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RESEARCH ARTICLE

Winter climate variability in the southern Appalachian Mountains, 1910–2017

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Located in the mid-latitudes and exhibiting the greatest topographic relief in the eastern United States, the southern Appalachian Mountains (SAM) contain some of the most diverse climatological environments in the United States. This diversity is most pronounced in the winter season when temperature and snowfall can vary drastically across the region. In this study, we identify long-term trends and variation of temperature and snowfall in the SAM of the southeastern United States during climatological winter (DJF) from 1910 to 2017. Along with recognizing statistically significant climatic trends, we also identify the influence of several teleconnection patterns, namely the El Niño-Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), and Pacific Decadal Oscillation (PDO) that further scientific understanding of how this region has remained a climatic anomaly. Results of this study indicate the SAM have experienced a statistically significant long-term cooling trend since the early 20th century, with recent decades suggesting a reversal towards a warming pattern. Snowfall exhibited 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 were frequently found during El Niño and negative NAO seasons, with the opposite being true during La Niña and positive NAO winters. The influence of these teleconnection patterns was spatially dependent, with lower elevations and eastern-facing slopes being highly dependent on the phase of ENSO for snowfall, whereas higher elevations and western-facing slopes were more reliant on the NAO. The identification of pattern couplings is critical to improving understanding of the anomalous climate of the SAM, enhancing seasonal forecasting, and predicting future climate change in the region.

KEYWORDS

climate variability, mid-latitudes, mountains, snow, teleconnections

1 | INTRODUCTION

Winter climate variability in mountainous regions is difficult to ascertain, primarily due to the complex topography and diverse climates in these areas (Barry, 2008). Understanding the impacts of climate change in mountains is crucial due in part to elevation-dependent warming, which can accelerate change in regional ecosystems, biodiversity, and hydrological regimes (Mountain Research Initiative, 2015). Unfortunately, due to limitations in data and accessibility, 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, where precipitation in the winter season is linked with a variety of synoptic patterns and the influence of orographic effects can result in large gradients across short distances (Martin *et al.,* 2015; Sugg *et al.,* 2016). The poor understanding of how temperature and snowfall have changed in mountainous regions such as this limits our ability to effectively communicate to the public and better prepare for future climate change.

Recognized as a global climate change anomalous region and the national "warming hole," the southeastern United States experienced a statistically significant decline in mean temperatures during the 20th century (Portmann *et al.,* 2009; Partridge *et al.,* 2018). While minimum winter temperatures declined 1.5 °C from 1920 to 1992 (Ellenburg *et al.,* 2016), 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; Soulé, 2005; Kunkel *et al.,* 2006). Although Riedel (2006) suggests decadal variability influenced the regional cooling, other research has shown that the combination of natural and anthropogenically produced aerosols were partially responsible for at least some of the negative temperature anomalies observed in the mid-20th century (Weber *et al.,* 2007; Kelly *et al*., 2012b).

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 southeastern United States 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 21st century (Krasting *et al.,* 2013). Paradoxically, some modelling 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).

Global and hemispheric teleconnection patterns have been linked with regional climate variability on a variety of scales (Barnston and Livezey, 1987). Hartley (1999), Seager *et al*. (2009), and Nag *et al*. (2014) linked seasonal patterns of temperature and precipitation across the southeastern United States to several of these large-scale modes of climate variability, including the North Atlantic Oscillation (NAO) (Wallace and Gutzler, 1981), El Niño Southern Oscillation (ENSO) (Trenberth, 1997), and the Pacific Decadal Oscillation (PDO) (Mantua *et al.,* 1997). This is also true for the SAM, where these patterns have been identified as a primary driving force behind seasonal temperature and snowfall fluctuations, with negative temperature anomalies being reinforced by negative patterns of the NAO and mitigated by a positive NAO (Warren and Bradford, 2010; Lesser and Fridley, 2016). Notably, the anomalous negative NAO phases of the late 2000s have been linked to the increase in cold air outbreaks and snowfall amounts observed along the eastern seaboard of the United States (Cohen *et al.,* 2010; Chang *et al.,* 2012; Westby *et al.,* 2013; Ning and Bradley, 2014). The relationship between ENSO and winter precipitation is harder to delineate, as winter seasons associated with El Niño (La Niña) patterns favour above (below) average precipitation in the SEUS (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).

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 (Figure 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) (Laseter *et al.,* 2012; Lesser and Fridley, 2016). 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 (Perry and Konrad, 2006; Perry *et al.,* 2007; Martin *et al.,* 2015). Miller type-A and Miller type-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). Other synoptic patterns known to produce snowfall in the SAM include upper-level cut-off lows, clippers, and northeastward-tracking Colorado lows (Perry *et al.,* 2010; Kelly *et al*., 2012a). Spatially, Gulf lows contribute a majority of snowfall to eastern-facing slopes, whereas northwest flow snow events contribute more than 50% of the annual snowfall to windward and high elevation locations (Perry and Konrad, 2006; Keighton *et al.,* 2016).

There is a need for better understanding of how interactions between large climate modes are influencing seasonal variability and change in anomalous regions. The typical understanding for snowfall in the southeastern United States is built upon the assumption that a combination of a negative NAO and El Niño conditions in the Pacific will produce positive snowfall anomalies (Seager *et al.,* 2010). However, the NAO more frequently acts as the dominant modulating force with anomalously cold and snowy conditions being found in less conducive ENSO patterns with negative NAO patterns. This was the case with the 2010–2011 winter season in the eastern United States and SAM, where La Niña conditions were expected to produce warmer and less snowy conditions in the region. However, a persistently negative Arctic Oscillation (AO) and NAO pattern produced one of the coldest and snowiest years on record (Liu *et al.,* 2012).

