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Large Scale Climate Patterns Affecting Snow Variability in the Eastern United States: Identification and Prediction

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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 snowfall and number of snow days, is described. Number of snow days 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. The spatial patterns of the first two principal components are presented, along with independent correlations of the principal components with climate variables to identify regions of importance and specific climatic forcings. Finally, a simple forecasting procedure is employed to determine if the patterns and teleconnections that are identified in the analysis are worthwhile for forecasting snowfall in the eastern U.S.

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 United States 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 United States 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 United States. Increased meridionality causes decreased precipitation in the northwestern and southeastern United States, by steering tropical convective storms northward, and bringing dry Artic air to the southeastern United States. 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 United States 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 El Nino and 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.

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.

Data

Snowfall and climate data at 227 stations located throughout the eastern United States was used in this study. Data was obtained from the NWS Cooperative (COOP) network of climate observation stations for the period of 1951 through 2001. Station locations are shown in Figure 1. Winter season (November to March) records at each station were obtained for total seasonal precipitation, mean seasonal maximum temperature, total snowfall, number of snow days, number of days with snow on the ground, and maximum temperature on precipitation days. While the records at each of these stations are quite complete, some data gaps were present. The study records for each variable were screened for gaps, and stations were eliminated from individual variable analysis if they lacked values for three or more years during the period of analysis. The remaining gaps were filled with the average value for the variable at that station during the study period.

General Relationships in Climate and Snowfall Variables

Plots of the average values of each variable for the study period at every station were created to identify general patterns in climate and snowfall over the eastern United States.

Plots of the average values of mean seasonal maximum temperature in Figure 2(a) and maximum temperature on precipitation days (not shown) illustrate the expected zonal decrease in temperature moving northward through the eastern United States. A plot of mean total seasonal precipitation in 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.

Mean values of total seasonal snowfall and number of snow days were greatest just east of the Great Lakes region as shown in Figures 3 (a) and (b), where low seasonal temperatures and high amounts of precipitation serve to produce large amounts of snow. On the other hand, total seasonal snowfall and number of snow days were very low (less than 5 days of snow and less than 200 mm of total season snowfall) south of Missouri, Kentucky, and Virginia. As a result of their low values, stations south of this region do not contribute to significant patterns in the analysis. Stations with total seasonal snowfall less than 200 mm and/or less than 5 snow days, which were all south of 35°N, were not included in the subsequent analysis.

Serial correlations were computed at each station between the snow and climate variables (total seasonal precipitation and mean seasonal maximum temperature) and plotted at each station to ascertain any spatial patterns in correlation. In addition, serial correlations between total seasonal precipitation and mean seasonal maximum temperature and between total seasonal snowfall and number of snow days were also plotted to see how these two sets of variables relate to one another.

A map of the correlation between total seasonal snowfall and number of snow days at each station, present in Figure 4, shows significant positive correlation between the two variables over the entire study area. The strong positive correlations are expected, as for years with many snow storms generally have high seasonal snowfall totals.

Maps of serial correlations at each station between total seasonal snowfall and mean seasonal maximum temperature indicate a large region of significant negative correlation northward of 35°N latitude in Figure 5 (a). In regions above 35°N, temperature can be a deciding factor in whether precipitation will fall as rain or snow. At stations north of 43°N the correlation begins to decrease slightly, as these stations typically experience cold weather and most precipitation during the winter season will fall as snow. Serial correlations between number of snow days and mean seasonal maximum temperature exhibit a similar relationship in Figure 5 (b), although the decreases in correlation northward of 43°N are not as pronounced. Similar physical mechanisms related to the formation of snow contribute to the patterns in these plots.

A map of the serial correlation between total seasonal snowfall and total seasonal precipitation at each station is shown in Figure 6 (a). A low to moderate positive correlation between the two variables can be seen at the majority of stations north of 35°N. Where temperature is not a limiting factor, the amount of snow falling in a given winter will clearly increase as the total season precipitation increases. Indeed, correlations are highest in the Northwest and New England regions, where cold temperatures prevail throughout the winter and snowfall is heavily dependent upon precipitation rather than temperature. Some stations in the southern portion of the study area, close to 35°N, exhibit a low negative correlation. In this region seasonal snowfall is more dependent upon temperature than precipitation. Serial correlations between number of snow days and total seasonal precipitation demonstrate a similar relationship in Figure 6 (b). Once again, similar physical mechanisms related to the formation of snow contribute to the patterns in these plots.

