Identification of large scale climate patterns affecting snow variability in the eastern United States

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ABSTRACT: This study investigates dominant patterns of snow variability and their relationship to large-scale climate circulations over the eastern half of the United States. Two snowfall variables – total seasonal snowfall (TSF) and number of snow days (NSD) – are examined. A principal components (PC) analysis is conducted on data from 124 snowfall stations. The leading mode of variability for both TSF and NSD is driven by the North Atlantic Oscillation (NAO). The secondary mode of variability for TSF is driven by the Pacific/North American pattern (PNA), while the secondary mode of variability for NSD is driven by a dipole pattern and is attributable to regional influences and noise. These patterns exhibit persistence, which provides prospects for seasonal predictions of snowfall variables. This research compliments and extends the work of Serreze et al. (1998), who performed a PC analysis of geopotential heights during the winter season and correlated the spatial patterns of the leading modes of variability with seasonal snowfall values. Copyright © 2007 Royal Meteorological Society

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1. Introduction

Variability in snowfall and snow cover has a profound impact from global scales to individual communities. Large snowfall events affect communities by effectively shutting down businesses and creating transportation problems. In the eastern United States, the predictions of annual snowfall amounts are important for community planners, water resources managers, and snow-dependent recreational facilities. Predicting snow is a relevant and difficult problem as snowfall is highly localized in its occurrence and is influenced both directly and indirectly by a number of climatic factors, including temperature, precipitation, large-scale atmospheric circulation patterns, and topographic effects (Brown, 2000; Serreze et al., 2001; Serreze et al., 1998; Clark et al., 1999; Cayan, 1996; McCabe and Dettinger, 2002). Thus, there is a present need for a thorough understanding of the factors that affect snowfall frequency and magnitude for accurate predictions of snowfall in a given winter season.

The paper begins with broad background information on large-scale climate patterns that influence the eastern U.S. Following this is a description of the data sources utilized, and a brief description of the general relationships between climate variables (temperature and precipitation) and snowfall variables. Next, a principal component analysis (PCA) on two station variables, total seasonal snowfall (TSF) and number of snow days (NSD), is described. The spatial patterns of the first two principal components (PC) are presented, along with independent correlations of the PC with climate variables to identify regions of importance and specific climatic forcings. The paper concludes with a summary and discussion.

Several aspects of this work help to advance the research of climate factors affecting variability in snowfall in the eastern United States. First, the methodology employs a PCA on two snowfall variables over a study area comprising of the entire eastern U.S. Second, the study includes the number of days snow fell at each station as a variable in the analysis. NSD is a variable not often studied in literature, but quite relevant to policy makers interested in the number of times it will snow in their region each winter.

2. Background

The eastern United States climate is impacted by large-scale atmospheric circulation in both the Pacific and Atlantic regions (Mantua et al., 1997; Thompson and Wallace, 1998; Kushnir et al., 1999; Hurrell, 1995b). The North Atlantic Oscillation (NAO) is a primary mode of atmospheric variability over the North Atlantic region on decadal time scales (Hurrell, 1995a; Barnston and Livezey, 1987; Kushnir et al., 1999; Walker and Bliss, 1932; Wallace and Gutzler, 1981). Wallace and Gutzler (1981) link the intensity of the Icelandic low, as associated with the NAO, to 700 mb pressure anomalies over...
land surfaces in the Atlantic region. A strong Icelandic low is conducive to positive pressure anomalies over the eastern US and northwestern Europe. Hurrell (1995b) and Kushnir et al. (1999) describe the physical mechanisms of the NAO, including its impact on European and American climates.

The Pacific/North American pattern (PNA) has also been identified as a major contributor to climate variability over North America during winter (Barnston and Livezey, 1987; Wallace and Gutzler, 1981). Leathers et al. (1991) indicate that the PNA is highly correlated with monthly temperature and precipitation over most of the contiguous U.S. from September to May. Deepening of the Aleutian low during positive PNA years causes the jet stream to bring cold Arctic air and lower temperatures to the eastern U.S. Increased meridionality causes decreased precipitation in the northwestern and southeastern U.S., by steering tropical convective storms northward, and bringing dry Arctic air to the southeastern U.S. Northern Hemisphere temperature and precipitation variations are related to the PNA on interannual time scales. The PNA pattern is modulated by sea surface temperature (SST) anomalies in the Pacific Ocean, specifically the El Nino-Southern Oscillation (ENSO) phenomenon.

