WINTER CLIMATE VARIABILITY IN THE SOUTHERN APPALACHIAN MOUNTAINS, 1910-2017

A Thesis
by
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Abstract

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This thesis investigates climatic variability of the winter season in the southern Appalachian Mountains and identifies the associated large-scale atmospheric forcing patterns. Recognized as an anomalous region regarding climate change, this study identifies long-term trends and variation of temperature and snowfall during climatological winter (DJF) from 1910 to 2017. The identification of several teleconnection patterns, namely ENSO, NAO, and PDO, allow for further understanding of how this region has remained a climatic anomaly. Results of this study indicate that the southern Appalachian Mountains have experienced a statistically significant long-term cooling trend since the early 20th century, with recent decades suggesting a reversal of this cooling. Snowfall is characterized by high interannual variability, with the 1960s and 1970s producing anomalously high amounts of snowfall. Several atmospheric forcing couplings are identified that align with anomalous conditions in the region. Most notably, negative temperature anomalies and higher snowfall amounts are frequently found during moderate El Niño and negative NAO seasons, with the opposite being true during strong La Niña and positive NAO winters. The

influence of these teleconnection patterns is spatially dependent, with areas east of the Blue Ridge Escarpment highly dependent on the phase of ENSO, whereas higher elevations and western slopes favor the NAO. The identification of these pattern couplings is critical to not only improving understanding of the anomalous climate of the southern Appalachian Mountains but also in enhancing seasonal forecasting and predicting future climate change in the region.

Acknowledgments

As I look forward to completing my Master's degree, I know that none of my academic accomplishments would have been possible without the unconditional support of my mom and grandparents, Helen, Judy, and Clyde, who always pushed me to dream bigger. Whether it was venturing out to survey the damage from Hurricanes Frances and Ivan, chasing severe weather in the Midwest, or staying up all night to see the first snowflakes from a winter storm, my family have always been and continues to be my biggest champions and they will never know how much I appreciate it. Their support and my passion for understanding the world around me led to Appalachian State, where I have not only grown as a researcher, but also as a person.

Before attending Appalachian State and immersing myself in climate change literature, I began my academic career at the University of North Carolina at Asheville (UNCA) where I received my B.A. in History. I appreciated the multiple opportunities the university presented me and value my time spent there doing research in the mountains where I grew up. Dr. Dan Pierce, Dr. Alvis Dunn, Dr. Eric Roubinek, and my classmates were vital to creating a positive academic atmosphere and provided me an opportunity to grow as a productive member of a larger global society. Dr. Douglas Miller also introduced me to the climate of the southern Appalachian Mountains. He has been an encouraging mentor in my academic pursuits and I will always appreciate our weekly discussions on temperature inversions on Old Fort Mountains. While my academic pursuits have shifted

since my time at UNCA, I will always value the community building experiences that the university provided me.

Following my time at UNCA, I envisioned remaining in the university environment, where important intellectual conversations regarding the issues of today are discussed freely. This ultimately led me to Appalachian State, where the transition from a humanities-based undergraduate experience to a science-based graduate program was difficult at times, but I truly believe that my multidisciplinary background enhanced my skills as a researcher. Dr. Baker Perry was an encouraging force in my academic pursuits in the Geography program and presented me with multiple opportunities to grow as a researcher and broaden the reach of my work by encouraging me to present my work both regionally and internationally. Along with presenting at the Annual Celebration of Student Research at Appalachian, I have also presented the findings of my work at the Eastern Snow Conference in Ottawa, Canada. Dr. Perry has provided a helpful hand in guiding my research and has been a constructive critic of every academic paper, presentation, and iteration of my thesis. My graduate experience at Appalachian State has been transformative, both academically and personally, allowing me to pursue opportunities and experiences that would not have been possible elsewhere.

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Lastly, I want to thank my committee members for their guidance and support in completing my thesis. They were always available to lend a helping hand in understanding complex climatic patterns, performing data analysis, and providing critical feedback. As with any thesis or academic work, the availability of data is crucial for performing meaningful analysis. We are fortunate in climate studies to have a wide range of climate databases and I would like to acknowledge several organizations that provide these data to the public. Namely, I would like to recognize the Southeast Regional Climate Center and the sister climate centers across the country for providing climate interpretation tools to citizens across the United States. I would also like to thank the National Center for Environmental Information, National Center for Atmospheric Research, and the Earth System Research Laboratory for providing the necessary climatic data needed to complete this study. The analysis from these datasets allowed me to present my results both regionally and internationally, which not have been possible without funding from the Department of Geography and Planning as well as the Office of Student Research.

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Foreword

The main body of this thesis is formatted to the guidelines for manuscript submission to the *International Journal of Climatology*, an official journal of the Royal Meteorological Society.

Introduction

The southeastern United States (SEUS) has been identified as a 20th century regional climate anomaly meaning that this region actually experienced a decline in mean annual temperatures while the majority of the planet warmed (Portmann et al., 2009; Ellenburg, 2016). The vast majority of this cooling occurred from the 1930s to the late 1970s, although the region has experienced a slight rebound in temperatures over the last few decades (Hansen et al., 2001; Kunkel et al., 2006). Some potential causes of the cooling identified in the literature include interdecadal variability (Riedel, 2006) and/or increases in aerosol production in the region (Laseter et al., 2012). Unfortunately, few studies have attempted to understand these trends in the southern Appalachian Mountains, where the topography of the region has a much greater influence over weather patterns than the surrounding low elevation locations. The lack of research in the region has made it particularly difficult to communicate the implications of climate change to a region that is among the least concerned about climate change in the United States (Howe et al., 2015).

Exhibiting the greatest topographic relief in the eastern United States, the SAM contain some of the most diverse biological, topographical, and climatological environments in the United States. These differences in climate are perhaps exhibited most clearly in the winter season where spatial variation in snowfall is immense, with some valley locations averaging less than 25 cm of snowfall and adjacent mountaintops surpassing 250 cm (Martin et al., 2015). Although few studies have investigated trends in snowfall in the SAM, declines in snowfall and snow cover have been observed in many regions of the continental United States since the start of the 20th century (Kunkel et al., 2016), with statistically significant ($p < 0.05$) decreases documented in the SEUS since 1930 (Kluver and Leathers, 2015). The

observed winter climate variability and change from other regions, along with the economic benefits that the winter season provides for many in the southern Appalachian Mountains, highlights the importance of investigating variability and change in the SAM.

Although research has generally been sparse in the SAM, studies have identified several global and hemispheric patterns that influence climatic variability. Negative temperature anomalies found in the SAM, especially in the winter season, are reinforced by negative Arctic Oscillation (AO) and North Atlantic Oscillation (NAO) patterns and mitigated by the positive phase of these patterns (Warren and Bradford, 2010). Typically, in order to produce positive snowfall anomalies in the southern U.S., a combination of a negative AO/NAO and El Niño conditions in the Pacific must be present (Seager et al., 2009). While the identification of these large-scale patterns and their expected impacts in the region are important, little research exists to understand how they have influenced the lack of long-term warming trends. Therefore, this research presents an up-to-date analysis of temperature and snowfall trends in the climatically diverse SAM. It is also the first study to identify large-scale global and hemispheric pattern couplings favorable for producing winter climate anomalies in the region.

A variety of data were obtained for analysis in this study. For each of the pre-defined climate regions, I obtained daily snowfall and temperature data for individual COOP stations from the National Center for Environmental Information's Global Historical Climatology Network (Perry, 2006). I wanted to first understand how temperature and snowfall in the winter season had changed in the southern Appalachian Mountains by individual climate regions. This was accomplished this by performing the Mann-Kendall test, a non-parametric test frequently used to identify trends in climate data. After discovering significant negative

trends in temperature and high variability in snowfall, I found it important to analyze relationships between the variability and large-scale patterns. In order to do this, winter indices of the ENSO, NAO, and Pacific Decadal Oscillation (PDO) patterns were obtained. Statistical analysis assisted in identifying the relationship of snowfall and temperature with respect to each identified global and hemispheric pattern. After establishing the strongest relationships between the identified global and hemispheric patterns in relation to climate conditions in the SAM, I coupled teleconnection patterns to identify favorable conditions for producing anomalous climatic conditions in the study.

The results of this study are critical for furthering our understanding of climatically anomalous regions globally. A significant decline in mean winter temperatures, similar to what is seen across the southeastern United States, is confirmed but the high variability in snowfall suggests the region is not seeing the drastic changes to winter conditions currently experienced in the mountain west. This study also revealed new couplings of global and hemispheric patterns that have influenced the climate of the southern Appalachian Mountains. This research can be used as a springboard for developing a deeper understanding of climate change in mountainous regions. In particular, the results of this research provide greater clarity on climatic variability and the influence of hemispheric and global patterns, which can be used to inform policymakers and the public alike about the complexities of the climate system and improve understanding of future climate change.

Winter Climate Variability in the Southern

Appalachian Mountains, 1910-2017

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Abstract

This paper investigates climatic variability of the winter season in the southern Appalachian Mountains and identifies the associated large-scale atmospheric forcing patterns. Recognized as an anomalous region regarding climate change, this study identifies long-term trends and variation of temperature and snowfall during climatological winter (DJF) from 1910 to 2017. The identification of several teleconnection patterns, namely ENSO, NAO, and PDO, allow for further understanding of how this region has remained a climatic anomaly. Results of this study indicate that the southern Appalachian Mountains have experienced a statistically significant long-term cooling trend since the early 20th century, with recent decades suggesting a reversal of this cooling. Snowfall is characterized by high interannual variability, with the 1960s and 1970s producing anomalously high amounts of snowfall. Several atmospheric forcing couplings are identified that align with anomalous conditions in the region. Most notably, negative temperature anomalies and higher snowfall amounts are frequently found during moderate El Niño and negative NAO seasons, with the opposite being true during strong La Niña and positive NAO winters. The influence of these teleconnection patterns is spatially dependent, with areas east of the Blue Ridge Escarpment highly dependent on the phase of ENSO, whereas higher elevations and western slopes favor the NAO. The identification of these pattern couplings is critical to not only improving understanding of the anomalous climate of the southern Appalachian Mountains but also in enhancing seasonal forecasting and predicting future climate change in the region.

1. Introduction

Winter climatic variability in mountainous regions is difficult to ascertain, primarily due to the complex topography and diverse climatology associated with these areas (Barry, 2008). Unfortunately, due to these challenges, research on climate change in high elevation regions has been limited, especially in the winter season, making communication of potential implications on those that live in these areas exceedingly difficult. This is particularly an issue in the southern Appalachian Mountains (SAM) of the southeastern United States (SEUS), where precipitation in the winter season is linked with a variety of synoptic patterns and the influence of orographic effects can result in large accumulation disparities across short distances (Martin et al., 2015; Sugg et al., 2016). The lack of research in the region has likely contributed to the growing skepticism towards climate science within some communities in the Appalachian Mountains, where citizens are among the least concerned about climate change in the country (Howe et al., 2015). The poor understanding of how temperature and snowfall have changed in mountainous regions limits our ability to not only effectively communicate to the public, but also to better prepare for future climate change.