Characterizing winter variability in the SAM is important to improving our understanding of the influence that global and hemispheric teleconnection patterns have on regional

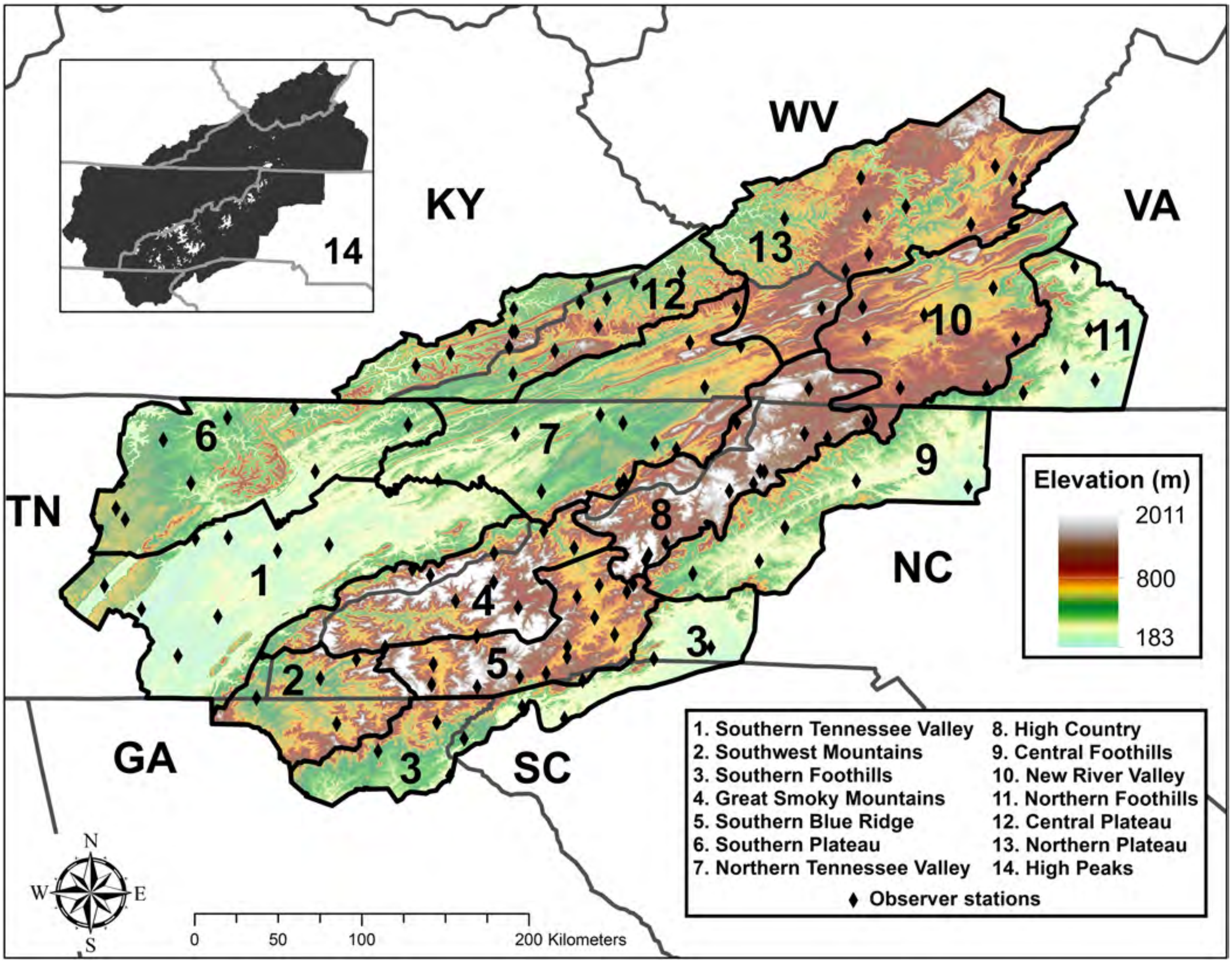

FIGURE 1 Topography of the SAM located primarily in the southeastern United States and associated cooperative observer stations. The non-continuous high peaks (Region 14) are shaded white on the inset map [Colour figure can be viewed at wileyonlinelibrary.com]

temperature and snowfall patterns. Furthermore, an examination of linkages between large-scale atmospheric forcing mechanisms may improve seasonal forecasting and efforts to model future climate change. The objectives of this research are to: (a) identify variability and trends in mean winter temperature and total snowfall in the SAM, and (b) 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 | DATA AND METHODS

2.1 | 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 of 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 divided into 14 unique climate regions based on similarities in climate normals, elevation, and topography (Figure 1). These climatic regions were further defined by grouping National Weather Service Cooperative Observer Program (COOP) stations by similarities in climatological snowfall averages.

Due to the topographic diversity in the study area (Sugg *et al.,* 2016), the SAM experience considerable variability in climate normals by region. For example, climatological mean winter temperatures between 1987 and 2017 varied by nearly 6.7 °C among the Southern Foothills, High Country, Central Foothills, and High Peaks. 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). Differences such as these highlight the importance of analysing the SAM subregionally, as it allows us to more accurately reveal the spatial variability of trends and relationships between global patterns.

2.2 | Temperature and snowfall data records

Our analysis focuses on the climatological winter season, December–February, of 1910–2017 as the relationships among temperature, snowfall, and atmospheric forcing patterns in the region weaken with the poleward migration of the jet stream during the transition to spring (Hartley, 1999). 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 (Figure 1). These data undergo thorough quality checks from both the National Weather Service and the National Center for Environmental Information, ensuring their quality and usefulness. Data from these stations were collected by volunteer observers, which poses some concern regarding the challenges in accurately measuring snowfall, the validity of some datasets, and observer error (Robinson, 1989; Doesken and Leffler, 2000). There are also several inhomogeneities in COOP observer data that must be acknowledged including instrumental changes, movement of individual stations, and changes of observation time (Quayle *et al.,* 1991; Menne *et al.,* 2010; Fall *et al.,* 2011; Hausfather *et al.,* 2016). In order to maintain an accurate representation, we excluded data from stations with less than 90% completeness during individual winter seasons.