Various climatic conditions in the eastern U.S. pertaining to snow have been studied over the past few decades, including snowfall and precipitation amounts and inter-relationships with temperature. Janowiak and Bell (1999) examine wintertime cold-air outbreaks in the U.S., and note that the frequency of outbreaks in the eastern part of the U.S. decreases during both positive ENSO years (El Nino) and negative ENSO years (La Nina) winters. Groisman and Easterling (1994) observed that annual precipitation has increased by 13% in southeastern...
Canada and by 4\% in the U.S over the past century. More recent studies have associated snowfall with geopotential height and SST anomalies. Serreze et al. (1998) identify three dominant large-scale climate patterns that contribute to variability in snowfall over the eastern U.S.: the PNA, the TNH (Tropical-Northern Hemisphere), and the EP (east Pacific) pattern. In addition, the authors denote two distinct snowfall regions, divided by limiting factors in snow production. The first includes the upper Midwest, Kansas, and Nebraska, where snowfall is a function of precipitation. The second includes the remaining Midwest, the southeast, and the northeast, where snowfall is a function of temperature. Hartley and Robinson (1999) studied potential links between climate anomalies and SST anomalies along the east coast of the U.S. They note that negative SST anomalies off the northeast coast during fall produces above average snowfall from the central Appalachians to the east coast during the following winter. Additionally, they found that lower 700 mb geopotential heights over the southeastern U.S. and Atlantic in wintertime, when preceded by a cold fall, tend to result in lower wintertime temperatures, creating more potential for precipitation to fall as snow. Bradbury et al. (2003) linked New England snowfall variability to the NAO, ENSO, and the pacific decadal oscillation (PDO) via regional storm tracking patterns. They also identify a significant correlation between snowfall and regional SST anomalies, and suggest snowfall may also
be indirectly modulated by NAO influence of SST variability.

The previous section illustrates how past research has contributed to the understanding of snowfall variability over the eastern U.S. More investigation into the specific patterns, circulations, and areas of the globe that influence snowfall variability is necessary to make accurate predictions of seasonal snowfall for water managers and policy makers in this region. The intention of this study is to examine the association of station snow variables in the eastern portion of the contiguous U.S. with northern hemisphere climate variables, including SST, pressure and winds, with the hope of including these new relationships into future snowfall prediction models.

3. Data

Climate data from 227 observation stations located throughout the eastern half of the United States is utilized in this study. The seasonally-averaged winter data (November–March) was obtained from the National Weather Service Cooperative (COOP) network of stations for the period 1951–2001. This equates to one annual value per variable per station. It is well known that inconsistencies exist within the COOP data, including sampling time and frequency, measuring equipment, local effects, etc. None of these issues have been explicitly dealt with in this study.

Station locations are shown in Figure 1. Climate records for each station include number of precipitation days, total seasonal precipitation, maximum temperature on precipitation days, mean seasonal maximum temperature, NSD, number of days with snow on the ground, and TSF (actual depth). The records are substantially complete, although missing annual values for a variable occasionally exist. To minimize uncertainty, a station was eliminated from a variable set if it lacked annual values for three or more years during the period of analysis. The number of stations retained in the variable sets ranged from 216 stations (TSF) to all 227 stations (total seasonal precipitation). Any remaining gaps were filled with the average value for the variable at that station during the study period.