Exhibiting the greatest topographic relief in the eastern United States, the SAM contain some of the most diverse biological, topographical, and climatological environments in the United States (Fig. 1). Despite the observed warming globally, the degree to which temperatures have been increasing in the SAM over the past few decades has not been as extreme as that observed in other mountainous areas of the United States (e.g., the mountain west) (Lesser & Fridley, 2016). The mountainous terrain of the SAM also plays a pivotal role in weather patterns, where orographic effects result in high spatial variability in snowfall amounts with many valley locations averaging less than 25 cm of snowfall each winter and

the adjacent mountaintops routinely surpassing 250 cm (Martin et al., 2015). While the diverse climate of the region is becoming better understood, there remains limited understanding of how large-scale global and hemispheric patterns influence the climate of the region seasonally. While lacking analysis of the high elevations and focusing the research primarily in valley locations, Hartley (1999) linked negative temperature anomalies and higher snowfall totals to the negative phase of the North Atlantic Oscillation (NAO). Improved understanding of the influence that large-scale atmospheric forcing has on temperature and snowfall can help explain the anomalous climate of the SAM, enhance future seasonal forecasting, and improve the modeling of future climate change in the region.

Characterizing winter variability in the SAM is an important element to understanding the influence that global and hemispheric teleconnection patterns have on masking the impacts of climate change on an anomalous region. The diversity of topography and climate norms in the SAM enhances the need to develop further understanding of the climatic variability in the region. Due to the importance of analyzing anomalous climate change regions, the objectives of this research are to: (1) identify variability and trends in mean winter temperature and total snowfall in the SAM and (2) classify couplings of global and hemispheric patterns that produce abnormal climate conditions in the SAM. The results of our research will provide greater clarity on climatic variability and the influence of hemispheric and global patterns, which can be used to inform policymakers and the public alike about the complexities of the climate system and inform future climate change.

2. Background and Literature Synthesis

Identified as an anomalous global climate change region, the SEUS experienced a cooling trend of mean temperatures in the 20th century (Portmann et al., 2009). Most of this cooling occurred from the 1930s to the late 1970s, with a slight rebound since that time

(Hansen et al., 2001; Kunkel et al., 2006). Although all climatological seasons experienced some decline in temperatures in the 20th century, minimum temperatures in the winter season experienced the greatest amount of cooling with a -1.5°C trend from 1920 to 1992 (Ellenburg et al., 2016). Despite this long-term decline in temperatures, evidence does suggest that there has been a recent reversal of the long-term trend, with the region experiencing a significant increase in temperatures since the 1970s (Hansen et al., 2001; Kunkel et al., 2006). While Riedel (2006) suggests decadal variability influenced the regional cooling, Laseter et al. (2012) argue that aerosols were partially responsible for at least some of the negative temperature anomalies observed in the mid-20th century.

Declines in snowfall and snow cover have been observed in many regions of the continental United States since the start of the 20th century (Kunkel et al., 2016), with statistically significant decreases documented in the SEUS since 1930 (Kluver and Leathers, 2015). Some climate models suggest that most of North America will likely see further declines in both seasonal and annual snowfall by the end of the century (Krasting et al., 2013). Paradoxically, some modeling studies indicate that the frequency and intensity of heavy snowfall events may actually increase due to these events occurring near an optimal temperature that is less sensitive to a warming global climate (O'Gorman, 2014). The number of days with snow cover in the winter season also has experienced a widespread decline in the United States, although there are anomalous regions where the length of the snow cover season has increased (Zion et al., 2011; Knowles, 2015).

Due to their location in the mid-latitudes and proximity to the Great Lakes, Gulf of Mexico, and Atlantic Ocean, the SAM are in an area ideal for the development of snowstorms throughout the winter season. Miller A and Miller B cyclones that originate in

the Gulf of Mexico before tracking along the Atlantic Coast are the primary contributors to heavy snowfall in the region (Miller, 1946; Perry et al., 2010). A variety of other synoptic patterns known to produce snowfall in the SAM includes upper-level cut-off lows, clippers, and northeastward tracking Colorado lows (Perry et al., 2010; Kelly et al., 2012). Spatially, Gulf lows contribute a majority of snowfall to eastern-facing slopes, whereas Northwest flow snow (NWFS) events contribute more than 50 percent of the annual snowfall to windward and high elevation locations (Perry and Konrad, 2006; Keighton et al., 2016).

The decline in temperatures and snowfall across the SEUS suggests there are other naturally occurring factors influencing the climatic variability in the region. Warren and Bradford (2010) suggest that global and hemispheric teleconnection patterns have been the primary driving force behind temperature fluctuations in the SEUS and SAM, with negative temperature anomalies during the cool season being reinforced by negative patterns of the NAO and mitigated by a positive NAO. This is particularly the case in the Great Smoky Mountains National Park, where Lesser and Fridley (2016) found that the NAO influences mean seasonal temperatures throughout the year. Despite having a weaker relationship with temperature than the NAO, the El Niño-Southern Oscillation (ENSO) also has an association with temperature in the SAM, with El Niño (La Niña) conditions favoring lower (higher) winter temperatures (Riedel, 2006).

These large-scale atmospheric forcing patterns also have strong relationships with snowfall in the SEUS, including in the SAM. Hartley (1999) found that snowfall in parts of the mountains shares a strong inverse relationship with the NAO and that the association between them weakens further south and east of the mountains. The anomalous negative NAO phases of the late 2000s have been identified as a driver of the increased snowfall

amounts seen along the eastern seaboard of the United States during the 2009-2010 and 2010-2011 seasons (Cohen et al, 2010; Osborn, 2010; Chang et al., 2012). ENSO also plays a role in climatological winter precipitation, with winter seasons associated with El Niño (La Niña) patterns favoring above (below) average precipitation (Mo and Schemm, 2008). However, this relationship does not necessarily translate to more snowfall for the SAM as El Niño conditions in the winter season can also influence the 500-hPa pattern, routinely leaving the SAM without the necessary cold air to produce snowfall (Perry, 2006).

The interpretation of oscillation couplings is important for identifying potential impacts on weather regionally. Typically, in order to produce positive snowfall anomalies in the SEUS a combination of a negative NAO and El Niño conditions in the Pacific must be present (Seager et al., 2010). However, it is far more frequent to have these patterns not be in unison with their expected impacts regionally, ultimately causing one oscillation to act as a modulating force. This was the case with the 2010-2011 winter season in the eastern U.S and SAM, where La Niña conditions were expected to produce warmer and less snowy conditions in the region. However, despite the presence of La Niña, a persistently negative AO/NAO pattern produced one of the coolest and snowiest years on record in the eastern United States (Liu et al., 2012). Rather than emphasize research on one particular oscillation, it is important to identify how the interaction of these patterns influences expected regional outcomes.

3. Data and Methods

Study Area and Climate Regions

Stretching from Georgia to West Virginia and encompassing the Black, Blue Ridge, and Great Smoky Mountains, the study area is known to be one of the most climatologically,

ecologically, and topographically diverse regions in the United States. Elevations within the SAM reach their peak at 2,037 m on Mt. Mitchell, the highest point east of the Mississippi River. Using previously defined climate regions (Perry, 2006; Sugg et al., 2016), the SAM were into 14 unique climate regions based on similarities in climate normals, elevation, and topography (Fig. 1). These climatic regions were further defined by grouping National Weather Service (NWS) Cooperative Observer stations (COOP) by similarities in snowfall totals.

There are a wide range of topographic and climatic differences across each of the identified regions in the SAM. The Southwest Mountains (Region 2) and Southern Foothills (Region 3) are found along the southernmost extent of the SAM, making up the mildest regions in the study area. The Great Smoky Mountains (Region 4) contains many high elevation locations and is in a prime location to receive NWFS events. The Southern Blue Ridge (Region 5) contains a mixture of high mountain peaks and low elevation valleys. The High Country (Region 8) is home to many of the interior high elevations, as well as a primary location for the region's ski industry. The Central Foothills (Region 9) are located to the southeast of the Blue Ridge Escarpment and experience a sharp decline in elevation. To the west of the highest peaks in the region are the Northern Tennessee Valley (Region 7) and Southern Tennessee Valley (Region 1), which are characterized by their low terrain when compared to the surrounding regions. The Central (Region 12) and Southern (Region 6) Plateaus make up the westernmost extent of the SAM, and have generally higher elevations than their valley counterparts. At the northern extent of the study area, the Northern Plateau (Region 13) exhibits similar temperature norms to the High Country. In Virginia, the New River Valley (Region 10) and the Northern Foothills (Region 11) have cooler climates than

the foothills to their south. Lastly, the High Peaks (Region 14) is not continuous, but rather highlights all locations within the study area > 1,200 m (4,000 ft) in elevation, which can average 1,700 percent more snowfall from NWFS than other lower elevation locations within close proximity (Perry and Konrad, 2006).

Due to these topographic differences, the SAM experiences considerable variability in climate normals by region. For example, mean winter temperatures (DJF) between 1987 and 2017 varied by nearly 6.7ºC among the Southern Foothills, High Country, Central Foothills, and High Peaks. The lowest mean winter temperatures are found in the High Peaks (Region 14; -0.8ºC), with increasingly higher averages in the High Country (Region 8; 1.4ºC) and Central Foothills (Region 9, 4.2ºC). The highest average winter temperatures are found along the southernmost extent of the study area, in the Southern Foothills (Region 3; 5.9ºC). Similar patterns for snowfall are found in the SAM over the same time period, with the High Peaks (Region 14; 104 cm) averaging nearly 18 times as much snowfall than the Southern Foothills (Region 3; 6 cm). It is also important to identify the variability experienced within each climatic region. This is most pronounced in the Southern Blue Ridge (Region 5), where annual liquid precipitation at Lake Toxaway totals 2,329 mm, whereas less than 80 km to the northwest, Asheville averages 947 mm annually. Differences like these highlight the importance of analyzing the SAM regionally, as it allows us to more accurately reveal the spatial variability of trends and potential relationships between global patterns.

Temperature and Snowfall Records

We define the winter season as the climatological winter months of December, January, and February. The relationships between temperature, snowfall, and global/hemispheric patterns are strongest during this period and weaken with the transition to

spring (Hartley, 1999). The analysis period spans from December 1910 to February 2017. For each of the climate regions, we obtained daily snowfall and temperature data for individual COOP stations from the National Center for Environmental Information's Global Historical Climatology Network (Fig. 2). These data undergo thorough quality checks from both the National Weather Service and the National Center for Environmental Information, ensuring the quality and usefulness in this study. Data from these stations were collected by volunteer observers, which poses some concern regarding the considerable challenges in accurately measuring snowfall, the validity of some datasets, and observer error sometimes influencing snowfall totals (Robinson, 1989; Doesken and Leffler, 2000; Rasmussen et al., 2012). In order to maintain an accurate representation, we excluded data from stations with less than 90 percent completeness during the winter season.

We calculated mean temperature and snowfall for each region by averaging the recorded climate variables from each of the region's COOP stations. The High Peaks and Central Plateau only have reliable data records since the 1930s with sporadic gaps, limiting the analysis of these regions comparatively to the other 12. There are several stations with missing data, with the average number of years with adequate data for the 12 regions being 103 years. The technique of averaging each of the climate region's weather stations helps to alleviate some of the issues that would be prevalent with missing or inaccurate data at individual COOP stations. This allows for a better in-depth analysis of regional trends and variability rather than local patterns of change.

