	+2.87 °C	-0.18 °C	+0.19 °C	+0.55 °C	+1.82 °C	-10.67 mm
December	**+7.89 °C*****	**+3.33 °C***	+2.43 °C	+1.54 °C	+1.16 °C	+0.96 mm

Table 1: Temporal changes over 1976-2014 for stations located at 1000-1499 m elevation above sea level in the southern Appalachians. Monthly values of extreme minimum temperature (Extreme T_{min}), minimum temperature (T_{min}), mean temperature (T_{mean}), maximum temperature (T_{max}), and extreme maximum temperature (Extreme T_{max}) are in degrees C, while total snowfall is provided in mm. Statistically significant values in bold are indicated by * for values significant at ≤ 0.05, ** for values significant at ≤ 0.01, and *** for values significant at ≤ 0.001.

Trend values of extreme minimum temperature in Table 1 include the largest temperature increases over the time period. All 12 months warmed with eight of the months having significant trends. The winter months of December, January, and February (Figure 4) each approaching 8 °C of warming over the time period.

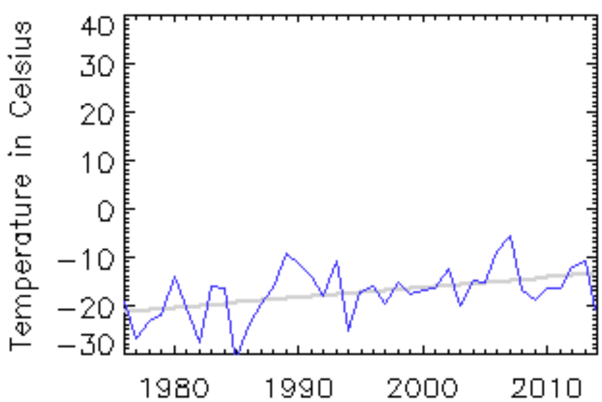

FIG. 4. Values of extreme minimum temperature in degrees C for February (in blue) for elevation of 1000-1499 m above sea level. The linear fitted line (in gray) illustrates the increase of +7.91 °C over the 1976-2014 period.

Minimum temperature values illustrate warming trends for 11 of the 12 months. The only negative temperature trend found in the study at this elevation range exists for November minimum temperature. The value was of low magnitude (-0.18 °C) and was not found to be significant. Nine of the 12 months have a statistically significant result. With the exceptions of October, the magnitude of warming is not as great as expressed in the extreme minimum temperature values, but winter months of December and January (Figure 5) experienced the greatest increases of +3.33 and +5.20 °C, respectively. The results from extreme minimum temperature and minimum temperature suggest that both daily and annual minimum temperatures are warming significantly for most stations.

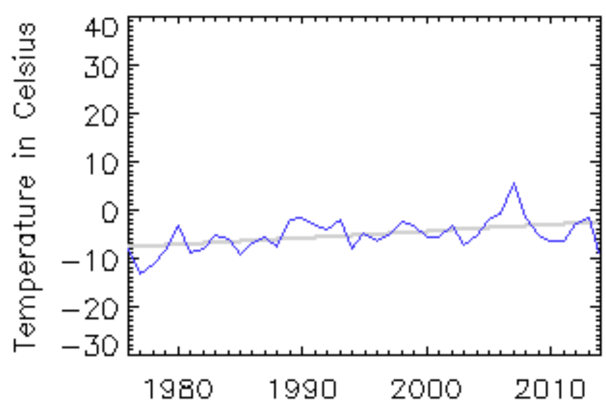

FIG. 5. Values of minimum temperature in degrees C for January (in blue) for elevation of 1000-1499 m above sea level. The linear fitted line (in gray) illustrates the increase of +5.20 °C over the 1976-2014 period.

Mean temperature trends again indicate warming for all 12 months. Eight of the 12 months have significant values. Compared to minimum temperature, the magnitude of warming tends to be less for all months with the exception of November. January stands out again as the month with the greatest amount of warming (Figure 6).