Monthly NAO and Southern Oscillation Index (SOI) values were obtained from the National Oceanic & Atmospheric Administration’s (NOAA) Climate Prediction Center web site, and represent the sea-level pressure differences between Iceland and the Azores. Monthly PNA values, as derived by the Wallace and Gutzler
4. General relationships of climate variables

In an effort to identify general patterns in temperature and precipitation governing the physical mechanisms of snow over the eastern United States, plots of average station variables over the wintertime study period were created. Average values of mean seasonal maximum temperature (Figure 2(a)) and maximum temperature on precipitation
days (not shown) illustrate the expected zonal decrease in temperature with increased latitude. A plot of mean total seasonal precipitation (Figure 2(b)) points to a high center of precipitation in the south central portion of the study area over Alabama and Mississippi, with decreasing amounts of precipitation moving away from this center, especially over the Midwestern states. Precipitation in the form of snow is recorded according to its snow water equivalent. This spatial pattern is not unexpected, and coincides with well-know precipitation patterns. Coastal states typically experience higher quantities of precipitation, due to their proximity to the ocean, than those farther inland (Joyce, 2002). El Nino tends to emphasize this wintertime pattern, while La Nina has a propensity to reverse the trend, especially in the southeast and Ohio valley, becoming drier and wetter, respectively (Livezey, 1999).

TSF and NSD (Figure 3(a) and (b)) tend to be highest surrounding the Great Lakes region and into the northeast, where cold seasonal temperatures and high amounts of precipitation serve to produce large amounts of snow. The Great Lakes region receives snowfall based on the lake effect, a phenomena caused by cold arctic air blowing over the relatively warm lakes, picking up moisture, then rising, causing the moisture to condense, and finally snowing over the downwind land (Heidorn, 1998; Niziol et al., 1995). Numerous studies have investigated wintertime precipitation in the northeast (Bradbury et al., 2002, 2003; Hartley, 1996; Hartley and Keables, 1998) as previously outlined, attributing variability to sea-surface temperatures, geopotential heights, and the NAO, allowing for colder temperatures, causing more precipitation to fall as snow. Contrastingly, TSF and NSD were very low (less than 5 days of snow and less than 200 mm of total season snowfall) south of Missouri, Kentucky, and Virginia, due to warmer seasonal temperatures. Therefore, as a result of their low values and minimal contribution to snowfall patterns, stations south of 35°N are not included in the subsequent analysis.

A spatial map of correlations between TSF and NSD at each station, presented in Figure 4, shows significant positive correlation over the entire remaining study area. Correlations of these and other variables in the paper were computed using the Pearson correlation coefficient and were tested for field significance using the Monte Carlo technique outlined in Livezey and Chen (1982) and described in von Storch and Zweirs (1999). This technique recognizes that spatial data across a region are not independent, and determines the probability of obtaining a significant result simply by chance. The field significance level, computed using a Pearson correlation coefficient and 1000 Monte Carlo simulations of a random time series, was 11.6 for the 121 stations with both TSF and NSD data. The number of stations with significant correlations was determined for each spatial map of correlation presented in this paper, and was found to be above the field significance level, or 95th highest ranking of randomized significance, in all cases reported. The strong positive correlations of TSF and NSD are expected and intuitive, as years with numerous snow storms typically produce high seasonal snowfall totals. Cold air is dominant in this region, causing precipitous days to often be snowy days. The variability in correlations is mostly due to local features, such

Figure 10. Correlation of (a) EOF1 of total snowfall with total precipitation, and (b) EOF1 of total snowfall with number of snow days. Values outside of $+/-0.178$ indicate 90% significance.

Figure 11. Spatial pattern of EOF2 of total snowfall.

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Figure 12. (a) PC2 of total snowfall correlation with 500 mb geopotential height; shaded regions are 90% significant. (b) PC2 of total snowfall (solid line) and December–February PNA-index (dashed line) time-series. This figure is available in colour online at www.interscience.wiley.com/ijoc

as topography, prevailing wind patterns, lake or ocean proximity, etc., evident by neighbouring stations with significantly differing correlation values.

A map of the correlation at each station between TSF and mean seasonal maximum temperature indicates a large region of significant negative correlation (Figure 5(a)). Again, this is instinctive, as temperatures are a dominant factor in whether precipitation will fall as rain or snow. Small negative correlations are evident near 35°N, where significant snowfall is less likely due to generally warmer conditions; a change in maximum seasonal temperature will not typically convert this region
from a rainy to snowy region. Likewise, small negative correlations are present near the Great Lakes regions, but for the opposite reason; temperature variability will not typically transform this snowy region into a rainy one during the wintertime. Correlations between NSD and mean seasonal maximum temperature exhibit a similar relationship (Figure 5(b)), as expected, due to the relatively strong correlation of total snowfall and NSD. Small negative correlations are not as pronounced, though, as temperature variability plays a more pivotal role on a daily basis. (Some stations with small correlations in Figure 5(a) were removed for Figure 5(b) along 35°N for lack of data values, as described in the previous section. As a result, the interpretation for NSD is not as well supported as for TS.)