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 compared to the other 12 regions. The average number of years with adequate data for the 12 regions is 105 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.

2.3 | 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 regional weather. We obtained winter indices of ENSO and PDO patterns by averaging the monthly values for climatological winter. We used the Niño 3.4 SST Index anomaly to identify patterns of ENSO, which is identified by taking the average SST from 5°S–5°N to 170°–120°W and is preferable to other ENSO indices for this study due to the longevity of the record (https://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/). Using similar techniques implemented by Jia and Ge (2017), we categorized El Niño (La Niña) events based on the particular NAO and PDO phase. El Niño (La Niña) events have Niño 3.4 SST anomaly values $x \geq 0.5$ °C ($x \leq -0.5$ °C) and neutral patterns have values -0.5 °C $< x <$ 0.5 °C. Using SST anomaly data poleward of 20°N in the Pacific basin, the average DJF index of the PDO represents two distinct phases. Positive (negative) indices for the PDO indicated a warm (cool) phase for that winter season (https://www.ncdc.noaa.gov/teleconnections/pdo/).

The NAO, despite its close association with the AO, is more relevant for investigating variability in North America (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 principal component-based dataset, which tracks the seasonal movements of the Icelandic low and Azores high (Hurrell and Deser, 2009; National Center for Atmospheric Research Staff, 2017). For the purpose of our study, averaged seasonal values of the NAO found to be negative (positive) translate to a seasonal pattern dominated by the negative (positive) phase of the pattern.

2.4 | 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 (Wilks, 2011). A negative (positive) *tau* statistic indicated a decreasing (increasing) trend. The significance level for these tests was set at $p < .05$. In order to better verify these trends, we also identified outliers and potential weights on the trend by removing seasons that were more than two standard deviations above and below the 1977–2017 climatological mean. Along with identifying trends in snowfall between 1910 and 2017, we also sought to recognize any potential recent changes to the long-term trend by identifying changes over the past 50 years.

2.5 | Identifying relationships

Using Spearman 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 ($p < .05$). In order to further explain the relationships between each of the global and hemispheric teleconnection patterns, temperature, and snowfall, we used the Mann–Whitney hypothesis test to find differences in the winter climate based on the phases of each pattern (Wilks, 2011). 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

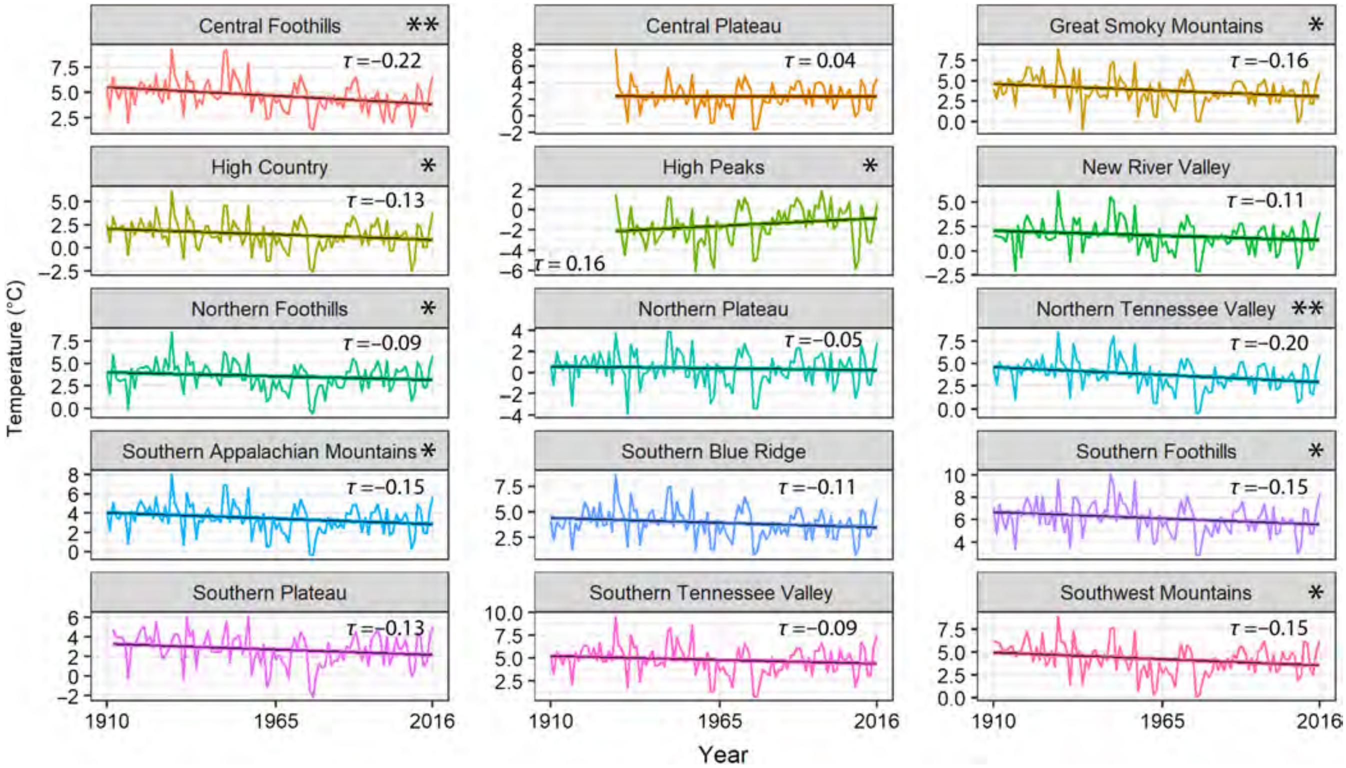

FIGURE 2 Trends in mean winter temperature (°C) (1910–2017) for subregions of the SAM. Statistically significant trends ($p < .05$) are noted with * and ($p < .01$) with **. The Kendall's tau coefficient (τ) shows the association between time and temperature [Colour figure can be viewed at wileyonlinelibrary.com]

climatic variables based on the warm and cool phases of the patterns.

