TEMPERATURE VARIABLE TRENDS FOR HIGH ELEVATIONS OF THE SOUTHERN APPALACHIANS 1951-2015

Ryan P. Shadbolt *
Central Michigan University, Mt. Pleasant, Michigan

1. INTRODUCTION

Small, isolated island ecosystems are vulnerable to environmental change. In a similar way, mountain peak ecosystems are isolated and may be referred to as "sky islands" (Heald, 1967; Kupfer et al., 2005; Malanson et al., 2017). The southern Appalachian range provides an interesting case study with deciduous broadleaf tree species at elevations below 1000 meters above sea level. Above 1000 meters, evergreen boreal species and other rare ecosystems known as grassy balds, which include alpine tundra species, are increasingly more common (Whittaker, 1966). 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 (Robinson et al., 2002; 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 was provided in Shadbolt (2016) for the years 1976-2014. Results for additional variables are included here in this new study. Model projections of the region's temperature will now have an extensive baseline of various temperature values for comparison.

* *Corresponding author address*: Ryan P. Shadbolt, Central Michigan University, Dept. of Geography, Mt. Pleasant, MI 48859; e-mail: shadb1rp@cmich.edu.

2. DATA AND METHODS

The southern Appalachian study site includes portions of Tennessee, Georgia, North Carolina, and South Carolina within the southeastern United States. 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 nineteenth century.

For the study that follows, six monthly variables were considered: cooling degree days (CLDD), heating degree days (HTDD), the number of days in a month where minimum temperature ≤ 0 °F (DT00; -17.8 °C), the number of days in a month where minimum temperature ≤ 32 °F (DT32; 0 °C), the number of days in a month where maximum temperature ≥ 90 °F (DT90; 32.2 °C), and number of days in a month where maximum temperature ≤ 32 °F (DX32; 0 °C). Monthly values for a station were determined by calculating the mean value of the variable from all daily observations collected during the month. Missing daily observations were common and impact monthly values. To minimize the impact of missing observations, stations needed to report at least 75% 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 required 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 August 1948; however, at elevations ≥ 1500 m no stations reported during October 1950. To allow for direct comparisons between the two elevation categories, the beginning month was selected as January 1951 and the most recent complete year at the time of analysis was 2015, making the complete period of record 1951-2015.

Beginning with January 1951, 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 Pearson's 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 (2015) and starting (1951) values of the linear fit was determined to express the linear temporal trend of each variable over the 65-year period.

3. RESULTS

A total of 13 stations were identified at elevations 1000-1499 m (Figure 1) and seven stations were identified at elevations ≥ 1500 m (Figure 2). Statistically significant results from the temporal analysis were common. All significant results will be expressed in Tables 1-2 to follow. 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 a statistically significant month with the largest temporal change.

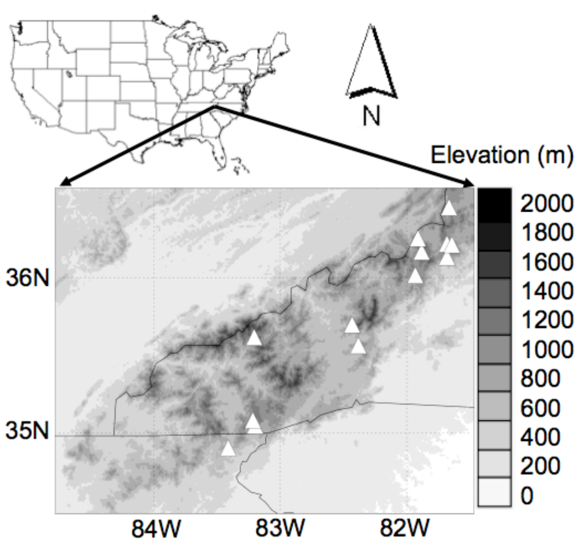

FIG. 1. Study site bounded by 34.50 to 36.55 °N and 81.50 to 84.75 °W. Elevation in meters above sea level is included in gray tones. Triangles indicate 13 station locations at an elevation of 1000-1499 m.