A correlation map between TSF and total seasonal precipitation at each station is shown in Figure 6(a). Boxes represent positive correlation, circles represent negative correlation. A low to moderate positive correlation between the two variables exists at the majority of stations north of 37°N. Where temperature is not a limiting factor (i.e. it is predominantly cold), the amount of snow falling in a given winter will increase as the total season precipitation increases. Indeed, correlations are highest in the northern regions, where cold temperatures prevail throughout the winter and snowfall is heavily dependent upon precipitation. In areas of low positive correlation, the influence of temperature and local topography could be more significant than total seasonal precipitation. A few stations in the southern portion of the study area exhibit small negative correlations; here, seasonal snowfall is more dependent upon temperature than precipitation. Correlations between NSD and total seasonal precipitation demonstrate a similar relationship (Figure 6(b)), although positive correlations in the north are not as strong, as the size and duration of storms are also factors.

5. Interpretation and analysis of regional and large-scale climate patterns

Two variables of great interest to water managers and utility personnel, TSF and NSD, were retained for further analysis. A PCA was conducted on the two variables independently to assess their potential associations with well-known large-scale climate patterns, as reported in previous studies. Owing to the orthogonal nature of the PCA, dominant climate patterns are readily identifiable by correlation with large-scale climate variables (sea-surface temperature, sea-level pressure, etc.) The PCA was performed on stations for each variable that met the aforementioned criteria; this resulted in 124 stations for TSF and 121 stations for NSD.

The first PC of TSF and NSD explain approximately 30 and 35% of the variance, respectively, while each of the remaining PCs explains less than 15% of the variability in its respective variable. Figure 7(a) and (b) illustrate this for the first ten PCs. North’s Rule of Thumb, as described in von Storch and Zueirs (1999), is employed for determining the number of PCs to retain. This roughly equates to the first three for TSF (totaling 51.9% of the variance explained), and the first two for NSD (totaling 45.8% of the variance explained). The remaining PCs, collectively explaining approximately half of the variance in the data, are assumed to be representative of local features or noise in the data. This result is a product of the large geographic region and numerous stations being considered. Smaller regions or fewer stations in closer proximity typically result in greater percentages of variances explained. For example, if only the southeastern quad of this region is considered, the variance explained in the first three PCs increases to approximately 75 and 70% for TSF and NSD, respectively – a substantial jump. Further limiting the region to Virginia and Maryland increases the variance explained to nearly 90%.

Although the large-scale climate patterns affecting the entire eastern half of the U.S. may be expected to be less pronounced than for smaller areas, the PCA still greatly aids in understanding what drives the interannual variability of TSF and NSD. The following sections outline each PC retained, via spatial loading patterns, association with large-scale climate patterns, and interrelationships with other variables.

5.1. Total seasonal snowfall (TSF) PC1

PC1TsF explains approximately 30% of the variance. Figure 8 provides a representation of the spatial loadings of the first empirical orthogonal function (EOF1TSF). The EOF1TSF pattern indicates that this first mode instills a relatively uniform influence over the entire eastern U.S. for the stations included, especially across the extended Great Lakes region and northern east coast, and may be inferred as an average snowfall index.
A correlation map of the PC1 TSF time-series with 500 mb geopotential height, in the concurrent season, is presented in Figure 9(a). This pressure pattern resembles the NAO, with the classic Atlantic dipole, although the regions of highest correlation do not coincide exactly with the major centers of action of the NAO (i.e., Iceland and Portugal) as defined by van Loon and Rogers (1978). Nonetheless, the similarity is evident. Also present is a strong high pressure centered over the Midwest/Great Lakes region. The
PC1_{TSF} time-series and December–February NAO index are illustrated in Figure 9(b). As expected, there is only a moderate correlation with the standard NAO index (correlation coefficient = 0.47), indicating that alternative indices may need to be identified to predict seasonal snowfall.