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 favourable 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 favoured to produce anomalously cool and snowy conditions in the SAM. We then compared these seasons to those associated with less conducive +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 Mann–Whitney U tests at a significance level of $p < .05$.

3 | RESULTS

3.1 | Trends in temperature

A majority (12/14) of the regions within the SAM have experienced a long-term decline in mean winter temperatures since 1910 (Figure 2). The significance of this cooling trend varies by subregion, with the eastern and southernmost extents of the SAM exhibiting significant ($p < .05$) negative trends in mean winter temperature. Although the westernmost regions of the SAM also exhibit the decrease in mean winter temperatures, the decline is not significant. Even after removing the highly anomalous 2009–2010 winter season, the cooling of mean winter temperatures is still evident. The High Peaks and Central Plateau are the only regions in the 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.

Whereas 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 ($p < .05$) positive trend in mean winter temperatures over the past 50 years. However, a majority of the SAM exhibits no discernable trend over the last half-century, with regions like the High Peaks and Great Smoky Mountains having high interannual variability in winter temperatures. Despite the 2016–2017 winter season finishing with the highest mean temperatures (5.7 °C) in the SAM since 1956–1957, there have been several years of anomalous negative temperature anomalies, with the 2009–2010 (0.3 °C) and 2010–2011 (1.2 °C) winter seasons finishing as two of the coldest on record for all regions.

3.2 | Variability in snowfall

Unlike temperature, there are no discernible trends in snowfall throughout the SAM. Instead, the region has experienced high interannual variability in seasonal snowfall totals since the early 20th century. Despite the lack of significant trends, a majority of eastward-facing slopes and southern foothills 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. Snowfall totals over the past 50 years have changed more dramatically, with nearly half of the regions identified in this study experiencing significant declines in snowfall ($p < .05$). Most notably, areas located along the southernmost extent of the study area experienced the greatest decline in snowfall.

4 | SPATIAL CHARACTERISTICS OF CLIMATE MODE RELATIONSHIPS

Seasons associated with predominantly negative NAO, warm PDO, or El Niño patterns are significantly ($p < .05$) colder and snowier than positive NAO, cool PDO, or La Niña winters. Notably, the strength and significance of the aforementioned associations are spatially unique within the SAM. Although the NAO shares significant relationships with temperature throughout the SAM, the association between the NAO and total snowfall is strongest in the High Peaks, High Country, and Northern Plateau and weakens considerably east of the Blue Ridge Escarpment and along the southernmost extent of the study area. Similar results were found with the PDO, as all 14 subregions in the SAM experience significantly ($p < .05$) lower mean winter temperatures and more snowfall during its warm phase. The relationship between the PDO is also strongest in high elevation regions such as the High Country, Northern Plateau, and High Peaks and is considerably weaker in foothill regions.

Despite its current use in seasonal forecasting, the relationship between ENSO and winter climate of the SAM is considerably weaker than what was found with the NAO and PDO. Only five regions within the SAM (Southwest Mountains, Southern Foothills, Southern Blue Ridge, Central Foothills, and High Peaks) exhibited statistically significant ($p < .05$) relationships between both temperature and snowfall with respect to ENSO. Unlike the NAO and PDO, ENSO has the greatest influence over east-facing slopes and southern regions of the SAM (Figure 3). These areas of the SAM are more dependent on the ability to tap gulf moisture to produce snowfall through Miller-systems, which have been linked to the presence of El Niño conditions in the Pacific.

5 | INFLUENCE OF TELECONNECTION COUPLINGS

5.1 | NAO and ENSO

Due to the ENSO and NAO varying on a shorter time scale compared to the decadal nature of the PDO, the interpretation of the interaction between these patterns phases is critical to better understanding relationships on a seasonal level. Regionwide, winter temperatures during the −NAO/El Niño ($n = 22$) pattern averaged 2.2 °C, significantly colder ($p < .05$) that the 4.4 °C average found during +NAO/La Niña ($n = 15$) patterns. These differences are established throughout the study area, with the higher elevation subregions of the Northern Plateau and High Peaks routinely experiencing mean winter temperatures below 0 °C during −NAO/El Niño seasons.

Typically, El Niño favours negative temperature anomalies in the SAM and La Niña favours positive temperature anomalies. However, coupling El Niño with a +NAO ($n = 10$) and La Niña with −NAO conditions ($n = 17$) reveals that temperatures in the SAM averaged a non-significant 0.7 °C lower during −NAO/La Niña (2.9 °C) patterns than +NAO/El Niño (3.6 °C) patterns (Figure 4a). This is true for all 14 regions, with the greatest difference in temperature found in the High Peaks and Northern Plateau. Despite focus on the positive and negative patterns of ENSO regionally, it is also important to recognize the modulating role of the NAO during neutral phase of ENSO with temperatures during −NAO/neutral patterns ($n = 28$) averaging 1.7 °C cooler than +NAO/neutral patterns ($n = 15$).