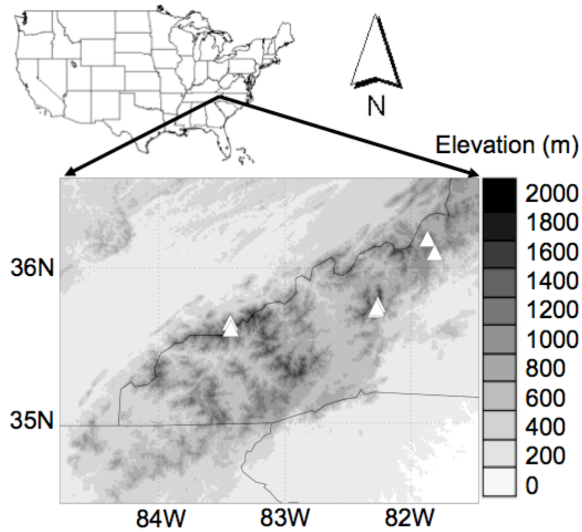

FIG. 2. Study site bounded by 34.50 to 36.55 °N and 81.50 to 84.75 °W. Elevation in meters above sea level is included in gray tones. Triangles indicate seven station locations at an elevation ≥ 1500 m.

3.1 *Temporal Trends at 1000-1499 m Elevation*

All temporal trend values for cooling degree days (CLDD), heating degree days (HTDD), the number of days in a month where minimum temperature ≤ 0 °F (DT00), the number of days in a month where minimum temperature ≤ 32 °F (DT32), the number of days in a month where maximum temperature ≥ 90 °F (DT90), and number of days in a month where maximum temperature ≤ 32 °F (DX32) are included in Table 1.

Trend values of cooling degree days in Table 1 indicate that all 12 months warmed with five warm season months having statistically significant increasing trends (April through August). In particular, July increased by more than 30 additional cooling degree days over the 65-year period (Figure 3).

Heating degree day values also illustrate warming trends for all 12 months as all trends decreased. Seven of the 12 months have a statistically significant result with significant results occurring in all seasons. Four months decreased by more than 30 heating degree days: March (Figure 4), April, November, and December.

Month	CLDD	HTDD	DT00	DT32	DT90	DX32
January	+16.15	-43.07	-0.43	-2.04	+0.41	-0.53
February	+1.11	-41.33	-0.64	-0.94	**+0.06***	+0.23
March	+0.08	**-75.70****	-0.04	**-5.19****	0.00	-0.83
April	**+8.02***	**-42.15***	0.00	**-3.21***	+0.18	+0.10
May	**+5.52***	-25.33	0.00	-0.61	0.00	0.00
June	**+18.22***	**-26.57****	0.00	-0.09	+0.10	0.00
July	**+32.61*****	-6.79	0.00	0.00	+0.11	0.00
August	**+23.04***	**-9.21***	+0.01	+0.07	+0.10	+0.04
September	+6.47	**-25.39***	+0.01	-0.24	-0.10	+0.01
October	+0.16	-33.40	0.00	**-3.48****	+0.04	**+0.22***
November	+0.05	**-62.22****	-0.07	**-4.66****	0.00	**-1.13***
December	+7.37	**-77.94***	-0.52	**-4.42***	+0.20	-1.44

Table 1: Temporal changes over 1951-2015 for stations located at 1000-1499 m elevation above sea level in the southern Appalachians. Monthly values are expressed in number of days for cooling degree days (CLDD), heating degree days (HTDD), the number of days in a month where minimum temperature ≤ 0 °F (DT00), the number of days in a month where minimum temperature ≤ 32 °F (DT32), the number of days in a month where maximum temperature ≥ 90 °F (DT90), and number of days in a month where maximum temperature ≤ 32 °F (DX32). 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.