Figure 10 illustrates correlations of EOF1_{TSF} with two station variables: total seasonal precipitation and NSD. The intent of these figures is to aid in identifying regional relationships and variable dependence that may not be intuitive. Correlations between EOF1_{TSF} and total precipitation are predominantly positive over the east coast and Atlantic states region (Figure 10(a)). This is anticipated, as positive phases of the NAO typically imply warmer temperatures and more precipitation over the eastern half of the study area. In this region snowfall is dependent upon precipitation as shown in Figure 6; thus a positive NAO increases snowfall. These positive correlations fade moving inland, and the Midwest and upper Midwest act in contrary fashion for positive NAO phases, experiencing drier than normal conditions due to cold dry air surging from Canada. Opposite patterns result for negative phases of the NAO. The correlation between EOF1_{TSF} and the NSD presents a relatively low positive correlation throughout the majority of the southern and eastern portions of the study area, with weak negative correlations in the upper Midwest (Figure 10(b)). This implies that the NAO-like mode of PC1_{TSF} has minimal bearing on the NSD, but does constitute more (less) days of snow in the south and east (Midwest) for positive phases, and vice-versa.

5.2. Total seasonal snowfall (TSF) PC2
PC2_{TSF} explains approximately 13% of the variance. Figure 11 exhibits the spatial loading of EOF2_{TSF}. A dipole pattern of negative loadings in the Midwest and positive loadings on the Atlantic Coast are clearly evident.

Correlation maps of PC2_{TSF} and 500 mb geopotential heights create sandwich patterns in both the Atlantic and Pacific oceans. While the dominant mode of total snowfall is driven by patterns in the Atlantic, the secondary mode is driven by patterns in the Pacific and over the north American continent. The geopotential correlation map, Figure 12(a), illustrates a strong low pressure zone just off the southeastern tip of the U.S., a weaker low pressure zone in the north Pacific Ocean, and a high pressure zone over the northwest U.S. This three-point configuration is similar to the PNA pattern described by Barnston and Livezey (1987). A positive PNA phase typically produces below-average precipitation in the upper Midwest, as denoted in Figure 11, thereby decreasing snowfall. A positive PNA also pulls cold air from Canada to the eastern half of the United States and decreases temperatures, thus increasing the proportion of precipitation that falls as snow. Figure 12(b) depicts the PC2_{TSF} time series along with the December–February PNA time series as derived by Wallace and Gutzler (1981); again, the moderate correlation ($r = 0.27$) emphasizes the need to develop alternative indices for seasonal snowfall prediction.

5.3. Total seasonal snowfall (TSF) PC3
The third and final principal component retained for total snowfall, PC3_{TSF}, explains approximately 9% of the variance; Figure 13 exhibits the spatial loading of EOF3_{TSF}. A contrasting pattern of low negative correlation throughout the central Midwest portion of the study area below the Great Lakes and low positive correlation in the far eastern and western portions of the study area is evident.

Figure 14(a) maps the correlation of PC3_{TSF} with SST. The familiar correlation in the equatorial Pacific waters points to a potential connection with an ENSO-like pattern. El Niño years typically compel warmer and drier conditions in the upper Midwest and cooler and wetter conditions in the southeast; La Niña years typically produce opposite effects. These conditions are consistent with the EOF3_{TSF} spatial loadings of Figure 13, where the Midwest and east coast have opposing responses to the pattern. Figure 14(b) presents the PC3_{TSF} and December–February SOI time series; not surprisingly, the moderate correlation ($r = 0.28$) reflects the spatially large and diverse study area.

5.4. Number of snow days (NSD) PC1
PC1_{NSD} explains approximately 35% of the variance. The spatial loadings of EOF1_{NSD}, presented in Figure 15, closely approximate the spatial loadings of PC1_{TSF}. Once again, PC1_{NSD} can be inferred as an average index of the NSD during the winter season.

A correlation map of PC1_{NSD} with 500 mb geopotential height for the same season is presented in Figure 16(a). This correlation is distinctly similar to PC1_{TSF}, and also resembles the NAO pattern. The time-series of PC1_{NSD} and the December–February NAO are displayed in Figure 16(b). The correspondence between

![Figure 15. Spatial pattern of EOF1 of number of snow days.](image-url)
the NAO index and PC1_{NSD} is slightly stronger ($r = 0.52$) than the NAO with PC1_{TSF}. Physical mechanisms controlling snow frequency and variability are similar to those described for PC1_{TSF}. This dominant NAO-like pattern may prove useful for seasonal predictions of the NSD.