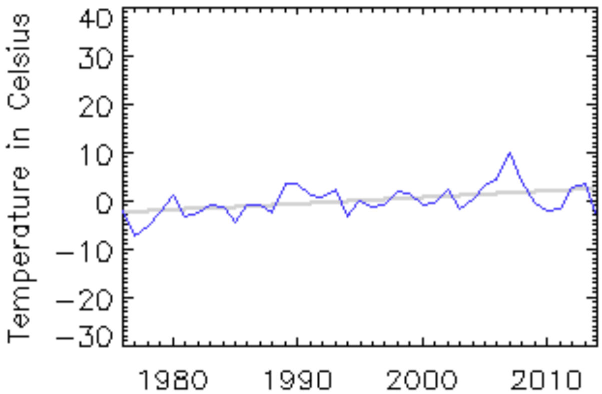

FIG. 6. Values of mean temperature in degrees C for January (in blue) for elevation of 1000-1499 m above sea level. The linear fitted line (in gray) illustrates the increase of +4.93 °C over the 1976-2014 period.

All 12 months experienced warming values of maximum temperature over the time period. However, with the exception of November, the magnitude of warming is less compared to the mean and minimum temperature trends. In this case five of the months had significant results: January at +4.70 °C (Figure 7), February at +2.23 °C, May at +1.64 °C, June at +1.47 °C, and October at +1.60 °C.

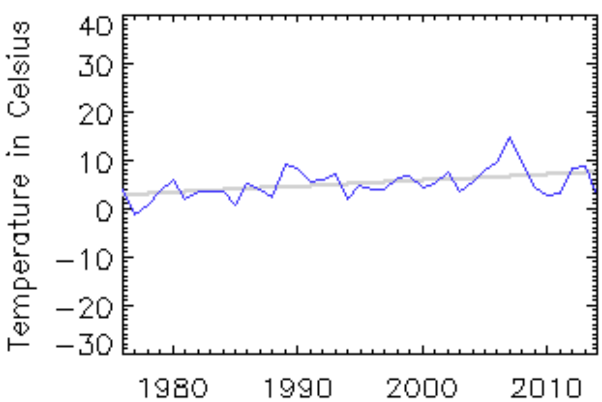

FIG. 7. Values of maximum temperature in degrees C for January (in blue) for elevation of 1000-1499 m above sea level. The linear fitted line (in gray) illustrates the increase of +4.70 °C over the 1976-2014 period.

For extreme maximum temperature all 12 months experienced overall warming trends, although five of the months experienced warming less than 1 °C. Nonetheless, three months still experienced significant warming: January, June, and October. January stands out once again as the month with the greatest increase of +7.29 °C (Figure 8).

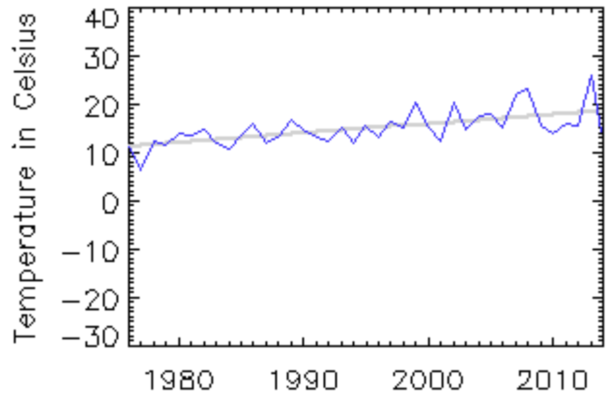

FIG. 8. Values of extreme maximum temperature in degrees C for January (in blue) for elevation of 1000-1499 m above sea level. The linear fitted line (in gray) illustrates the increase of +7.29 °C over the 1976-2014 period.

Although all temperature variables generally illustrate warming trends, variation in those trends is evident. Extreme minimum and minimum temperatures tended to warm more compared to the maximum and extreme maximum temperatures. The results indicate that cold nighttime and wintertime temperatures are warming the most. Results also demonstrate that the overall daily and annual temperature ranges are decreasing.

High-elevation environments are often similar to high latitude environments. In this case, we cannot conclude that an ice-albedo feedback is present in the 1000-1499 m elevation range. With warming temperatures overall it is expected that total snowfall should be decreasing. Results in Table 1 do in fact show that five of the 12 months are experiencing less snowfall now compared to the beginning of the record, while three months (March, October, and December) have experienced small increases. However, none of the trend values are statistically significant.