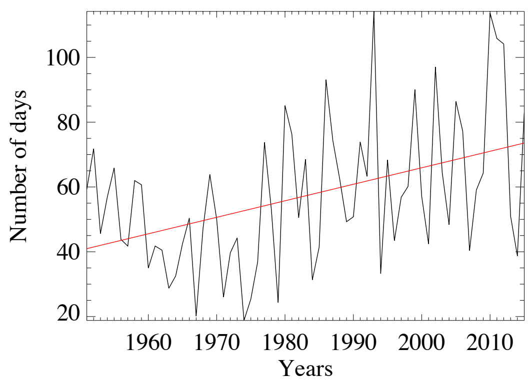

FIG. 3. Trend of cooling degree days for July (in black) for elevation of 1000-1499 m above sea level. The linear fitted line (in red) illustrates the increase of +32.61 degree days over the 1951-2015 period.

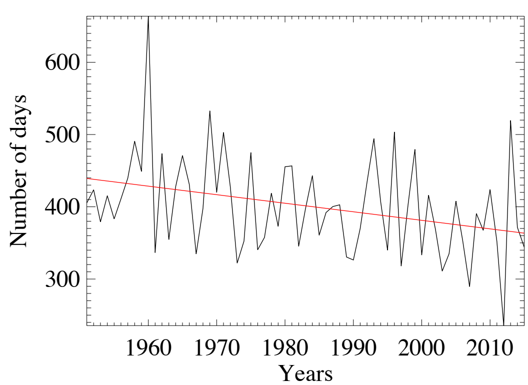

FIG. 4. Trend of heating degree days for March (in black) for elevation of 1000-1499 m above sea level. The linear fitted line (in red) illustrates the decrease of -75.70 degree days over the 1951-2015 period.

No significant trends resulted for the number of days in a month when minimum temperature was ≤ 0 °F. However, for the number of days when minimum temperature was ≤ 32 °F five statistically significant decreasing trends resulted, each indicating warming trends. The significant trends show that at least three fewer days occur in a month when minimum temperature drops to the freezing point. For the month of March the value was as much as -5.19 days (Figure 5).

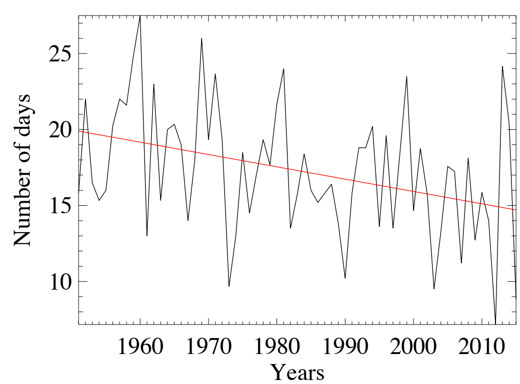

FIG. 5. Trend of number of days when minimum temperature was ≤ 32 °F for March (in black) for elevation of 1000-1499 m above sea level. The linear fitted line (in red) illustrates the decrease of -5.19 days over the 1951-2015 period.

The frequency of days when maximum temperature exceeds 90 °F is rare at elevations above 1000 m. These infrequent occurrences during February of recent years resulted in a significant increasing trend of +0.06 days (Figure 6).

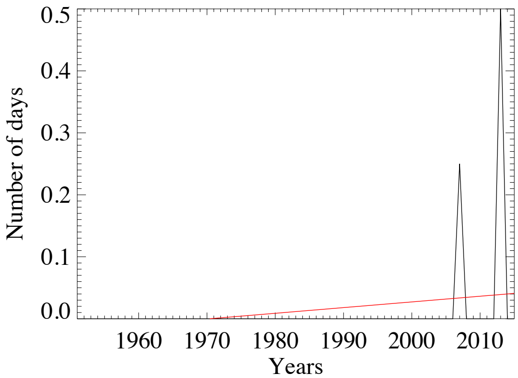

FIG. 6. Trend of number of days when maximum temperature was ≥ 90 °F for February (in black) for elevation of 1000-1499 m above sea level. The linear fitted line (in red) illustrates the increase of +0.06 days over the 1951-2015 period.