Snowfall was most extensive in the SAM during −NAO/El Niño winters, with this seasonal combination averaging 36.2 cm of accumulating snowfall. In stark contrast to this, snowfall during +NAO/La Niña patterns averaged significantly less ($p < .05$) with only 15.9 cm (Figure 5a). However, when investigating opposing NAO patterns on ENSO, we found that snowfall in the SAM is significantly higher during −NAO/La Niña (30.0 cm) winters compared to +NAO/El Niño (20.7 cm). The importance of the negative NAO for snowfall in the region also carries over for neutral ENSO seasons, as nearly twice as much snowfall occurred during −NAO/neutral ENSO seasons (33.8 cm) compared to +NAO/neutral ENSO winters (18.4 cm).

5.2 | PDO and ENSO

Temperatures in the SAM vary greatly dependent on the phase of ENSO and the associated phase of the PDO, with neutral ENSO patterns associated with a cool PDO ($n = 23$) exhibiting the warmest conditions in the region (4.3 °C) and El Niño seasons associated with the warm PDO ($n = 19$) being the coolest (2.3 °C). Upon closer investigation, the influence of the interaction between the PDO and ENSO was less prominent than what was found with the NAO, as there are no significant ($p < .05$) differences in mean winter temperature during El Niño seasons dependent on the phase of the decadal pattern. El Niño events associated with a warm PDO average only 0.78 °C lower than with cool PDO ($n = 13$) events (Figure 4b). Similarly, no significant differences were found during neutral ENSO seasons dependent on the phase of the PDO, with neutral/+PDO winters

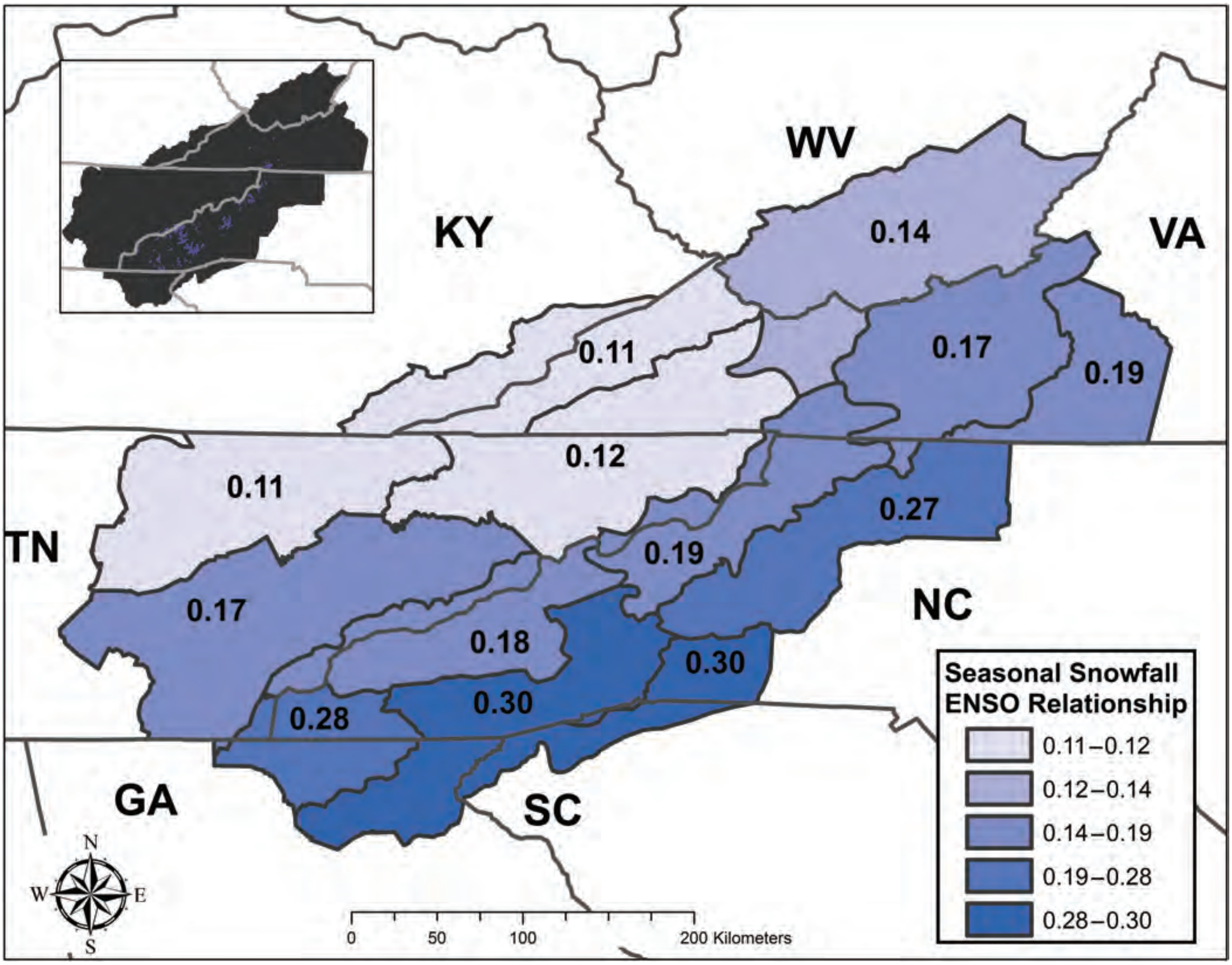

FIGURE 3 Spearman rank correlation analysis determined strength of the relationship between the DJF Niño 3.4 SST index anomaly and seasonal snowfall [Colour figure can be viewed at wileyonlinelibrary.com]

(n = 20) averaging 0.95 °C cooler than neutral/cool PDO seasons. The only significant differences related to the PDO were found when analysing La Niña events in the winter season with La Niña/cool PDO patterns (n = 25) averaging 1.49 °C warmer than La Niña/+PDO seasons (n = 7).