Global and Hemispheric Patterns

Identified as recurring and persistent large-scale patterns of pressure and circulation, global and hemispheric teleconnection patterns have a profound impact on weather

conditions regionally. We obtained winter indices of the ENSO and Pacific Decadal Oscillation (PDO) patterns by averaging the December, January, February (DJF) monthly values. We used the Niño 3.4 SST Index anomaly to identify patterns of ENSO, which is identified by taking the average SST from 5S-5N and 170-120W (https://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/). A seasonal value found to be ≤ -0.5 implied that the winter season was associated with a La Niña pattern, values ≥ 0.5 indicated a winter pattern associated with El Niño, and values that fell between -0.5 and 0.5 indicated a neutral phase of ENSO. Using SST anomaly data poleward of 20N in the Pacific basin, the average DJF index of the PDO represents two distinct phases. Positive (negative) DJF indices for the PDO indicated a warm (cool) phase for that winter season (https://www.ncdc.noaa.gov/teleconnections/pdo/).

We also investigated the influence climatic conditions in the Arctic can have on variability in the SAM. The NAO, despite its close association with the Arctic Oscillation (AO), is more relevant for investigating variability in North America than the AO (Ambaum et al., 2001). Due to the close relationship between the patterns and the prevalence for using the NAO in researching variability in the NH, we excluded the AO from analysis. We obtained the DJF indices of the NAO from the National Center for Atmospheric Research (NCAR) principal component (PC)-based dataset, which tracks the seasonal movements of the Icelandic low and Azores high (Hurrell and Deser, 2009; NCAR, 2017). For the purpose of our study, any averaged negative (positive) values found in a given season for the NAO translate to a seasonal pattern dominated by the negative (positive) phase of the pattern.

Trend Analysis

Before identifying trends in our time series, we first investigated any autocorrelation that corresponded to the time series of the winter climate data. After finding no issues with autocorrelation in our datasets, we used the Mann-Kendall test to identify trends in mean winter temperature and seasonal snowfall totals for each of the climatic regions. We used the Mann-Kendall nonparametric test due to the non-normal distribution of the data. A negative (positive) *tau* statistic indicated a descending (ascending) trend. The significance level for these tests were set at $p < 0.05$. In order to better verify these trends, we also identified outliers and potential weights on the trend by removing seasons that were found to be more than two standard deviations away from the mean. In all, eleven winter seasons met the outlier criteria of having been more than two standard deviations away from the 1987-2017 mean. Along with identifying trends in snowfall between 1910 and 2017, we also found it important to recognize any potential recent changes to the long-term trend by identifying changes over the past 50 years.

Identifying Relationships

Using Spearman's rank correlation, we identified the relationship of temperature and snowfall with respect to the identified global and hemispheric patterns of each climate region and tested for significance at p=0.05. In order to better identify relationships between each of the global and hemispheric teleconnection patterns, temperature, and snowfall, we used the Mann-Whitney hypothesis test. In conducting the Mann-Whitney tests, we found differences in the winter climate based on the phases of each pattern. For the NAO, we isolated winter temperature and snowfall based on positive or negative phases of the patterns. Similarly, for the PDO, we grouped the climatic variables based on the warm and cool phases of the

patterns. In regards to ENSO, we removed neutral phases of the pattern, and grouped seasonal conditions based on El Niño and La Niña phases. We further separated winter seasons by upper and lower quartiles of each pattern identified to have influence on the climate of the SAM. This allowed us to gain a better perspective of differences in temperature and snowfall during the most and least favorable patterns of each naturally occurring forcing analyzed in this study.

After establishing the strongest relationships between the identified global and hemispheric patterns in relation to climate conditions in the SAM, we coupled patterns in order to identify favorable conditions for producing anomalous climatic conditions in the study area. For example, we identified every winter season that was associated with –NAO and +PDO patterns, which are favored to produce anomalously cool and snowy conditions in the SAM. We then compared these seasons to those associated with less favorable +NAO and –PDO conditions. We made similar comparisons between seasonal combinations of the NAO and ENSO, as well as the PDO and ENSO. We tested the significance of the differences of snowfall and temperature based on these pattern couplings through independent-sample t and Mann-Whitney U tests.

We analyzed winter temperatures and snowfall in the SAM relative to the strength of ENSO and the phase of the NAO and PDO. Using similar techniques implemented by Jia and Ge (2017), we categorized El Niño (La Niña) events based on the particular NAO and PDO phase. Strong El Niño (La Niña) events have values > 0.8 (< -0.8) and moderate El Niño (La Niña) events that have values > 0.5 and < 0.8 (< -0.5 and > -0.8). Based on the classifications outlined by Jia and Ge (2017), we identified 13 moderate El Niño events, 12 moderate La Niña events, 19 strong El Niño events, and 20 strong La Niña winter seasons.

4. Results

Trends in Temperature

The results of the Mann-Kendall test reveal that a majority (12/14) of the regions within the SAM have experienced a long-term decline in mean winter temperatures since 1910 (Fig. 3). The significance of this cooling trend is very much spatially dependent, with regions found along the eastern and southernmost extents of the SAM exhibiting significant ($p < 0.05$) negative trends in mean winter temperature. Although the westernmost regions of the SAM also exhibit cooling decrease in mean winter temperatures, the decline is not significant in nature. Even after removing the highly anomalous 2009-2010 winter season, which was more than two standard deviations away from the long-term mean, the cooling of mean winter temperatures is still evident. The High Peaks and Central Plateau are the only regions in our study area that have experienced an increase in mean winter temperatures (1931-2017), although the lack of data in these regions could influence this finding.

Higher winter temperatures dominated the early 20th century in the SAM with nine of the ten warmest winter seasons on record in the region having occurred before 1960. The 1931-1932 winter season, the warmest on record, averaged 8.0°C for DJF, nearly 4.7°C higher than the 1987-2017 normal mean winter temperature of 3.3°C. The decrease in winter temperatures culminated during the 1960s and 1970s, with the 1977-1978 winter season recording a mean temperature of -0.4º C region-wide and stands as the coldest on record for 11 of the regions. This sort of anomalous negative mean seasonal temperature was common in the 1960s and 1970s, with 14 winter seasons during those decades averaging lower mean winter temperatures than the 1987-2017 climatological normal. In stark contrast to this, the 1920s and 1930s recorded only three years with mean winter temperatures below normal.

Although the long-term record indicates cooling in the study area, analysis of seasonal winter temperatures in the SAM since 1967 suggest a reversal in temperature trends for some of the climatic regions. 30% of the identified regions exhibit a significant ($p < 0.05$) positive trend in mean winter temperatures over the past 50 years. However, a majority of the SAM exhibit no discernable trend over the last half-century, with regions like the High Peaks and Great Smoky Mountains indicating high interannual variability in winter temperatures. Highlighting the variability of more recent winter seasons, 58% of seasons between 1980 and 2017 have experienced mean winter temperatures higher than the 1951-1981 normals (2.9ºC). Despite the 2016-2017 winter season finishing with the highest mean temperatures (5.7ºC) observed in the SAM since 1956-1957, there have been several years of anomalous negative temperature anomalies, with the 2009-2010 (0.3ºC) and 2010-2011 (1.2ºC) winter seasons finishing as two of the coldest on record for all regions.

Variability in Snowfall

Unlike temperature, there are no discernable trends in snowfall throughout the SAM. Since the early 20th century, the region has experienced high interannual variability in seasonal snowfall totals. Despite the lack of significant trends, the Mann-Kendall analysis does show that a majority of eastward-facing slopes and southern regions have experienced a general decline in snowfall over time, whereas most high elevation and westward-facing climatic regions exhibit non-statistically significant increases in snowfall amounts (Fig. 3).

The greatest amount of snowfall for the region occurred during the 1917-1918 winter season, where the SAM averaged 70.2 cm. This is in contrast to the 1931-2932 winter season, where the SAM averaged 1.2 cm of snowfall accumulation region-wide. Similar to temperature, snowfall in the 1960s and early 1970s was highly anomalous, with snowfall

between December 1962 and February 1972 averaging 39.7 cm across the SAM, with the High Country averaging 71.6 cm over the same time period. Comparatively, the 2000s experienced nearly half as much snowfall, with the High Country averaging only 34.4 cm of snowfall between December 1999 and February 2008. This large discrepancy is apparent throughout the SAM, with the region as a whole averaging 17.5 cm during the 2000s.

Snowfall totals over the past 50 years have seen more impressive changes, with nearly half of the regions identified in this study experiencing significant declines in snowfall according to the Mann-Kendall analysis ($p < 0.05$). Most notably, those located along the southernmost extent of the study area have experienced the greatest decline in snowfall. Between December 1999 and February 2008, snowfall in the Southern Blue Ridge and Central Foothills averaged less than half of their 1951-1980 normal snowfall. Northern regions and those favored to receive NWFS have little identifiable trend in seasonal snowfall amounts over the same period.

Influence of the North Atlantic Oscillation

The results of the Mann-Whitney test and spearman's rank correlation indicate that for all 14 regions within the SAM, seasons associated with predominantly negative NAO are significantly ($p < 0.05$) cooler and snowier than positive NAO winters (Fig. 4). Differences in temperature dependent on the phase of the NAO are evident throughout the SAM, with winter seasons associated with a predominantly negative NAO pattern favoring negative temperature anomalies. Although the relationship between the NAO and snowfall is strong throughout the SAM, the strength of the inverse association is spatially dependent. The relationship between snowfall and the NAO is strongest in the High Peaks, High Country, and Northern Plateau, all of which receive a majority of annual snowfall from NWFS events.

The association between the NAO and snowfall, while still significant, weakens considerably east of the Blue Ridge Escarpment and along the southernmost extent of the study area (Fig. 4). Despite the spatial variability in the strength of the relationship, the highest snowfall totals in the SAM frequently align with predominantly negative NAO winters. Such was the case in the 2009-2010 winter season; where every region experienced snowfall totals exceed the 1987-2017 climatological norm.

Influence of the Pacific Decadal Oscillation and El Niño Southern Oscillation

Similar to the NAO, all 14 regions in the SAM experience significantly ($p < 0.05$) lower mean winter temperatures during the warm phase of the PDO (Fig. 4). The relationship between the PDO and temperature is strongest in high elevation regions like the High Country, Northern Plateau, and High Peaks and is considerably weaker in foothill regions. Unlike temperature, there is a noticeable spatial component to the differences in snowfall dependent on the phase of the PDO. Although the positive phase of the PDO favors heavier snowfall in the western regions, areas favored to receive a majority of their snowfall from Miller systems (Great Smoky Mountains, Central Foothills, New River Valley, Northern Foothills) do not exhibit these differences.

Mean winter temperatures in the SAM differ significantly ($p < 0.05$) according to the phase of the ENSO pattern, with El Niño conditions in the winter season being commonly associated with negative temperature anomalies, while higher temperatures were more prominent during La Niña patterns. Despite this finding, we also discovered, through our spearman's rank correlation analysis, that the relationship between ENSO and mean winter temperatures in the SAM is considerably weaker than with the NAO and PDO. This finding was heightened when identifying the association between ENSO and snowfall in the region.

Unlike the NAO and PDO, only east-facing slopes and southern regions exhibit significant relationships with snowfall dependent on the ENSO phase (Fig. 4). Despite the use of ENSO in seasonal forecasting, our results found that only five regions within the SAM (The Southwest Mountains, Southern Foothills, Southern Blue Ridge, Central Foothills, and High Peaks) exhibited statistically significant ($p < 0.05$) relationships between temperature and snowfall with respect to ENSO. It is important to note that, with the exception of the High Peaks, these regions accumulate a majority of their snowfall from Miller systems, while the regions identified to have little relationship with ENSO receive a majority of snowfall from NWFS events.