Unique results emerge for the number of days in a month when maximum temperature was ≤ 32 °F. Most months were not statistically significant. However, the autumn months of October (+0.22 days) and November (-1.13 days; Figure 7) had conflicting significant trends.

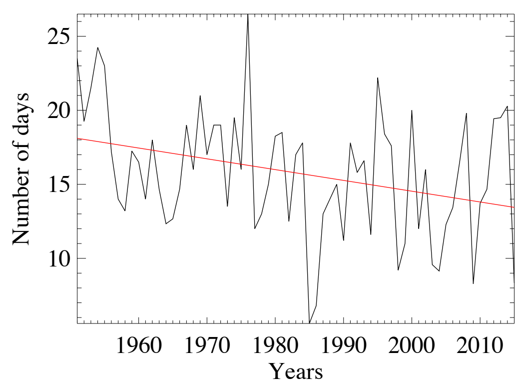

FIG. 7. Trend of number of days when maximum temperature was ≤ 32 °F for November (in black) for elevation of 1000-1499 m above sea level. The linear fitted line (in red) illustrates the decrease of -1.13 days over the 1951-2015 period.

All though the temperature variables for 1000-1499 m generally illustrate warming trends, variation in those trends is evident. Cooling and heating degree days had trends of the same sign for all months with many of those months experiencing significant trends. Results also generally indicate that fewer cold temperatures below the freezing point are occurring. For the month of the February a significant trend of more days exceeding 90 °F also occurred. The variable trends of number of days when maximum temperature is ≤ 32 °F was the only variable at the 1000-1499 m elevation range to have a significant trend indicating a cooling trend. That cool trend occurred for October.

3.2 ***Temporal Trends at ≥ 1500 m Elevation***

Temporal trend values for cooling degree days (CLDD), heating degree days (HTDD), the number of days in a month where minimum temperature ≤ 0 °F (DT00), the number of days in a month where minimum temperature ≤ 32 °F (DT32), the number of days in a month where maximum temperature ≥ 90 °F (DT90), and number of days in a month where maximum temperature ≤ 32 °F (DX32) are included in Table 2 for elevations ≥ 1500 m. Compared to the lower elevation range, fewer statistically significant results were found. Also, at the higher elevation range no values were significant at ≤ 0.001.

Similar to the lower elevation range, cooling degree days during warm season months from April through October experienced increases suggesting warming trends. Three of those months (May, June, and July) had significant values. June is included here as Figure 8 with its increase of +4.37 cooling degree days over the 65-year period.

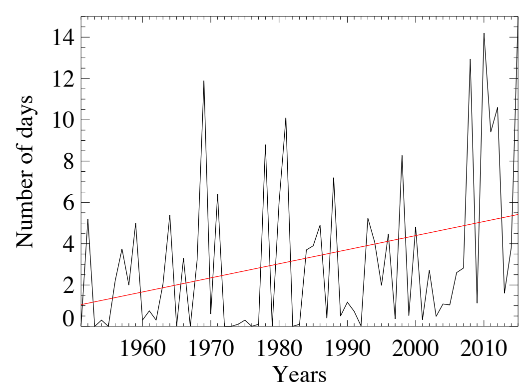

FIG. 8. Trend of cooling degree days for June (in black) for elevation of ≥ 1500 m above sea level. The linear fitted line (in red) illustrates the increase of +4.37 degree days over the 1951-2015 period.