Snowfall in the region is highly variable but the analysis revealed that the region has little reliance on the relationship between the ENSO and PDO. El Niño events associated with a warm PDO produce the most snowfall across the SAM with an average of 35.3 cm and La Niña coupled with a cool PDO averages the least amount of snowfall with 22.0 cm across the mountains (Figure 5b). While snowfall totals vary due to the phase of ENSO, the analysis revealed no significant differences depending on the warm or cool phase of the PDO within each ENSO pattern.

5.3 | NAO and the PDO

Similar to its interaction with ENSO, the NAO has a crucial role in determining temperatures in the SAM when aligned with the PDO (Figure 4c). During −NAO/+PDO seasons (n = 29) temperatures across the region are significantly (p < .05) cooler, averaging 1.5 °C lower than the 3.8 °C associated with +NAO/warm PDO seasons (n = 17). Similar results were found during cool PDO phases, with −NAO patterns (n = 25) averaging 2.9 °C, which is significantly less than the 4.5 °C associated with +NAO seasons (n = 36). These findings indicate 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 are consistent throughout all the subregions.

Winter seasons associated with −NAO/+PDO patterns also produce anomalously high snowfall, with the SAM averaging 34.7 cm, more than double the amount observed during +NAO/−PDO winters where average seasonal snowfall is 17.0 cm (Figure 5c). 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

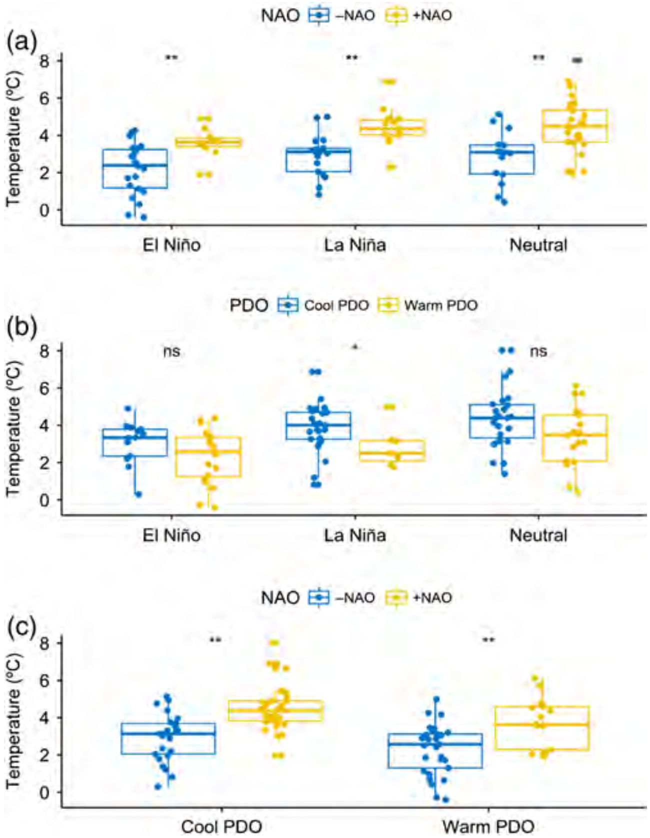

FIGURE 4 Box and whisker plots displaying mean winter temperature (°C) experienced during specific coupling patterns between 1910 and 2017. Each point represents an individual winter season. Statistically significant differences ($p < .05$) are noted with *, ($p < .01$) with **, and non-significant with ns [Colour figure can be viewed at wileyonlinelibrary.com]

+NAO/+PDO events across the region. This finding is amplified in western and high elevation regions, like the High Country, which averaged 61.0 cm of snowfall during −NAO/−PDO patterns and less than 42 cm during +NAO/+PDO patterns.

5.4 | Unique patterns

El Niño/−NAO/+PDO seasons (n = 16) favoured the most anomalously cold conditions in the SAM (2.1 °C) during the winter, with +NAO/−PDO/La Niña periods (n = 14) producing the highest winter temperatures (4.6 °C). These significant ($p < .05$) differences were evident throughout the study area; with the Southwest Mountains region experiencing 3.0 °C lower temperatures during El Niño/−NAO/+PDO winters. Temperature differences were not as extreme along the eastern extent of the study area, but still averaged 2.0–2.5 °C cooler during the conducive patterns. Snowfall amounts during −NAO/+PDO/El Niño seasons (34.8 cm) exhibited similar differences with the +NAO/−PDO/La Niña seasons averaging less than 15.5 cm. While dissimilarities in snowfall amounts were apparent throughout the study area, the eastern and southernmost extent of the study area experienced the largest differences.

6 | DISCUSSION

As a regional anomaly regarding climate change, the SAM have observed a statistically significant decline in mean winter temperature since the early 20th century with a recent shift suggesting a return to pre-1960s normals. Interestingly, the results show there are no statistically significant trends in snowfall throughout the region despite the decline in temperatures since 1910. There are several possibilities for these findings including the number of complexities associated with the development of snow in mountainous regions, where the availability of cold air, moisture, and lifting mechanisms are necessary to produce snowfall (Perry and Konrad, 2006). Snow density can affect snowfall totals across the region, as the same liquid equivalent precipitation can produce varying amounts of measurable snowfall dependent on where it falls (Roebber *et al.,* 2003). Unseen changes in the lower troposphere also influence snowfall totals, where the presence and strength of a warm nose (defined as a temperature inversion typically located between 850 and 700 hPa in the region) can mean the difference between snow and rain (Perry *et al.,* 2010). If temperatures in the warm nose rise above 0 °C, snow hydrometeors are more likely to melt, reaching the surface as a mixture of sleet and