Coupling of Global and Hemispheric Patterns

Winter temperatures in the SAM are highly dependent on the seasonal phases of several global and hemispheric teleconnection patterns. Differences in temperatures are highlighted the most during opposing phases of the NAO and PDO patterns. Mean winter temperatures in the SAM averaged 2.0°C warmer during +NAO seasons when compared to identified –NAO winters. Similarly, the winter seasons associated with –PDO patterns averaged 1.8°C warmer than +PDO seasons (Table 1). These differences in temperatures were magnified in northernmost extent of the study area and the High Peaks, where temperatures averaged 2.2-3.0°C lower during –NAO winters and 1.5-2.0°C lower during +PDO seasons. Our results indicate that there is far less difference in temperature based on the seasonal conditions of the ENSO pattern, with a slight prevalence for higher temperatures during La Niña seasons.

The SAM averaged 2.2 times as much snowfall during −NAO phases and 1.8 times more snowfall during +PDO seasons (Table 2). Spatially, the southern extent of the SAM

experienced the greatest difference in snowfall dependent on the phase of the NAO, with the Southern Tennessee Valley, Southwest Mountains, and Southern Foothills averaging 3 to 4 times as much snowfall during –NAO phases. Snowfall in the High Peaks is likely to be more extreme in the negative phase of the NAO with the region averaging 143 cm of snowfall during this favorable pattern. Unlike the NAO, differences in snowfall amounts dependent on the phases of the PDO and ENSO were spatially dependent, with eastern and low elevation regions experiencing more snowfall during El Niño and +PDO seasons (Table 2).

NAO and the PDO

Temperatures in the SAM during –NAO/+PDO seasons averaged 2.2°C lower than the 4.5ºC associated with +NAO/–PDO seasons (Fig. 5). We also found that temperatures during –NAO/–PDO seasons (2.9ºC) averaged 0.9°C lower than +NAO/+PDO seasons (3.8ºC), indicating that the negative phase of the NAO can overcome the cool pattern of the PDO and produce negative temperature anomalies in the SAM. Differences in temperature based on the combination of the NAO and PDO seasonal patterns is consistent throughout the SAM, which highlights the importance these combinations play over a large regional scale.

Winter seasons associated with –NAO/+PDO patterns also produce anomalously high snowfall, with the SAM averaging 34.7 cm, more than double the amount seen during +NAO/–PDO winters where average seasonal snowfall is 17.0 cm. These results are consistent throughout the SAM, with the greatest statistically significant differences seen in regions favorable to receive snowfall from both Miller Systems and NWFS. Analysis of counteracting phases of the NAO and PDO also revealed the importance of the NAO for snowfall within the SAM, as –NAO/–PDO patterns produced on average 1.5 times more

snowfall than +NAO/+PDO events across the region. This finding is amplified in western and high elevation regions, like the High Country, which averaged 61 cm of snowfall during –NAO/–PDO patterns and less than 42 cm during +NAO/+PDO patterns.

NAO and ENSO

Even though the relationship between temperature and ENSO was not as strong as with the PDO, the ENSO pattern varies more regularly than the PDO making the interpretation of their seasonal interaction critical. Temperatures during the –NAO/El Niño pattern averaging 2.2°C and +NAO/La Niña patterns averaging 4.4ºC, a 2.2ºC difference (Fig. 6). These differences are evident throughout the study area, with regions like the Northern Plateau routinely experiencing mean winter temperatures below freezing during –NAO/El Niño seasons and mean winter temperatures rarely below 0ºC during La Niña/+NAO patterns.

Typically, El Niño favors negative temperature anomalies in the SEUS and La Niña favors positive temperature anomalies, but coupling El Niño with a +NAO phase and La Niña with –NAO conditions reveals that temperatures in the SAM averaged 0.7ºC lower during –NAO/ La Niña (2.9ºC) patterns than during +NAO/El Niño (3.6ºC) patterns. This is true for all fourteen regions, with the High Peaks and Northern Plateau seeing the greatest difference in mean winter temperature. The neutral phase of ENSO also plays an important role on the climate of the SAM. Comparing –NAO/neutral patterns (2.8ºC) to +NAO/neutral patterns (4.5ºC) helps illustrate the importance of the NAO in the region.

Snowfall was more extensive in the SAM during –NAO/El Niño winters, with this seasonal combination of patterns averaging more than 36.2 cm. In stark contrast to this, snowfall during the +NAO/La Niña patterns, averages only 15.9 cm, which is 20.3 cm less

than what is seen during the more favorable –NAO/El Niño season (Fig. 7). Highlighting the importance of the NAO for the SAM as a whole, a majority of the identified regions experience more snowfall during –NAO/La Niña patterns when compared to the +NAO/El Niño seasons (Fig. 7). This is true for all of the identified regions, except for those found east of the Blue Ridge Escarpment and along the southernmost extent of the SAM, where difference in snowfall dependent on the pattern couplings were minimal.

–NAO/neutral ENSO seasons (33.8 cm) experience nearly double doubling the amount of snowfall seen during +NAO/neutral ENSO winters (18.4 cm). Warm neutral ENSO winter seasons coupled with the –NAO produce nearly 2.5 times as much snowfall (38.7 cm) as that seen during warm neutral ENSO winters coupled with a +NAO (16.1 cm). Highlighting the importance of the –NAO on snowfall in the SAM, –NAO/cool neutral ENSO patterns averaged 33.7 cm compared to the 20.9 cm seen during the average +NAO/cool neutral ENSO seasons. Our results illustrate the spatial complexity of this mountainous region, with the foothill regions having much more dependence on favorable Pacific patterns for producing higher amounts of snowfall (Fig. 8).

PDO and ENSO

In the SAM, there are no significant ($p < 0.05$) differences in mean winter temperature during strong El Niño events dependent on the phase of the PDO, with strong El Niño events associated with a +PDO registering only 0.3ºC warmer than with –PDO events. However, mean winter temperatures in the SAM during moderate El Niño events are significantly different ($p < 0.05$) with seasons associated with a +PDO pattern averaging 2.4ºC lower than winters dominated by moderate El Niño and –PDO conditions. These findings were evident throughout the study area, with the greatest temperature difference

found along the western and high elevation regions. No significant differences were found when analyzing La Niña events in the winter season with strong La Niña/–PDO patterns averaging 0.7ºC warmer than strong La Niña/+PDO seasons (Fig. 9).

There are no statistically significant differences in snowfall totals during strong El Niño events dependent on the phase of the PDO, with strong El Niño events associated with the –PDO averaging 0.8 cm more than strong El Niño/+PDO events. However, the difference in snowfall amounts with moderate El Niño events were significant ($p < 0.05$) in the SAM with moderate El Niño events associated with +PDO phases nearly doubling the snowfall amounts found in the region with average seasonal totals of 41.2 cm compared to the 21.0 cm found during moderate El Niño/–PDO patterns. These findings are evident throughout all 14 climate regions, with the greatest difference existing between snowfall totals found along the western regions and southernmost extent of the SAM, with the Southern Tennessee Valley seeing 4.1 times as much snowfall during +PDO/moderate El Niño events than –PDO/moderate El Niño seasons.

Although snowfall totals are below average, strong La Niña events coupled with –PDO patterns averaged 20.2 cm compared to strong La Niña seasons paired with a +PDO pattern averaging 18.1 cm, both less than that experienced during strong El Niño events (Fig. 9). Notably, the comparison of moderate La Niña events dependent on the phase of the PDO was less impressive than that of moderate El Niño events. Moderate La Niña winters coupled with a +PDO pattern amount to 1.3 times the amount of snowfall than moderate La Niña winters coupled with a –PDO. Similar to moderate El Niño events, there was a spatial component to differences in snowfall based on moderate La Niña winters. In western and high elevation regions, snowfall during La Nina winters accumulated 1.25 o 1.5 times as

much during +PDO winters than –PDO seasons. These differences decreased in eastern foothill regions.

Unique Patterns

Knowing that the greatest temperature differences in the SAM are experienced during moderate ENSO events, we also found mean winter temperatures during –NAO/+PDO/moderate El Niño seasons (1.0ºC) and +NAO/–PDO/moderate La Niña (4.6ºC). These differences were evident throughout the study area, with the Southwest Mountains region experiencing 4.3ºC lower conditions during the more favorable –NAO/+PDO/moderate El Niño periods. Temperature variances were not as extreme along the southernmost and eastern extent of the study area, but still averaged 2.0-2.5ºC different dependent on the associated pattern. Snowfall amounts during –NAO/+PDO/moderate El Niño seasons (42.8 cm) exhibit similar differences with the +NAO/–PDO/moderate La Niña seasons averaging less than 15.7 cm. The High Country averaged less than 28.5 cm of snowfall during the less favorable grouping of the global patterns but experienced 2.7 times as much snowfall during the more favorable phasing group, averaging more than 76.8 cm. While differences in snowfall amounts are apparent throughout the study area, the largest are found along the eastern and southernmost extent of the study area. The Southern Foothills, Southern Blue Ridge, and Great Smoky Mountains experienced 4-7 times the amount of snowfall during favorable phases of the teleconnection patterns.

5. Discussion

The analysis of trends and relationships between the winter climate of the SAM and large-scale global and hemispheric patterns reveals the spatial complexity of the region in regards to climatic patterns. A majority of the regions in the SAM have seen a decline in

mean winter temperature since the early 20th century. The more recent warming of winter temperatures have suggested a reversal of the long-term cooling trend, but this warming can be more correctly categorized as a return to pre-1960 normals, as the SAM have yet to experience consistent warmth in winter that was commonly seen in the 1920s and 1940s. Interestingly, our results show there are no significant trends in snowfall throughout the region despite the regional decline in mean winter temperatures since 1910. There are several possibilities for our findings. First, there are a number of complexities associated with the development of snow in mountainous regions, where the sufficiency of cold air, moisture availability, and proper lifting mechanisms are necessary to produce snowfall. Second, in mountain environments snowfall density can have a substantial influence on totals, as the same liquid equivalent precipitation can produce large differences in measurable snowfall across the region (Roebber et al., 2003). Third, there could be unseen changes in the lower troposphere, where the presence and strength of a warm nose can often mean the difference between snow and rain in the SAM (Perry et al., 2010). If temperatures in the warm nose rise above 0ºC, snow hydrometeors are more likely to melt, reaching the surface as a mixture of sleet and freezing rain (Bell and Bosart, 1988). Fourth, the track of storms, as well as the frequency of cold-air damming events could also play a role in the regional variability we see in snowfall trends compared to what we are seeing with temperature (Ellis et al., 2017).

Large-scale atmospheric circulation and forcing patterns have a considerable impact on the winter climate of the SAM, with the ENSO, NAO, and PDO all having significant relationships with temperature and snowfall in the region. Despite previous research inferring such relationships, our study shows that there is a unique spatial component to these

associations. Unlike the NWFS-favored regions, eastward-facing slopes and foothill locations favor ENSO in determining seasonal snowfall amounts. One explanation for these spatial differences are the synoptic patterns commonly associated with snowstorms in the SAM. For the eastern regions and foothill locations, gulf low storms, such as Miller A systems, are the dominant contributor to snowfall amounts and are much more prominent during El Niño patterns (Kluver and Leathers, 2015). While western regions and high elevation locations also benefit from Miller storms, a majority of the annual snowfall seen in these areas comes from NWFS events (Perry et al., 2007). The negative phase of the NAO is known to enhance the blocking high near Greenland that traps troughs along the East coast of the United States, which in turn entrenches cold air at lower levels, making conditions suitable to produce NWFS off the Great Lakes (Notaro et al., 2006; Seager et al., 2010; Cohen et al., 2014).