Month	CLDD	HTDD	DT00	DT32	DT90	DX32
January	0.00	+6.11	+0.73	-1.49	0.00	+0.56
February	0.00	-2.32	-1.13	+0.30	0.00	-0.26
March	0.00	-50.03	+0.13	**-4.33***	0.00	-1.69
April	+0.09	-24.92	+0.02	-1.38	0.00	+0.07
May	**+0.84****	-18.32	+0.03	-0.01	0.00	-0.04
June	**+4.37****	**-29.64***	0.00	-0.17	+0.02	+0.06
July	**+10.36***	-21.56	0.00	+0.05	+0.02	0.00
August	+6.04	-18.01	0.00	+0.02	0.00	0.00
September	+0.60	-19.34	0.00	+0.07	0.00	+0.01
October	+0.03	-13.50	+0.01	-0.40	0.00	+0.48
November	0.00	-45.76	**-0.35***	-1.61	0.00	-0.91
December	0.00	-55.70	-0.90	-2.33	0.00	-1.99

Table 2: Temporal changes over 1951-2015 for stations located at ≥ 1500 m elevation above sea level in the southern Appalachians. Monthly values are expressed in number of days for cooling degree days (CLDD), heating degree days (HTDD), the number of days in a month where minimum temperature ≤ 0 °F (DT00), the number of days in a month where minimum temperature ≤ 32 °F (DT32), the number of days in a month where maximum temperature ≥ 90 °F (DT90), and number of days in a month where maximum temperature ≤ 32 °F (DX32). 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.

With the exception of January, all other months encountered decreasing trends of heating degree days, which is expected to coincide with increasing trends of temperatures and cooling degree days. All though most months had consistent trends, only June (-29.64 degree days) had a significant value (Figure 9).

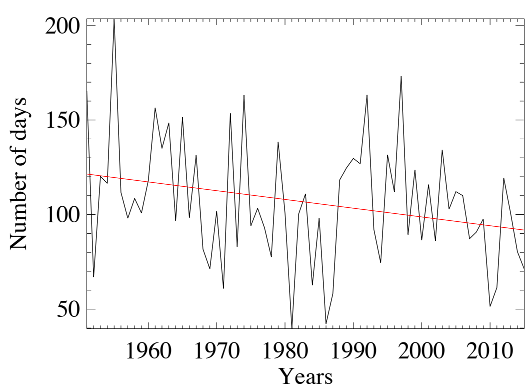

FIG. 9. Trend of heating degree days for June (in black) for elevation of ≥ 1500 m above sea level. The linear fitted line (in red) illustrates the decrease of -29.64 degree days over the 1951-2015 period.

Trends for the number of days in a month when minimum temperature was ≤ 0 °F or ≤ 32 °F were variable. During a period of warming temperatures, especially warming of minimum temperatures, it should be expected that fewer days will drop below ≤ 0 °F or ≤ 32 °F. The statistically significant values did indeed agree with that assumption. For days when minimum temperature was ≤ 0 °F, November had a decreasing trend of -0.35 days (Figure 10). March also had a decreasing trend of -4.33 days for minimum temperature dropping below ≤ 32 °F (Figure 11).

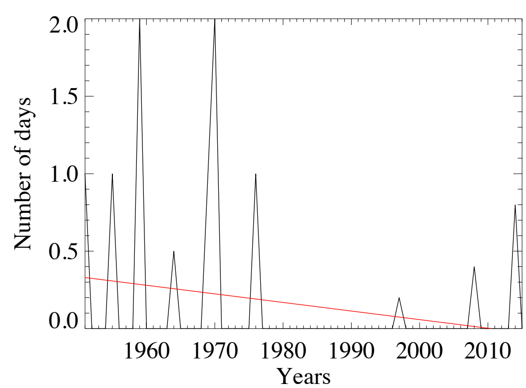

FIG. 10. Trend of number of days when minimum temperature was ≤ 0 °F for November (in black) for elevation of ≥ 1500 m above sea level. The linear fitted line (in red) illustrates the decrease of -0.35 days over the 1951-2015 period.