3.2 *Trends of Temperature and Snowfall at ≥ 1500 m Elevation*

Temporal trend values for minimum temperature, maximum temperature, mean temperature, extreme minimum temperature, extreme maximum temperature, and total snowfall are included in Table 2 for elevations ≥ 1500 m. Compared to the lower elevation range, fewer statistically significant results were found.

Month	Extreme T_{min}	T_{min}	T_{mean}	T_{max}	Extreme T_{max}	Total Snowfall
January	+4.11 °C	+2.42 °C	+2.10 °C	+1.75 °C	**+3.63 °C****	-6.56 mm
February	**+4.59 °C***	-0.33 °C	-0.87 °C	-1.31 °C	**-2.83 °C***	+14.74 mm
March	+0.81 °C	-1.13 °C	-1.43 °C	-1.74 °C	-1.44 °C	+251.95 mm
April	-0.21 °C	-0.56 °C	-0.32 °C	-0.05 °C	+1.73 °C	+39.78 mm
May	+0.81 °C	-0.41 °C	-0.08 °C	+0.24 °C	+1.26 °C	-12.87 mm
June	+2.30 °C	-0.21 °C	-0.03 °C	+0.17 °C	+1.22 °C	0.00 mm
July	-0.65 °C	-0.99 °C	-0.90 °C	-0.81 °C	-0.27 °C	-0.51 mm
August	+0.84 °C	-0.85 °C	-0.36 °C	+0.09 °C	-0.78 °C	0.00 mm
September	+0.54 °C	-0.97 °C	-0.46 °C	+0.05 °C	+0.32 °C	0.00 mm
October	-0.44 °C	+0.18 °C	+0.38 °C	+0.57 °C	**+2.43 °C****	+32.66 mm
November	+0.35 °C	-1.74 °C	-1.26 °C	-0.75 °C	+1.01 °C	+136.17 mm
December	**+5.93 °C****	+0.79 °C	+0.19 °C	-0.44 °C	-0.11 °C	+183.91 mm

Table 2: Temporal changes over 1976-2014 for stations located at ≥ 1500 m elevation above sea level in the southern Appalachians. Monthly values of extreme minimum temperature (Extreme T_{min}), minimum temperature (T_{min}), mean temperature (T_{mean}), maximum temperature (T_{max}), and extreme maximum temperature (Extreme T_{max}) are in degrees C, while total snowfall is provided in mm. Statistically significant values in bold are indicated by * for values significant at ≤ 0.05 and ** for values significant at ≤ 0.01. No values were found to be significant at ≤ 0.001.

For extreme minimum temperature three of the months (April, July, and October) experienced a small amount of cooling over the time period. Nine months warmed, with February and December (Figure 9) standing out as significant.

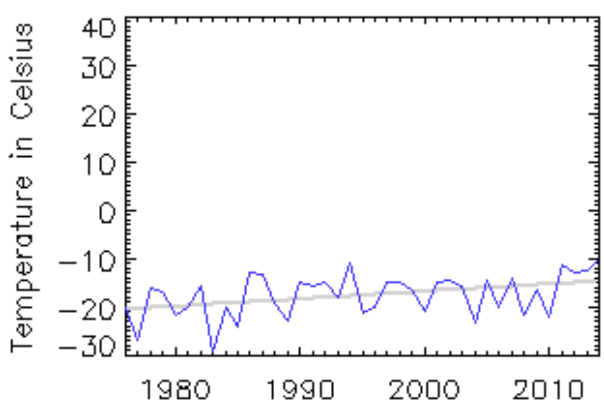

FIG. 9. Values of extreme maximum temperature in degrees C for December (in blue) for elevation of ≥ 1500 m above sea level. The linear fitted line (in gray) illustrates the increase of +5.93 °C over the 1976-2014 period.

At this higher elevation range, no monthly trends for minimum, maximum, or mean temperature were deemed statistically significant. For minimum temperature January, October, and December warmed while all other nine months cooled over the time period. The same was true for mean temperature, although the values were different. Maximum temperature had six months experiencing warming (January, May, June, August, September, and October) and six months with cooling (February, March, April, July, November, and December). One consistency from the three variables is that January warmed the most in each case, although the values were not significant. For minimum, mean, and maximum temperatures in all months experiencing cooling, none exceeded cooling of 2 °C or more.