The rapid warming of the Arctic, also known as Arctic Amplification (AA), may be influencing the winter climate of the mid-latitudes, potentially increasing the amount of extreme weather (Francis and Vavrus, 2012; Cohen et al., 2014; Screen, 2014). Cohen and Entekhabi (1999) linked AA to increases in Siberian snow cover and extreme periods of negative AO and NAO patterns. Similarly, research has linked an increase in the phenomenon known as sudden stratospheric warming and the Quasi-Biennial Oscillation (QBO) to recent winter extremes in the NH (Cohen et al., 2009; Scaife et al., 2014). Martin (2015) found that the 850-hpa wintertime cold pool has contracted over the past half-century at a similar rate to the decline of February Arctic sea ice extent. This is important to note due to the lagged relationship shared between Arctic sea ice extent and snowfall in the conterminous United States (Kluver, 2017). These identified changes in the Arctic could lead

to more consistent periods of negative NAO and AO patterns in the winter season, which in turn would not only favor a continued cooling trend in the SAM but may also result in more seasons with snowfall and temperature extremes.

The lack of data in higher elevations and the poor spatial coverage of observations in the SAM is a concern and a limitation of our study. Data on snowfall in the SAM are less extensive than those found on temperature, with entire months and seasons missing from several stations. This is especially a problem in the western extent of the study area and high elevation locations during high impact events and seasons, such as the 1960s, making results harder to interpret in some areas. Whereas our study accounted for missing data by only including stations with only 90 percent coverage of the winter season to be included in analysis, human error and improperly sited weather stations are commonly known problems with COOP station data and should also be recognized (Davey and Pielke 2005; Fall et al., 2011). It is also important to note that instrumentation used in measuring temperature has changed throughout time, which has been known to cause slight shifts in how data is recorded although these changes have not influenced the overall climate signal (Menne et al., 2010).

Despite the strength of the relationships found in this study, it is important to recognize prominent irregularities. Most notably, the relationship between the NAO and temperature begins to falter in the 1990s, with an increasingly positive NAO not corresponding to increasing positive temperature anomalies. This again becomes a noticeable irregularity in the 2013-2014 and 2014-2015 winter seasons where the NAO is highly positive but negative temperature anomalies exist (Fig. 10). One explanation for these abnormalities in recent years could be that the influence of the NAO is most influential

during its negative phase, as can be seen during the 2009-2010 and 2010-2011 winter seasons, whereas during the positive phase of the NAO, the favorable patterns of the ENSO or PDO may still produce anomalous conditions.

6. Summary and Conclusions

In this study, we analyzed long-term regional climate data along with several global and hemispheric teleconnection patterns to improve understanding of the winter climate in the SAM. Our analysis shows that the SAM have seen high interannual variability in snowfall, with a majority of the region seeing a long-term decline in temperature. Recent years and decades have exhibited more volatility, with general warming since the mid-1970s. We also identified several factors that help explain winter climate variability in the SAM. First, the phase of the NAO exhibits a significant relationship with temperature and snowfall for all the climatic regions of the SAMs. Winter seasons dominated by the negative phase of the NAO favor negative temperature anomalies and heavier snowfall for the region, with the inverse being true for years with stronger positive phases of the NAO. Second, the warm phase of the PDO often corresponds to lower temperatures and snowier conditions in the SAM. Third, El Niño events favor negative temperature anomalies and more snowfall, but the relationship is not as spatially coherent as with the NAO and the PDO. Many lower elevations within the study area and those favored to receive snowfall from Miller systems have greater dependence on the phase of ENSO.

Unlike most of the previous research performed in the region, we found it important to group specific teleconnection patterns in order to better understand how they relate with one another in relation to climatic impacts in the SAM. We identified several new couplings of global and hemispheric patterns that influence the climate of the SAM. First, seasons

associated with –NAO/+PDO patterns experienced cooler and snowier conditions across the SAM. Secondly, moderate phase El Niño events combined with –NAO signals produce the snowiest and coolest conditions in the SAM, especially for eastern-facing regions. Third, the influence of the ENSO on the region was dependent on its relative strength, with moderate events being heavily modulated by both the NAO and PDO. One potential reason as to why the region experiences more snowfall and lower temperatures during moderate ENSO phases could be the amount of latent heat release associated with the increased SST during strong El Niño events, which may not be as pronounced during moderate phases of the pattern (Zhang and McPhaden, 1995; Brennan and Lackmann, 2005). Lastly, we identified unique patterns that favor extremes in the SAM, with strong La Niña/–PDO/+NAO conditions favoring anomalously warm and less snowy conditions, and the inverse being true during moderate El Niño/+PDO/–NAO seasons. These unique patterns line up well with extremes in the climatological record of the SAM, with the anomalously cold and snowy 1977-1978 and 2009-2010 winter seasons, being examples of only a handful of seasons featuring the favorable El Niño/+PDO/–NAO combination.

By identifying atmospheric forcing groupings, we have revealed favorable scenarios for producing anomalous temperatures and snowfall in the region. The SAM have remained resistant to the rate of warming seen worldwide and the influence of these global and hemispheric patterns is one explanation as to why this has been happening. Cohen et al (2013) suggest that the AO/NAO, the dominant force of climatic variability in the region, could experience more extreme negative periods in the winter season due to AA and increases in the sudden stratospheric warming phenomenon. Future analysis will be needed to better understand how AA and sudden stratospheric warming are affecting and will

continue to affect the climate of the SAM. It is important to note, however, that the ideas surrounding AA are not universally accepted and need to be addressed with a high level of scrutiny (Fischer and Knutti, 2014; Barnes and Screen, 2015).

The identification of climatic trends and the influence of global and hemispheric patterns on variability in the SAM provides clarity as to why the region has remained a climate change anomaly. These findings can be used to bolster discussions with the public about the complexities of climate change and the climate system. This is especially important for regions like the SEUS and the SAM, where citizens are less likely to believe that climate change will affect them directly (Howe, 2015). To date, the SAM have remained resistant to the rate of warming seen worldwide but even slight changes to winter temperatures could have severe economic and environmental impacts. This finding is especially important to note due to the founding of several ski resorts in the region during the early and mid-1960s. Any reversal of the long-term temperature trend could threaten this vital part of the region's economy. Continued analysis of climatically anomalous regions, like the SAM, is crucial to understanding the impact of naturally occurring global and hemispheric forcings in masking, or in some cases, amplifying the impacts of the warming global climate.

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Table 1. Differences in mean winter temperature (ºC) associated with the lower and upper quartile ENSO, NAO, and PDO indices.

	DJF ENSO			DJF NAO			DJF PDO		
	Upper (*n* =27)	Lower (*n* =27)		Upper (*n* =27)	Lower (*n* =27)		Upper (*n* =27)	Lower (*n* =27)	
Region	Mean Temp.	Mean Temp.	Difference	Mean Temp.	Mean Temp.	Difference	Mean Temp.	Mean Temp.	Difference
Southern Tennessee Valley	4.0	4.9	-1.0	5.5	3.4	*2.1*	4.0	5.9	*-1.9*
Southwest Mountains	3.3	4.5	-1.2	5.0	2.8	*2.2*	3.3	5.3	*-2.0*
Southern Foothills	5.3	6.2	-0.9	6.6	5.1	*1.5*	5.5	7.1	*-1.5*
Great Smoky Mountains	2.8	4.0	-1.2	4.5	2.3	*2.2*	2.9	4.8	*-1.9*
Southern Blue Ridge	3.0	4.1	-1.1	4.6	2.7	*1.9*	3.2	5.0	*-1.8*
Southern Plateau	2.0	2.8	-0.8	3.5	1.2	*2.3*	1.9	3.5	*-1.5*
Northern Tennessee Valley	3.0	3.8	-0.8	4.3	2.4	*1.9*	3.0	4.8	*-1.8*
High Country	0.6	1.6	-1.0	2.2	0.1	*2.1*	0.6	2.4	*-1.8*
Central Foothills	3.9	4.7	-0.8	5.2	3.5	*1.7*	4.1	5.7	*-1.6*
New River Valley	0.7	1.7	-1.0	2.1	0.4	*1.7*	0.8	2.5	*-1.7*
Northern Foothills	2.8	3.6	-0.8	4.3	2.3	*1.9*	3.0	4.5	*-1.5*
Central Pleateau	1.5	2.5	-1.0	3.4	0.7	*2.7*	1.3	3.5	*-2.2*
Northern Plateau	-0.4	0.6	-1.0	1.2	-0.9	*2.0*	-0.5	1.5	*-1.9*
High Peaks	-2.5	-1.0	-1.5	-0.2	-3.2	*3.0*	-2.5	-0.4	*-2.1*
Southern Appalachian Mountains	2.6	3.5	-0.9	4.1	2.1	*2.0*	2.7	4.4	*-1.8*

Table 2. Differences in average snowfall (cm) associated with the lower and upper quartile ENSO, NAO, and PDO indices.

	DJF ENSO			DJF NAO			DJF PDO		
Region	Upper (*n* =27) Snowfall (cm)	Lower (*n* =27) Snowfall (cm)	Difference	Upper (*n* =27) Snowfall (cm)	Lower (*n* =27) Snowfall (cm)	Difference	Upper (*n* =27) Snowfall (cm)	Lower (*n* =27) Snowfall (cm)	Difference
Southern Tennessee Valley	18.2	12.2	*1.5x*	6.1	25.9	*4.2x*	21.0	7.5	*2.8x*
Southwest Mountains	13.6	7.7	*1.8x*	5.3	17.5	*3.3x*	15.5	5.3	*2.9x*
Southern Foothills	12.2	5.6	*2.2x*	4.7	15.1	*3.2x*	13.1	5.3	*2.4x*
Great Smoky Mountains	33.0	23.3	*1.4x*	14.7	36.2	*2.5x*	26.5	18.1	*1.5x*
Southern Blue Ridge	26.4	16.0	*1.7x*	11.2	30.6	*2.7x*	26.0	13.4	*1.9x*
Southern Plateau	21.4	18.0	*1.2x*	10.9	29.0	*2.7x*	22.7	10.7	*2.1x*
Northern Tennessee Valley	24.5	20.6	*1.2x*	10.9	34.5	*3.2x*	27.3	11.4	*2.4x*
High Country	61.1	42.2	*1.4x*	32.3	72.2	*2.2x*	56.3	33.6	*1.7x*
Central Foothills	27.2	13.0	*2.1x*	10.1	25.7	*2.5x*	23.6	13.0	*1.8x*
New River Valley	49.0	30.3	*1.6x*	27.6	50.8	*1.8x*	44.2	27.2	*1.6x*
Northern Foothills	34.1	19.7	*1.7x*	17.0	37.2	*2.2x*	32.1	15.3	*2.1x*
Central Plateau	55.9	43.7	*1.3x*	33.6	68.6	*2.0x*	59.3	28.9	*2.0x*
Northern Plateau	78.3	60.3	*1.3x*	50.9	82.5	*1.6x*	74.8	45.5	*1.6x*
High Peaks	138.6	90.8	*1.5x*	82.0	143.9	*1.8x*	123.1	72.2	*1.7x*
Southern Appalachian Mountains	33.5	23.0	*1.5x*	17.0	38.3	*2.2x*	32.0	17.8	*1.8x*