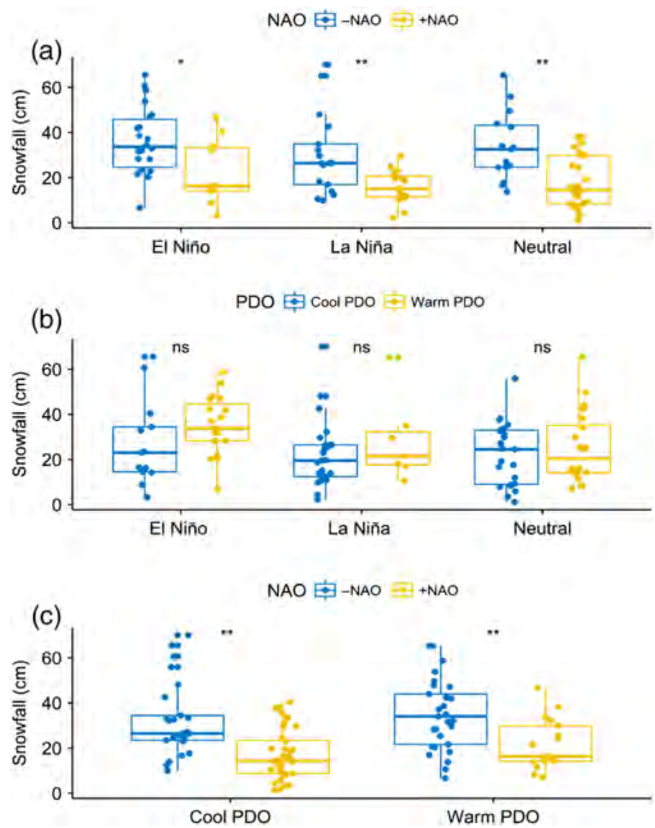

FIGURE 5 Box and whisker plots displaying total snowfall (cm) experienced during specific coupling patterns between 1910 and 2017. Each point represents an individual winter season. Statistically significant differences ($p < .05$) are noted with *, ($p < .01$) with **, and non-significant with ns [Colour figure can be viewed at wileyonlinelibrary.com]

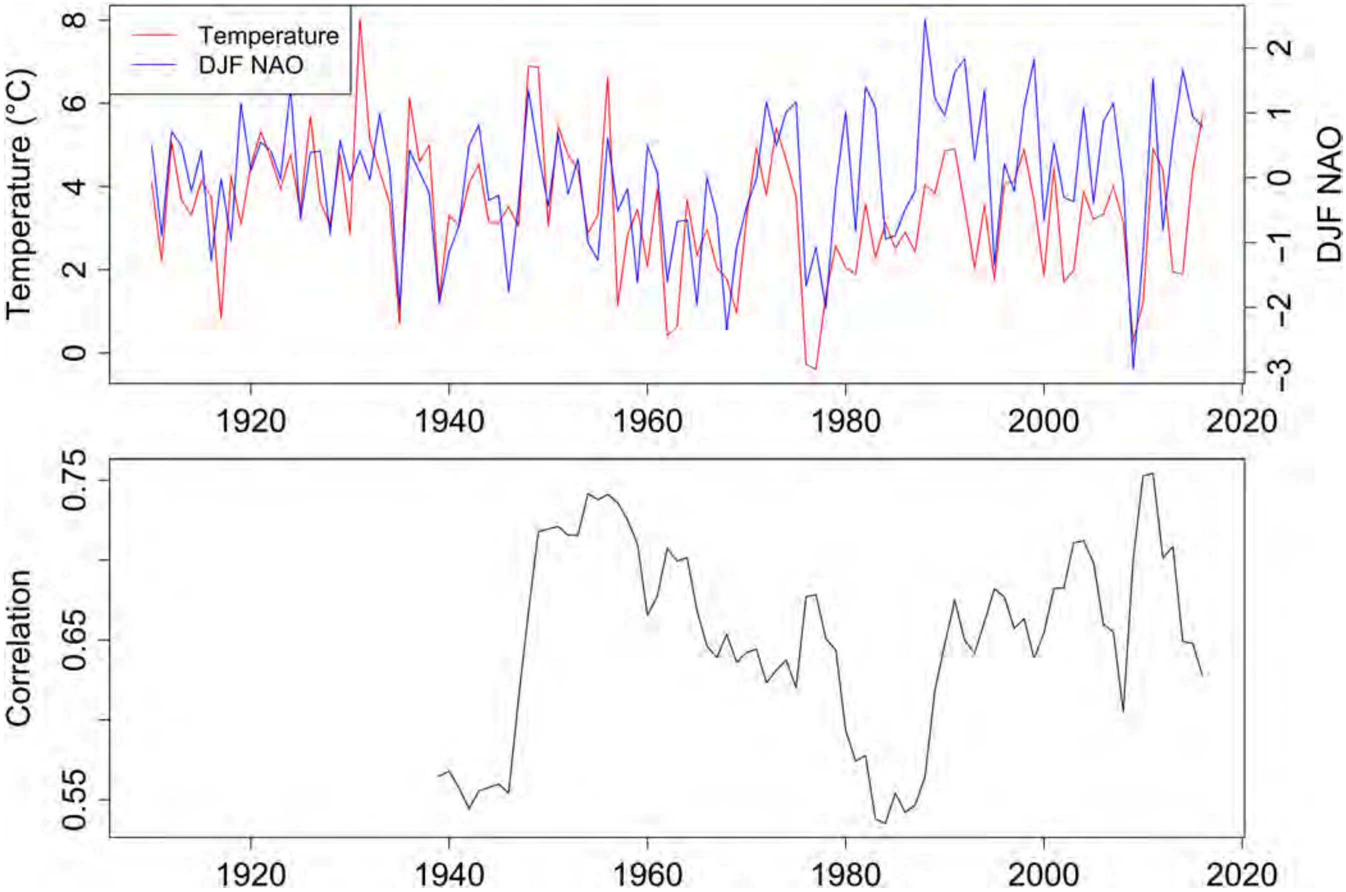

FIGURE 6 Time series between mean winter temperature (°C) in the SAM and the NAO alongside a 30-year running correlation that illustrates how the relationship has changed over time [Colour figure can be viewed at wileyonlinelibrary.com]

freezing rain (Bell and Bosart, 1988). The variety of storm tracks, as well as the frequency of cold-air damming events, could also play a role in the regional variability of snowfall totals compared to that observed with temperature (Ellis *et al.*, 2017).