Extreme maximum temperature trends at this elevation are unique in that the variable possesses the only statistically significant cooling trend found in the study. February cooled by -2.83 °C. March, July, August, and December also cooled, but were not significant. Seven months warmed (January, April, May, June, September, October, and November), two of which were significant. January warmed by +3.63 °C (Figure 10) and October by +2.43 °C.

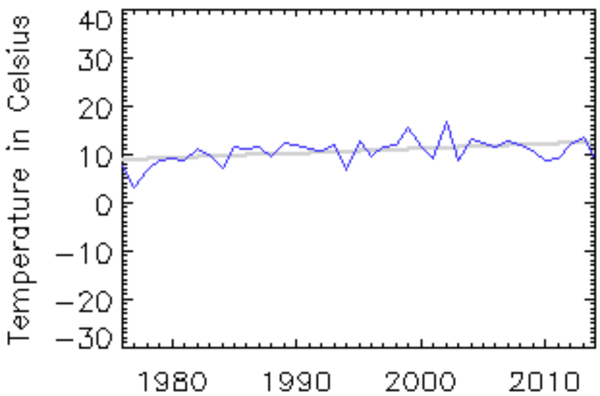

FIG. 10. Values of extreme maximum temperature in degrees C for January (in blue) for elevation of ≥ 1500 m above sea level. The linear fitted line (in gray) illustrates the increase of +3.63 °C over the 1976-2014 period.

Total snowfall values at ≥ 1500 m had six of the 12 months with an increasing value. In addition, three months had small decreases in snowfall and three months experienced no change. Again, none of the 12 months had a significant trend for total snowfall. The snowfall trends vary greatly, but values do suggest that snowfall is increasing during autumn and springtime months with less snowfall received during January. The decrease in January snowfall coincides with warming trends for all five temperature variables, one of which was significant.

Results at the higher elevation range are not as conclusive as seen at the 1000-1499 m range. At 1500 m or higher fewer significant results exist and many statistically insignificant cooling trends are present. Still, the magnitude of warming for extreme minimum and minimum temperatures tends to be greater than the magnitude seen in the mean, maximum, and extreme maximum temperatures, suggesting that temperature ranges may be decreasing at the highest elevations of the southern Appalachians as well.

4. DISCUSSION AND CONCLUSIONS

With the exception of February at elevations of 1500 m and higher, all significant results for the temperature variables were warming trends. In total, 33 significant warm results were found at the 1000-1499 m elevation range. The cold variables of extreme minimum and minimum temperature warmed the most, while mean, maximum and extreme maximum temperatures warmed less. The results indicate that both daily and annual temperature ranges decreased over 1976-2014. With extreme minimum temperatures warming by nearly 8 °C during wintertime months it is possible that cold-related human mortality decreased. On the other hand, with extreme maximum temperature increasing over the period, it is possible that heat-related human mortality increased. The noted significant changes in temperature may affect the diverse ecosystems of the region, which could be an area of justified future research.

Results at the 1500 m or higher elevation range were less distinct, although four of the five significant temperature results still highlighted warming for the region. Significant results were present only for the extreme minimum and extreme maximum temperature variables. When considering insignificant values, a trend of shrinking daily and annual temperature ranges was still evident. February for extreme maximum temperature at the high elevations was the only significant cooling trend present in the data. With all total snowfall trends found to be insignificant, it is not possible to conclude that snowfall in the region is contributing to a similar ice-albedo feedback present at the Northern Hemisphere’s high latitudes.

The findings of this study provide thorough coverage of the southern Appalachians temporal temperature trends over 1976-2014. Contrary to past research that is biased toward the results of low-elevation stations and concludes that the region has cooled compared to most other Northern Hemisphere locations, the study provided here illustrates that high-elevation sites often warmed significantly. In some cases the warming exceeded 7 °C over the 39-year time period.

5. ACKNOWLEDGEMENTS

In-kind support was provided by Central Michigan University.

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