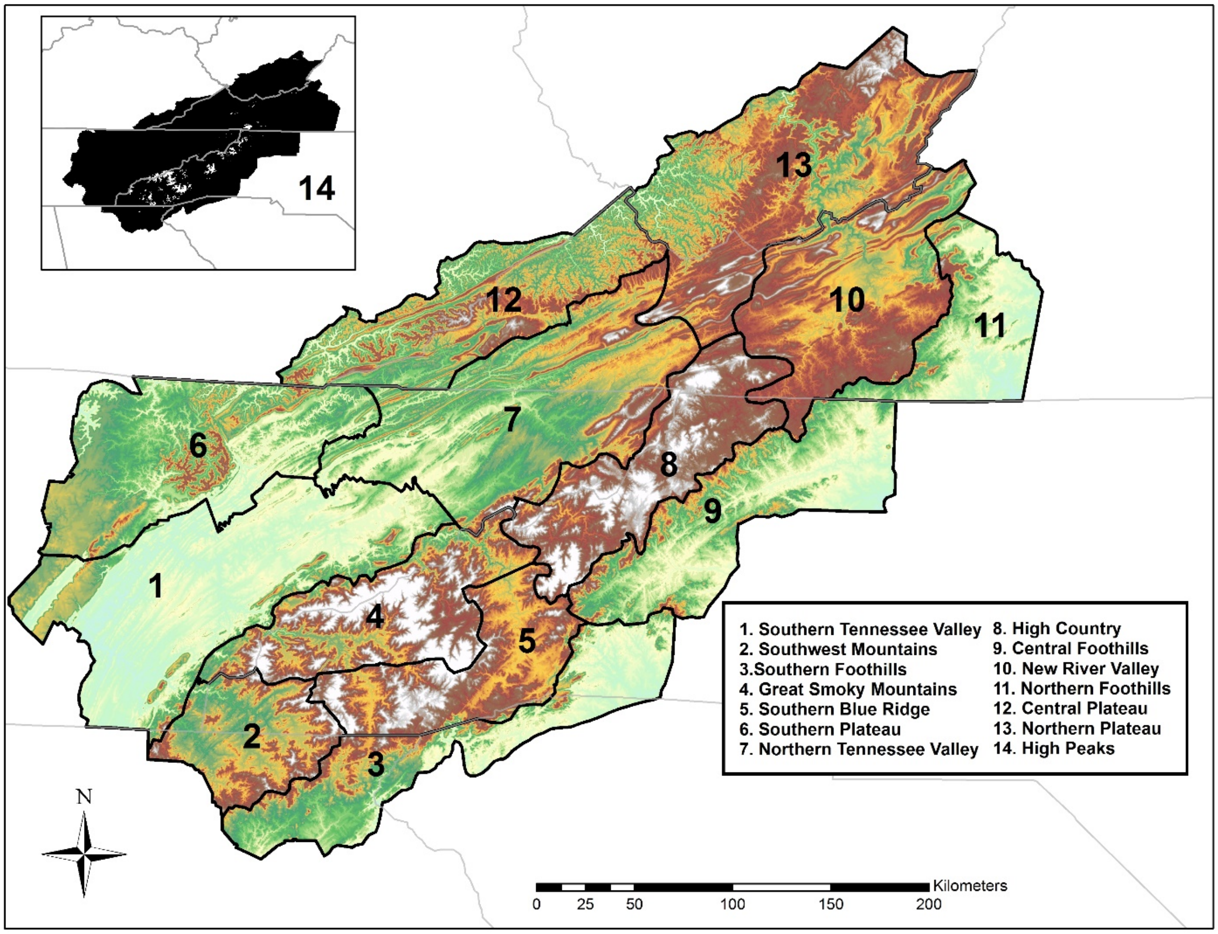

Fig. 1. Topography of the southern Appalachian Mountains located primarily in the southeastern United States. The High Peaks are shaded white on the inset map.

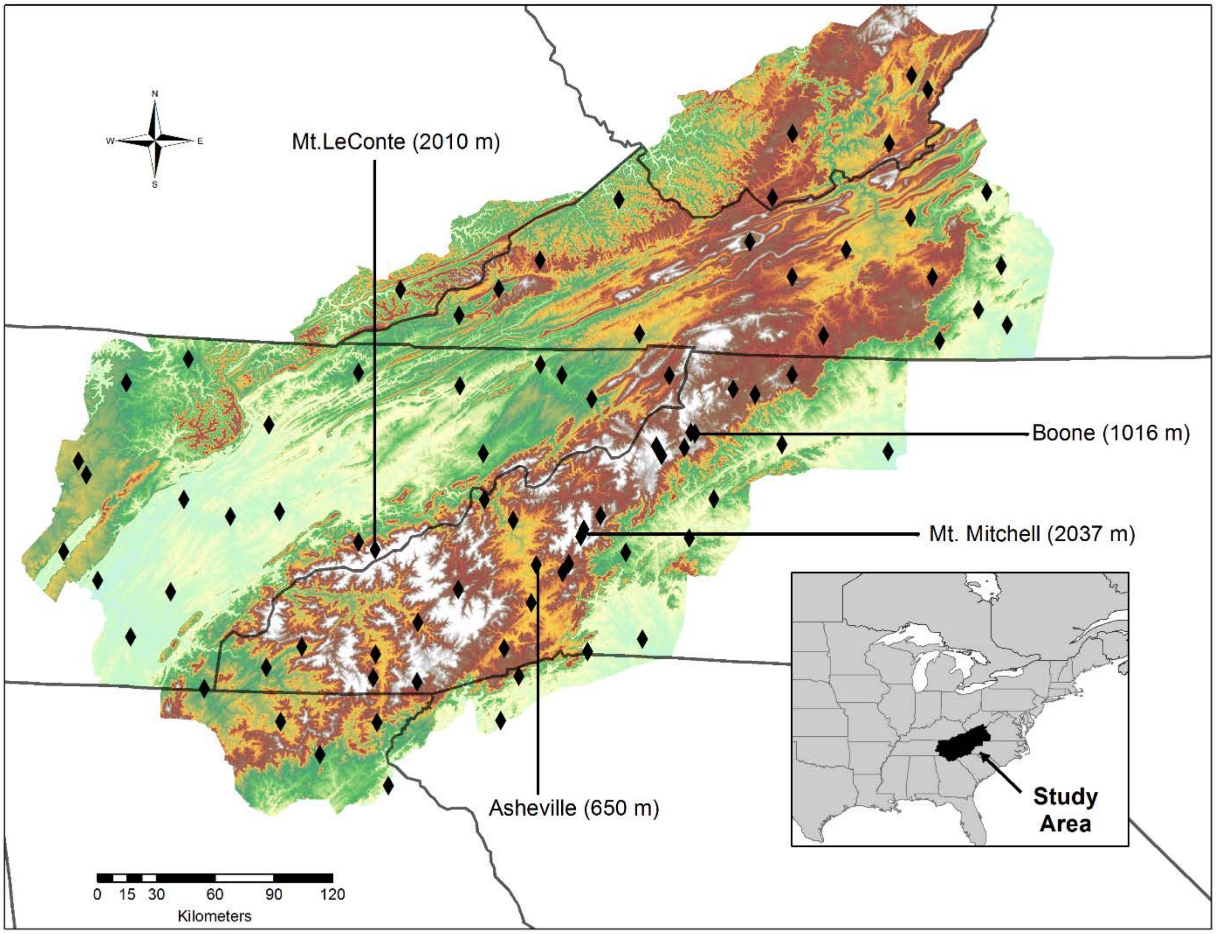

Fig. 2. SAM study area and distribution of NWS Cooperative Observer stations.

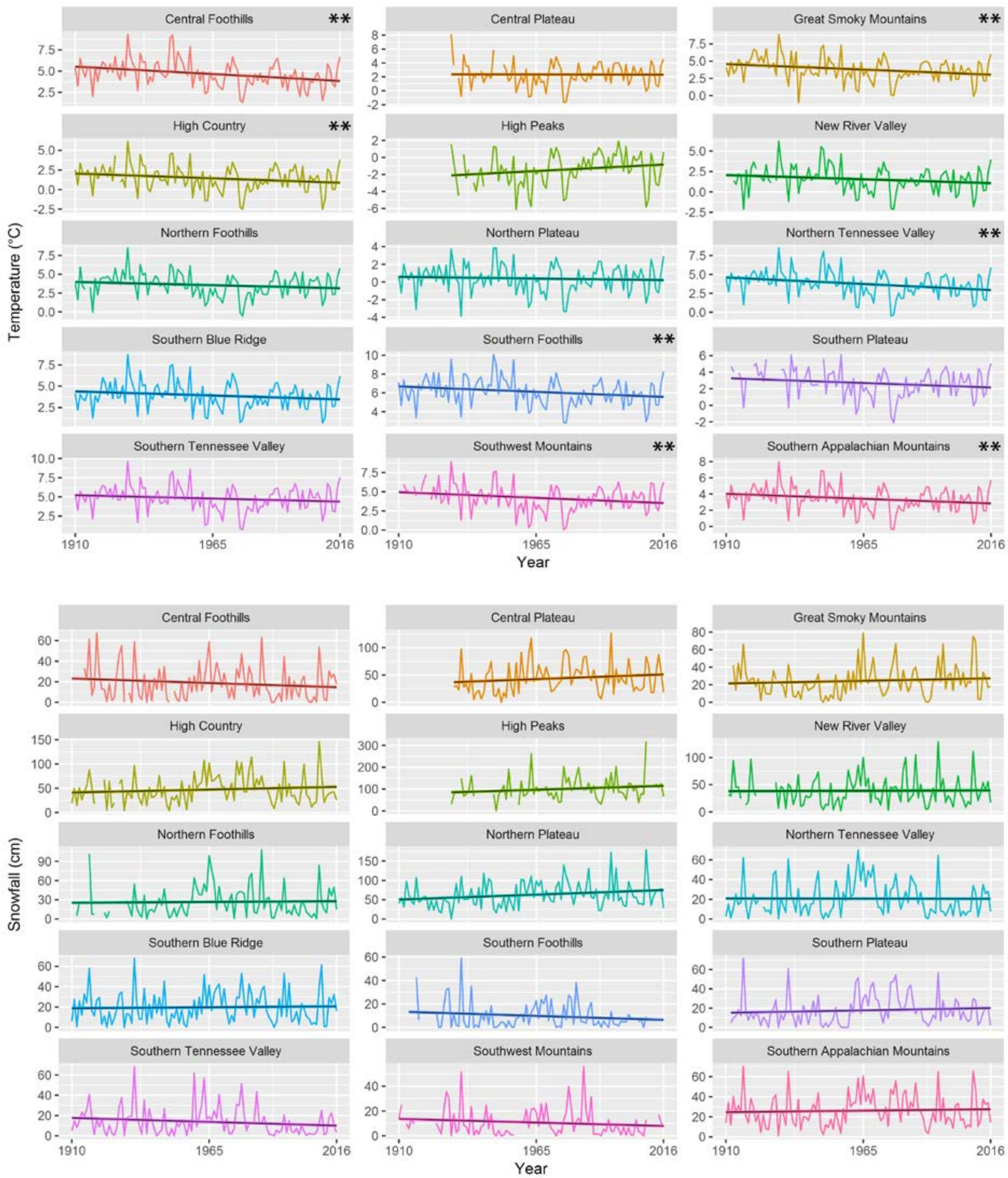

Fig. 3. Trends in mean winter temperature and total snowfall for regions of the southern Appalachian Mountains. Statistically significant trends ($p < 0.05$) are noted with **.