Results

A PCA was conducted on the total seasonal snowfall and number of snow days data to determine how these two variables are influenced by large-scale climate patterns. This analysis was performed on the reduced list of stations for each variable, which had those stations with less than 200 mm on average of total snowfall or less than 5 snow days on average removed. For each PC we produced spatial correlation maps of station precipitation, temperature, and snowfall across the eastern U.S., and spatial correlation maps of 500 hPa height and SST anomalies. The 500 hPa height and SST anomalies maps were created on NOAA's Climate Diagnostics Center (CDC) website.

The first two principal components of total seasonal snowfall and number of snow days combine to explain 42.9 and 46.6 percent of the variance respectively, as can be seen in Figures 7 (a) and (b). The remaining PCs each explain less than 10 percent of the variability in these variables and were not retained for further analysis.

The large-scale and regional patterns that can be inferred from the PCA greatly aid in understanding what drives the interannual variability of total snowfall in the eastern United States. Both spatial loadings and time-series representations provide insight into how specific climatologic patterns affect wintertime weather. The first two principal components from the analysis of the snow variables are identified and described in the following sections.

Total Snowfall (TS) Principal Component 1

Spatial Pattern

PC1 for total snowfall explains approximately 30% of the variance. Figure 8 provides a representation of the spatial loadings of PC1. The EOF spatial pattern indicates that this first PC instills a relatively uniform influence over the entire eastern U.S. for the stations included, and can be inferred as an average snowfall index.

Correlations with Geopotential Height

A correlation map of PC1 with geopotential height (same season) is presented in Figure 9. This correlation map, along with others not included here, resembles the NAO pattern. The NAO dipole is clearly evident in the north Atlantic in the geopotential height map shown in Figure 9 (a), although the regions of highest correlation do not coincide exactly with the major centers of action of the NAO (i.e., Iceland and Portugal, see vanLoon and Rogers, 1978). Also present is a strong high pressure centered over the Midwest/Great Lakes region. The time-series for PC1, with the NAO index included, is shown for the November-March season in Figure 9 (b). As expected, there is only a moderate correlation with the standard NAO index (correlation coefficient = 0.4), indicating that alternative indices need to be identified to predict seasonal snowfall.

Inter-relationships Between Variables

Figure 10 illustrates correlations of PC1 with two station variables: total precipitation and number of snow days. Along with the correlation maps, these figures aid in identifying regional relationships and variable dependence that may not be intuitive. Correlations between PC1 and total precipitation are strongest over the east coast region (Figure 10a). This is anticipated, as winds bringing moisture from the Atlantic over the coast dry out before reaching the interior states. Note that PC1 is negatively correlated with seasonal snowfall (Figure 8)—this means that the negative correlations presented in Figure 10 actually illustrate positive correlations between snowfall and precipitation. The correlation between PC1 of total snowfall and the number of snow days presents a strong negative correlation in the south-central portion of the study area and a weak negative to weak positive correlation in the northern and eastern areas under the NAO influence (Figure 10b). Although the leading mode of variability in snowfall is not necessarily related to number of snow days, these two variables are driven by the same large-scale pressure, temperature, and wind mechanisms. Their correlation implies that the NAO pattern causes the snowfall amounts for storms to be relatively homogeneous in the southern portion of the study area, and typically of a large nature, but much less homogenous for the north and east. In the northwest and northeast, the range of snowfall totals for a given day is more expansive, allowing for large and small events.

Total Snowfall (TS) Principal Component 2

PC2 for total snowfall explains approximately 13% of the variance. Figure 11 exhibits the spatial loading of the EOF2 of total snowfall. A dipole pattern of large positive loadings in the Northwest and large negative loadings on the Atlantic Coast can clearly be seen.

Correlation maps specify 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 high pressure zone just off the southeastern tip of the U.S., a weaker high pressure zone in the North Pacific Ocean, and a strong low pressure zone over the northwest U.S. This three-point configuration is similar to the Pacific/North American (PNA) pattern described by Barnston and Livezey (1987). Figure 12 (b) depicts the PC2 time series along with a PNA time series produced by Wallace and Gutzler (1981); again, the low correlation (r = 0.01) emphasizes the need to develop alternative indices for seasonal snowfall prediction.