The significance of the relationships between individual teleconnection patterns and the winter climate of the SAM can be explained by the physical mechanisms of each climate mode. During positive NAO winters, the Bermuda/Azores high enhances the flow of southerly wind anomalies and blocks the polar jet stream from entering the eastern United States, ultimately enhancing the likelihood of above normal temperatures (Ning and Bradley, 2015). However, negative NAO winter seasons result in a deepening trough over the eastern United States allowing for the intrusion of cold air outbreaks in the region (Notaro *et al.*, 2006; Westby *et al.*, 2013). The negative phase of the pattern also entrenches cold air in the region and improves the likelihood of Great Lake-enhanced northwest flow snowfall, which explains why the higher elevations exhibit much stronger relationships with the NAO than foothill regions (Notaro *et al.*, 2006; Seager *et al.*, 2010; Cohen *et al.*, 2014). It is important to note that there have been variations in the strength of the relationship between the NAO and seasonal temperature of the SAM (Figure 6). Further research is needed to better understand the variability of relationship strength between regional climate variables and large-scale patterns.

While much emphasis has been put into understanding the relationship between Pacific climate modes and the climate of the western United States, our results show that both ENSO and the PDO influence seasonal conditions in the SAM. In particular, the eastern foothills have much stronger relationships with ENSO than the rest of the region. This is due, in part, to the dependence on Miller-type systems for producing snowfall in the area, which are more common during El Niño patterns and yield heavier precipitation and more frequent snowfall (Frankoski and Degaetano, 2011). Similar to Higgins *et al.* (2002), we found that during La Niña winters, the SAM experience much higher temperatures, which hinders the ability to produce accumulating snowfall. The PDO often enhances the expected ENSO induced seasonal conditions in the region, with warm PDO phases complementing El Niño conditions and cool PDO conditions with La Niña patterns.

By coupling large hemispheric and global patterns, it becomes more clear why this region has remained a climate change anomaly and experienced high amounts of seasonal variability. In the SAM, anomalous winter temperatures and snowfall are modulated by a combination of the NAO, ENSO, and PDO. −NAO/El Niño patterns are the most conducive for producing negative temperature anomalies and higher snowfall amounts in the SAM. The reason these patterns sync to create anomalous conditions is due to the negative NAO entrenching Arctic air and El Niño conditions enhancing precipitation through a high number of Miller-systems, as was the case with the 2009–2010 winter season (Osborn, 2010; Seager *et al.,* 2010). Conversely, +NAO/La Niña winter patterns are more conducive to positive temperature anomalies and less snowfall.

The rapid warming of the Arctic, also known as Arctic Amplification, may be influencing the winter climate of the mid-latitudes, potentially increasing the amount of weather extremes, including cold spells, heat waves, drought, and flooding (Francis and Vavrus, 2012; Cohen *et al*., 2013; Cohen *et al.,* 2014; Screen, 2014). Increases in Siberian snow cover during the autumn have also been connected to more extreme periods of negative AO and NAO patterns (Cohen and Entekhabi, 1999). Similarly, research has linked an increase in the phenomenon known as sudden stratospheric warming and the Quasi-Biennial Oscillation to recent winter extremes in the Northern Hemisphere (Cohen *et al.,* 2009; Scaife *et al.,* 2014). These identified changes in the Arctic could lead to more consistent periods of negative NAO patterns in the winter season, which would favour a continued cooling trend in the SAM and may result in more seasons with snowfall and temperature extremes.

6.1 | Caveats

The lack of data in higher elevations and the poor spatial coverage of observations in the SAM is a concern and a limitation of this study. This is especially a problem in the western extent of the study area and high elevation locations during high impact events and seasons (e.g., the 1960s), making results harder to interpret in some areas. Human error and improperly sited weather stations are commonly known problems with COOP station data and should be recognized (Davey and Pielke, 2005; Fall *et al.,* 2011). Instrumentation used in measuring temperature has changed throughout time, which results in slight shifts in how data are recorded. However, these changes have not influenced the overall climate signal (Menne *et al.,* 2010).

7 | SUMMARY AND CONCLUSIONS

In this study, we analysed long-term regional climate data along with several global and hemispheric teleconnection patterns to further understand the climatic complexity of the SAM. Our results show that mean winter temperatures have experienced a statistically significant decline since the early 20th century with high interannual variability in snowfall. As a region that has remained resistant to the rate of warming observed worldwide and experienced little change in snowfall, our identification of favourable scenarios for producing anomalous temperatures and snowfall in the SAM helps provides clarity into how this region has remained a climatic anomaly. The findings of this study can be used to bolster discussions with the public about the complexities of climate change. This is especially important for regions like the southeastern United States and Appalachian Mountains, where citizens are less likely to believe that climate change will affect them directly (Howe *et al*., 2015). Continued analysis of climatologically anomalous regions, like the SAM, is crucial to understanding the impact of naturally occurring global and hemispheric forcings in masking or amplifying the impacts of the warming global climate.

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