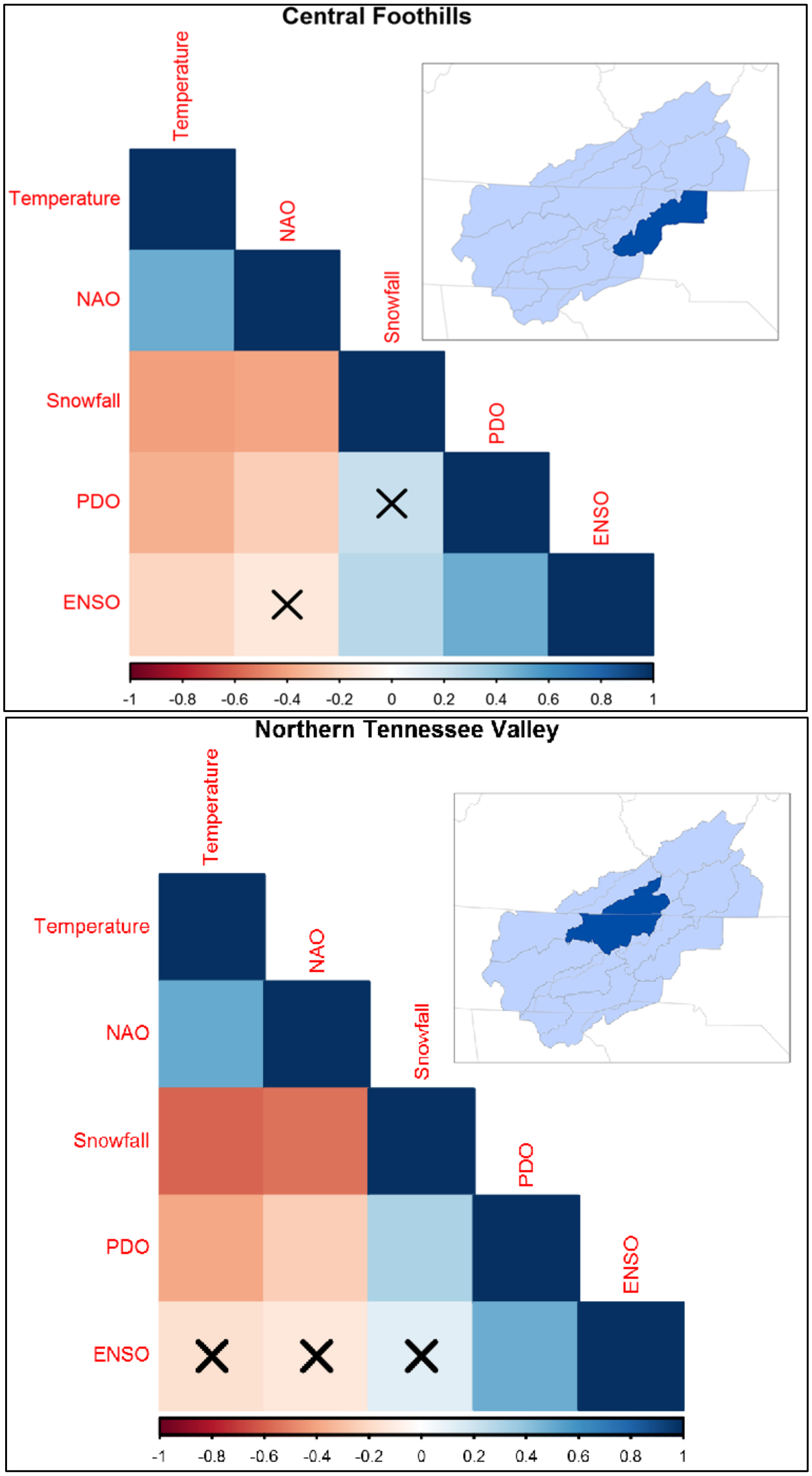

Fig. 4. Spearman's rank correlation for selected regions in the southern Appalachian Mountains. Tiles marked by *X* indicate non-significant relationships ($p < 0.05$).

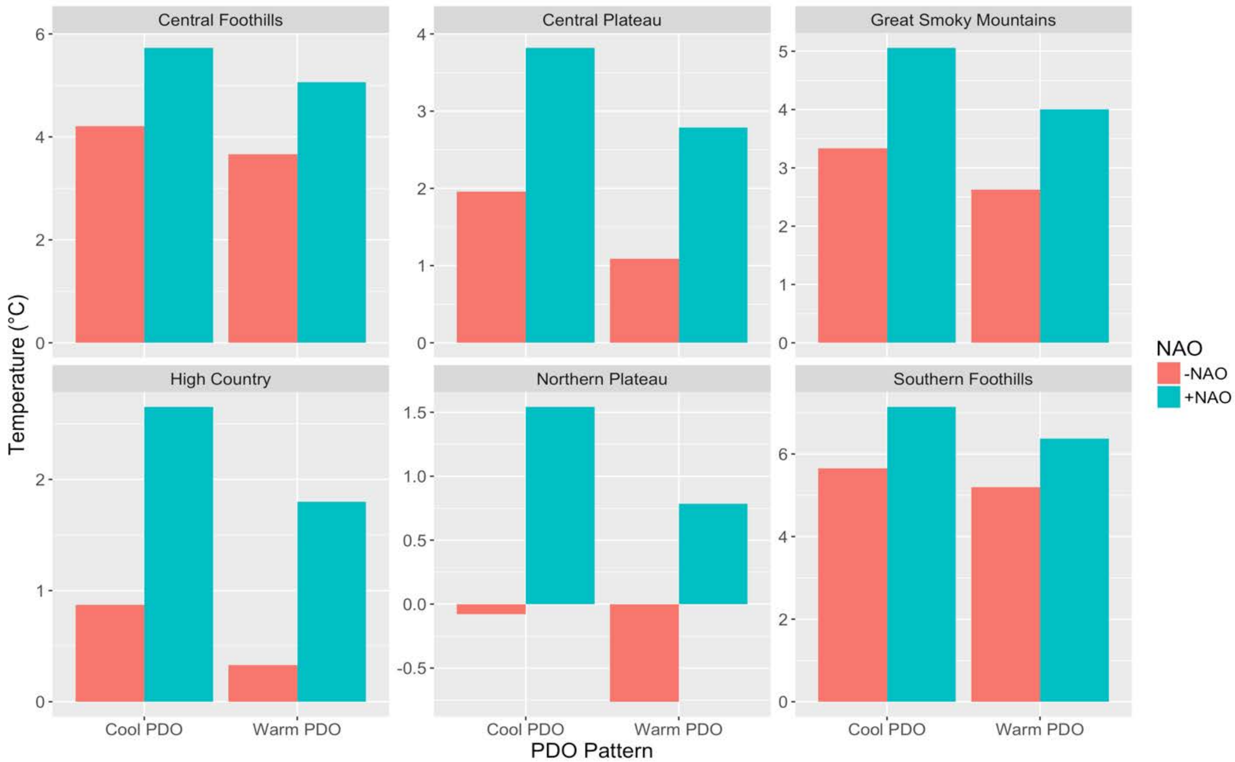

Fig. 5. Comparison of mean winter temperatures during cool and warm PDO phases associated with NAO patterns for selected regions.

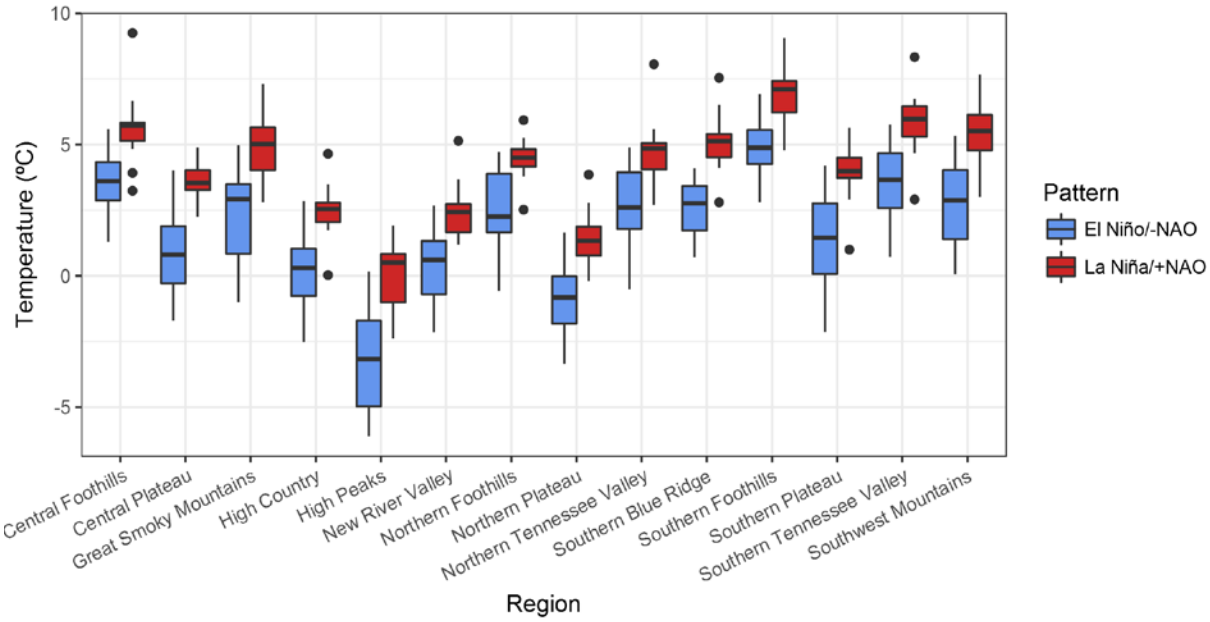

Fig. 6. Box and whisker plots displaying the average winter temperature experienced during El Niño/-NAO and La Niña/+NAO patterns by climatic region.

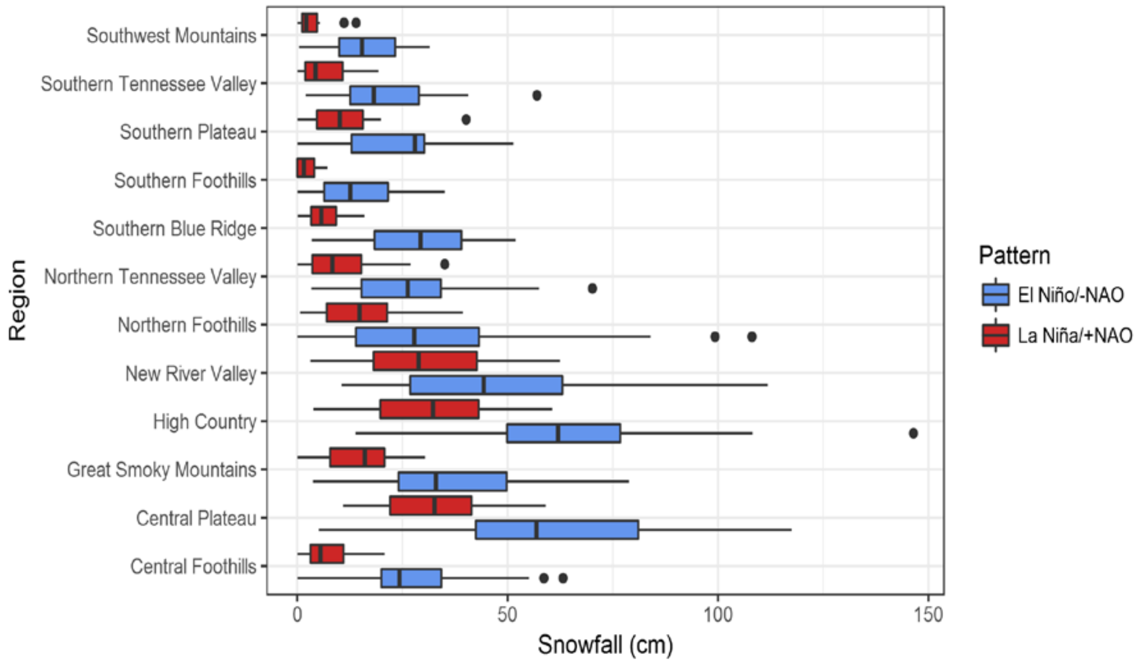

Fig. 7. Box and whisker plots displaying the average snowfall experienced during El Niño/-NAO and La Niña/+NAO patterns by climatic region.