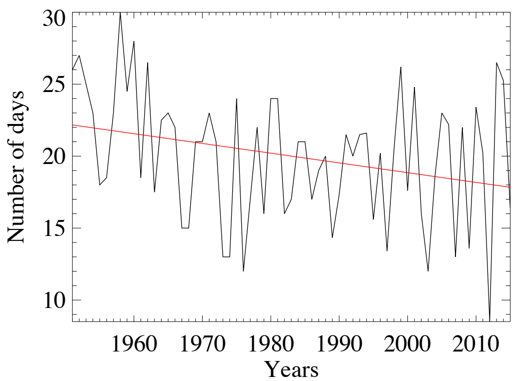

FIG. 11. Trend of number of days when minimum temperature was ≤ 32 °F for March (in black) for elevation of ≥ 1500 m above sea level. The linear fitted line (in red) illustrates the decrease of -4.33 days over the 1951-2015 period.

Above 1500 m the occurrence of temperatures exceeding 90 °F was rare. In fact, the trends were 0.00 for all months minus June and July with no significant values found. Regarding the number of days when maximum temperature fell below ≤ 32 °F, no significant correlations were present there either. However, values and variability in the trends were similar to those witnessed at the lower elevation range.

4. DISCUSSION AND CONCLUSIONS

Results presented here are focused entirely on stations located at 1000 m in elevation or higher with a total of just 20 stations existing in that range over the 65-year study period. Most stations in the region are positioned in lower elevations. Analysis of those lower stations results in decreasing temperature trends similar to those summarized by Robinson et al. (2002), IPCC (2013), and Melillo et al. (2014), especially when the start of the study period is extended back to early twentieth century. However, when considering recent decades at the high elevations during 1976-2014, significant results in Shadbolt (2016) highlight that minimum, mean, and maximum temperatures increased, especially in the 1000-1499 m elevation range. Extreme values of minimum and maximum temperatures (the coldest and hottest temperature reported in a month) were included in that study and in some cases those increases approached 14 °F (8 °C).

In this study the period of analysis was extended to 65 years (1951-2015). Similar to Shadbolt (2016), nearly all significant trends suggest warming in the region. One exception was October at elevations of 1000-1499 m for days when maximum temperature is ≤ 32 °F. In total, 20 significant results were found at the 1000-1499 m elevation range. In general, cooling degree days increased while heating degree days decreased. The number of cold nights dropping below 32 °F decreased, and the number of days when maximum temperature exceeded 90 °F increased for the month of February.

Statistically significant results were less common for stations positioned at or above 1500 m in elevation. Six significant trends were present pointing toward an increase in cooling degree days, a decrease in heating degree days, and a decrease in the number of days when minimum temperature drops below 0 or 32 °F.

Causation of cooling trends in the southeastern U.S. during the twentieth century was explored by Robinson et al. (2002). The authors uncovered a connection between warm Pacific sea-surface temperatures during El Niño events and cooler than normal temperatures in the southern states. Increased moisture and cloud cover was concluded to be responsible for decreasing mean temperature of the region. The high-elevation warming trends described here and in Shadbolt (2016) may suggest that local factors are contributing to contradicting trends compared to the rest of the southeastern region.

Upcoming research will consider the impacts of moisture and cloud cover on minimum and maximum temperature and temperature range not discussed by Robinson et al. (2002). The peaks in the southern Appalachians are low enough that snowfall does not persist throughout the year, but seasonal changes in snowfall amount may still contribute to surface temperatures at the high elevations in a similar way an ice-albedo feedback contributes in high-latitude environments.

The findings of this study provide thorough coverage of the southern Appalachians temporal temperature trends over 1951-2015. 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 over the 65-year period expressed by trends of cooling degree days, heating degree days, as well as the number of cold nights and warm days.

5. ACKNOWLEDGEMENTS

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