Number of Snow Days (NSD) Principal Component 1

Spatial Pattern

PC1 for number of snow days explains approximately 35% of the variance. The spatial loadings of PC1 of number of snow days, presented in Figure 13, closely approximate the spatial loadings of PC1 of total snowfall. Once again, this PC can be inferred as an average index of the number of snow days during the winter season.

Correlations with Geopotential Height

A correlation map of PC1 with geopotential height for the same season is presented in Figure 14 (a). This correlation is distinctly similar to PC1 for total snowfall, and also resembles the NAO pattern. The time-series for this PC1 (simultaneous) is displayed in Figure 14 (b), with the NAO index included, for the November-March season. The correspondence between the PC1 time-series and NAO index is slightly stronger that the PC1 of seasonal snowfall (correlation coefficient = 0.5). Nevertheless, correlations are stronger in other regions (Figure 14a), indicating that alternative indices may improve seasonal predictions of the number of snow days.

Inter-relationships Between Variables

Figure 15 illustrates correlations of PC1 with two station variables: total precipitation and number of snow days. Once again, these figures aid in identifying regional relationships and variable dependence that may not be intuitive. The correlation between the spatial loading of PC1 and total precipitation, as shown in Figure 15 (a), is similar to the correlation of PC1 of total snowfall to total precipitation, but shows more anomalies in the Midwest, perhaps indicating local affects that have an influence on the number of snow days per season. Figure 15 (b) shows a significant negative correlation between PC1 of number of snow days and total snowfall that is homogeneous over the entire study area. This indicates that for the dominant mode of number of snow days, which is influenced by the NAO pattern, a high seasonal snowfall results from a small number of snow days. This also suggests that years with high total snowfall have a small number of large snow events, and years with low total snowfall have a high number of small snow events.

Since the first PC of total snowfall and the first PC of number of snow days are closely tied to the NAO pattern, they are also closely correlated to each other. The correlation between the time-series of the PC1 of total snowfall and the time-series of the PC1 of number of snow days has a coefficient of 0.91. The correlation between the spatial loadings of the two first PCs is 0.69.

Number of Snow Days Principal Component 2

PC2 for number of snow days explains approximately 11% of the variance. Figure 16 shows the spatial loading of the second principal component of number of snow days. A dipole pattern similar to but opposite of the one in Figure 11 for PC2 of total snowfall is apparent. A correlation map with geopotential height, in Figure 17 (a), specifies a pattern more likely to be associated with regional influences. No known large-scale pattern appears evident, 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. Much of the atmosphere between 30° north and 30° south 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 SST pattern, Figure 17 (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.

Forecasting

A simple forecast model, outlined in this section, has been developed to illustrate a potential prediction method for seasonal snowfall totals within the eastern U.S. at specific station locations. The premise of the model is to use one-season lead (August-October) predictors (geopotential heights or sea surface temperatures, for example) to estimate the principal components for that year. This is accomplished by means of models, utilizing predictor values from the historical record, based on least squares, weighted least squares, or other appropriate methodology. Assuming the first two PCs are estimated by two independent models, the remaining PCs are determined through a simple bootstrap method of the available record. The estimated PCs for the current year are then multiplied by the eigenvalues to back-transform total snowfall predictions at each station. Finally, probabilistic predictions, based on ensembles of residuals from the models, can then provide an expected range of snowfall totals for a given level of risk (Helsel and Hirsch, 1995). A similar approach may be employed for determining the number of snow days in a winter season.

To demonstrate, the first PC for total seasonal snowfall is predicted utilizing the method described above. In accordance with the large-scale patterns associated with PC1, an NAO-like index is constructed by subtracting 500 mb geopotential height values near Greenland from values near the United Kingdom. This index value for the previous season of August through October serves as a total seasonal snowfall predictor. For comparison, simultaneous (November through March) values for this index are also obtained. Although correlation maps of this NAO-like index indicate little persistence between the lead and simultaneous seasons, the early formation of the NAO-like pressure systems may be observed, and suffice for predictive purposes. Figure 18 depicts the lead season predicted PC1s, simultaneously predicted PC1s, and actual PC1 values for the 1951 to 2001 winter seasons.