Figure 17 illustrates correlations of EOF1_{NSD} with total seasonal precipitation and TSF. The correlation between the spatial loading and total precipitation, as shown in Figure 17(a), is not dissimilar to the correlation of EOF1_{TSF} to total seasonal precipitation, but indicates greater anomalies in the midwest and Great
Figure 17. Correlation of (a) EOF1 of number of snow days with total precipitation, and (b) EOF1 of number of snow days with total snowfall. Values outside of $\pm 0.178$ indicate 90% significance.

Lakes region, perhaps indicating local features (such as the lake effect) that have an influence on seasonal NSD. Figure 17(b) shows a strong positive correlation between EOF1_NSD and total snowfall that is homogeneous over nearly the entire study area. This is intuitive, and agrees with prior figures in establishing the strong relationship between NSD and TSF, but also furthers the notion that the PC1_NSD mode is similar to the NAO in bringing more snow to the region, excluding the midwest.

As PC1_TSF and PC1_NSD both describe an NAO-like pattern, and possess nearly identical pressure patterns in the Atlantic Ocean, it is logical to believe the two are closely related. The correlation coefficient between the two is 0.91, significantly greater than the straight station correlations of the two variables (Figure 4).

5.5. Number of snow days (NSD) PC2
PC2_NSD explains approximately 11% of the variance; Figure 18 shows the spatial loading of PC2_NSD. A dipole pattern similar to the one in Figure 11 for EOF2_TSF is apparent. A correlation map with 500 mb geopotential heights, illustrated in Figure 19(a), specifies a pattern more likely to be associated with regional influences. No known large-scale patterns are identified, but a strong configuration is present. The geopotential correlation map illustrates a strong anomalously low pressure zone throughout the upper northeast U.S. and along the West Atlantic coastal waters. A strong anomalously high pressure zone resides over the southwest U.S., centered on Nevada. These two pressure systems abut in the middle of the study region, working in tandem to pull cold dry air from Canada and decrease snow in the Midwest. The dividing line between systems approximates the dividing line between positive and negative correlations in Figure 18, and may be responsible for the differing signs. Much of the atmosphere between 30°N and 30°S consists of anomalously low pressure zones, which form a band around the globe, demonstrating some annular oscillation patterns. This pattern is not a persistence of the previous season’s pattern, although much of the low pressure band is beginning to form. The sea-surface pattern correlation with PC2_NS, presented in Figure 19(b), includes cool SSTs off the East Coast and into the central Atlantic, and warm SSTs south, from the northwest coast of South America well into the Atlantic. This pattern persists and grows in intensity and spatial realm from the fall into the winter season for PC2_NS.

6. Summary and discussion
This study identifies large-scale climate patterns and their influence on wintertime precipitation and temperature variables for the eastern United States. Associations with well-known patterns, including the NAO, PNA, and ENSO, are interpreted based on a PCA on TSF and NSD. Broad physical mechanisms responsible for seasonal variability of snowfall are also explored.

Scale is a critical feature in interpretation of climatic influences on snow variables. Although it has been
quite well established in previous studies that well-known large-scale climate patterns do effect wintertime variables in the eastern United States, those patterns do not necessarily present themselves in a clear manner. This is mostly attributable to the large geographic extent of the study area, its diversity, and influence by local features. Stations located on the windward or leeward side of a mountain, for example, may be more influenced by orography than any global pattern. Specific modes often become more evident as the spatial region and/or number of stations is reduced.

The large-scale climate patterns identified also offer promise for prediction. Forecasting methods may include use of one-season lead predictors to estimate PCs, which may be back-transformed to predict TSF or NSD. This could be accomplished by means of statistical models, utilizing climatic predictor values from the historical record. Performing a PCA on a state-size region or...
smaller, and forecasting locally, in lieu of forecasting for the entire eastern United States, may ultimately prove more valuable and accurate.

References