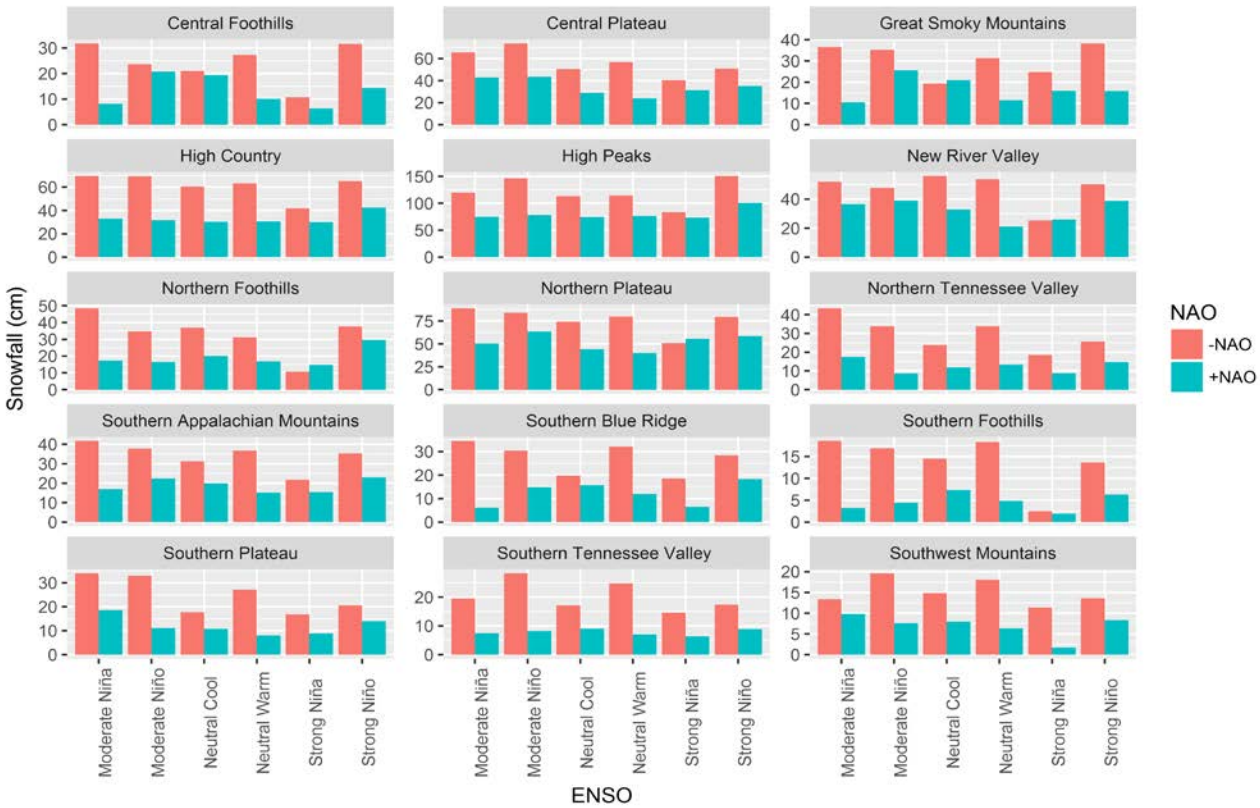

Fig. 8. Comparison of snowfall amounts for the southern Appalachian Mountains based on the strength of ENSO and the phase of the NAO.

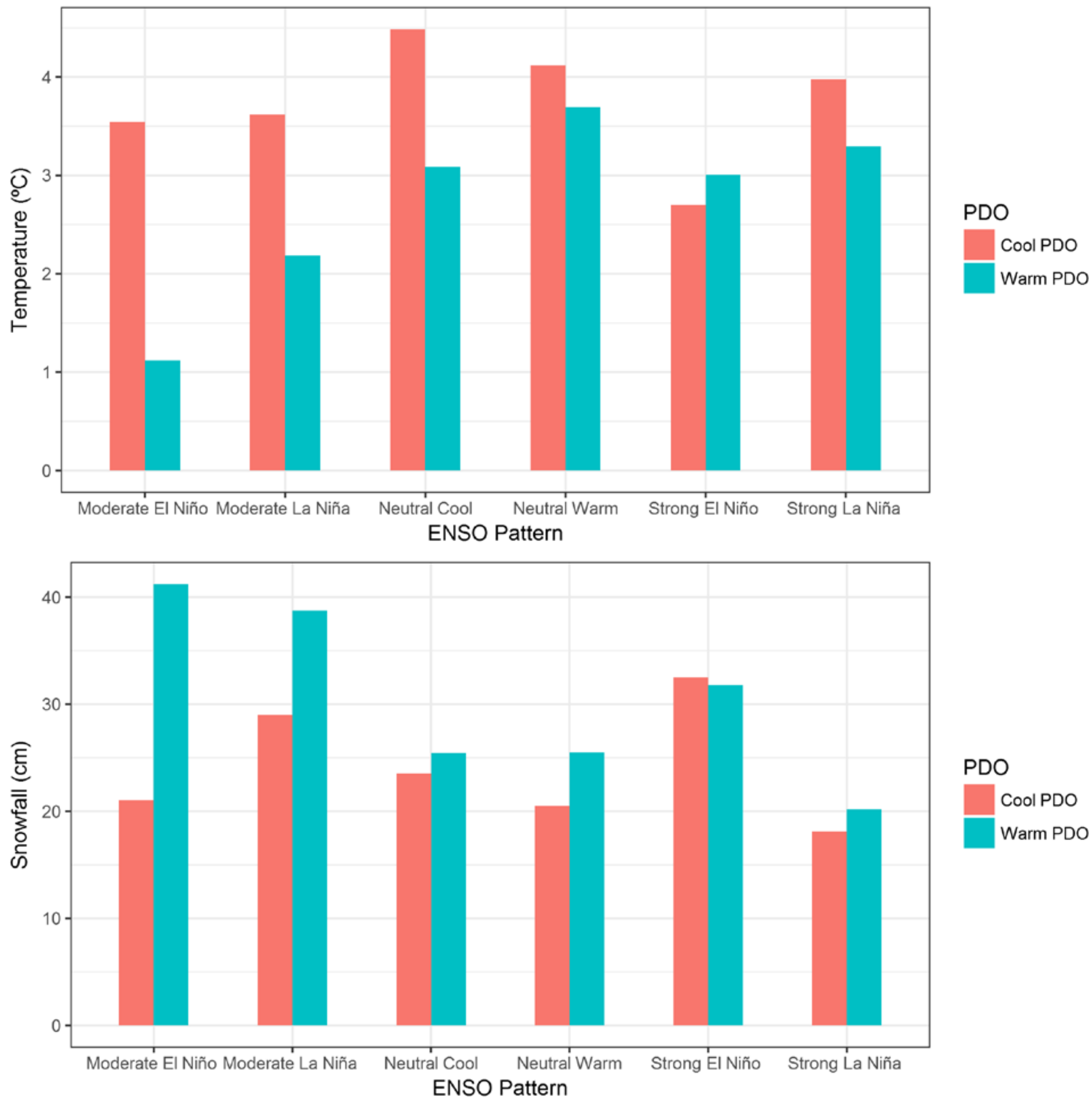

Fig. 9. Comparison of average temperature and snowfall for the southern Appalachian Mountains based on the strength of ENSO and the phase of the NAO.

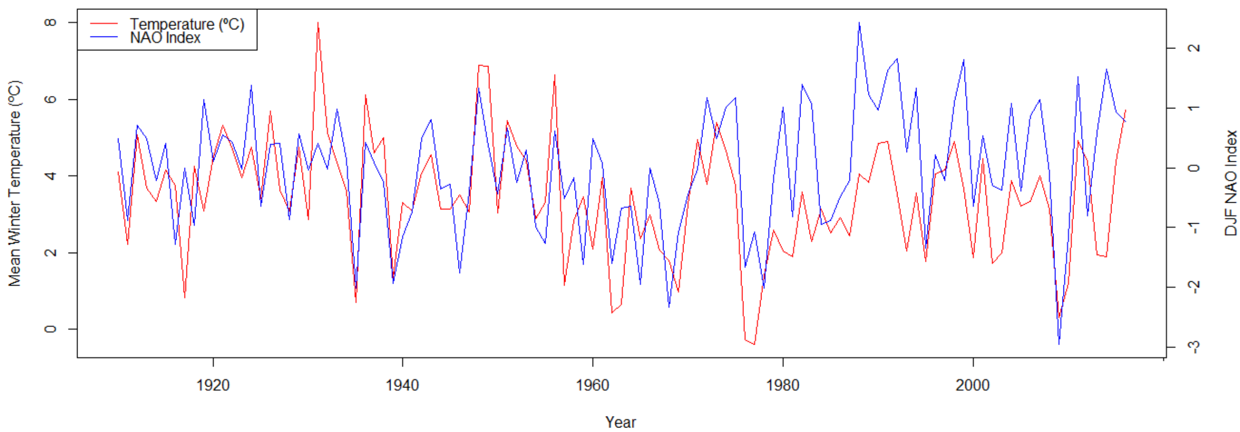

Fig. 10. Time series between mean winter temperature in the SAM and the NAO.

Vita

Montana Alan Eck was born and raised in the Blue Ridge Mountains, just outside of Asheville, NC in the small town of Old Fort. His mom and grandparents, Helen, Judy, and Clyde Eck brought Montana up on a small farm, where he gained an appreciation for the culture and life of rural America. After graduating from McDowell High School in the summer of 2012, he continued his education at the University of North Carolina at Asheville, ultimately graduating with honors in History in December of 2015. Soon after, Montana joined the Geography Program at Appalachian State University under the guidance of Dr. Baker Perry. The combination of his childhood experience in the southern Appalachian Mountains and his interests in snowfall made the decision to attend ASU for climate research a natural choice.

Montana spent the next year and a half working on his thesis, taking opportunities to share his research within the department, across campus at the Celebration of Research and Creative Endeavors, and even internationally at the Eastern Snow Conference in Ottawa, Canada. He prides himself in being able to share his work, home, and passions with a wider audience. In addition to enlarging his understanding of the world around him, Montana formed friendships at UNC Asheville and Appalachian State that he will cherish for a lifetime.

Upon graduating with an M.A. in Geography in December 2017 and enjoying the upcoming winter season, Montana plans to continue his passions in research and education by obtaining his PhD. He also plans to take time enjoy time exploring and traveling, as well as enjoying time with family and friends.