As expected, in most cases the lead season value lies further from the actual value than does the simultaneous value. Seasons in which the lead season value is close to the actual value obviously imply a good PC1 value correlation, and therefore, after determining all PC values, may predict total snowfall totals that are close to actual snowfall totals. Specific station snowfall totals are not presented here. In this example, the predictor index does not appear to accurately reflect PC1 value extremes, perhaps due to the marginal association with the NAO. Identification of additional indices or relevant climatic variables may certainly aid in the prediction of PC1. Due to the large geographic extent of the study area and numerous regional influences, more localized PC analyses, as opposed to one representing half the country, are also certain to provide better PC estimates, and therefore superior estimates of total seasonal snowfall at each station.

Conclusions

The first pattern to surface for the principal component analysis performed on the selected stations' variables in the eastern United States is the North Atlantic Oscillation, explaining approximately 30% of the variance for total snowfall and 35% for number of snow days. The Pacific/North Atlantic pattern is also evident in the second principal component for total seasonal snowfall, and explains approximately 13%. No large-scale climate patterns are identified for the second principal component for number of snow days, which explains approximately 11%, and is attributable to regional influences and noise. Correlation and composite maps reveal the physical attributes associated with the NAO pattern, and further confirms its status as the driver of the leading mode of variability in snowfall. Also, the correlations of total seasonal precipitation with the first empirical orthogonal function of total snowfall and number of snow days shows influence of the physical mechanisms associated with the NAO pattern. The insights garnered from this analysis are used to illustrate the potential for a forecast model that allows for specific station snowfall prediction based on PC estimates from one-season lead predictor variables. The ability of this model is demonstrated by predicting the first PC of total snowfall using a one-season lead and simultaneous-season NAO-like value. Further development of the forecasting model, perhaps by creating a series of more localized sub-models that are better able to capture regional influences, will improve forecasting ability in an effort towards the goal of providing accurate seasonal snow forecasts for water managers and policy makers in the eastern United States.

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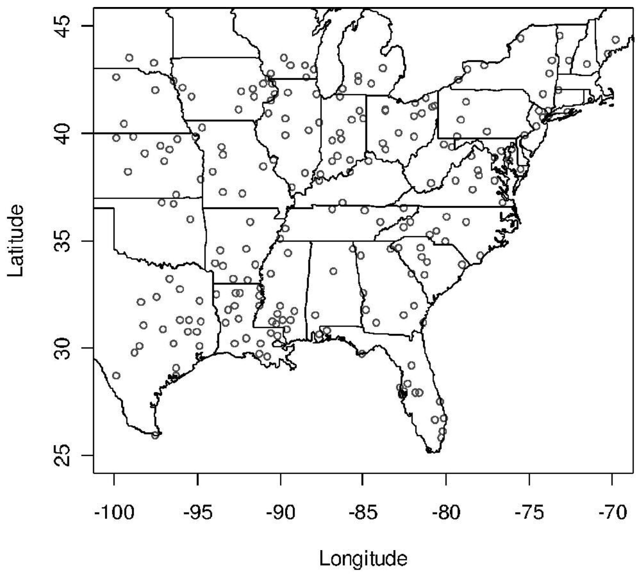
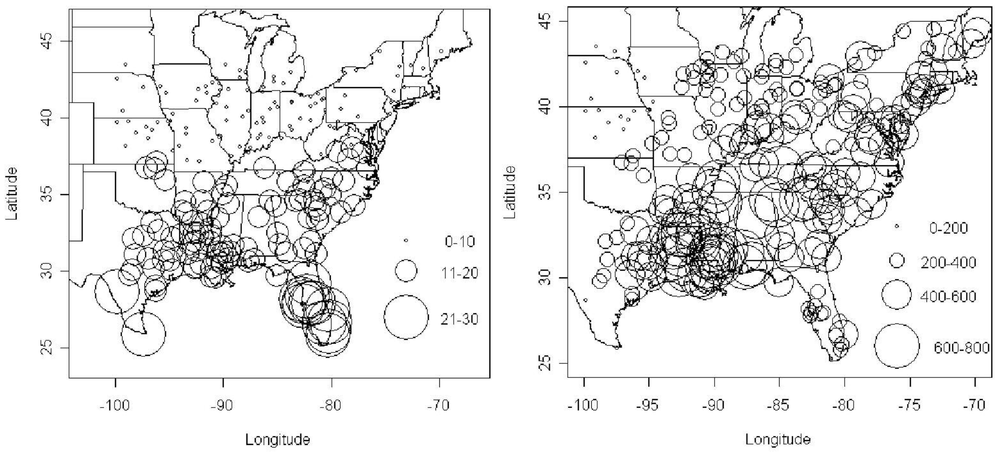
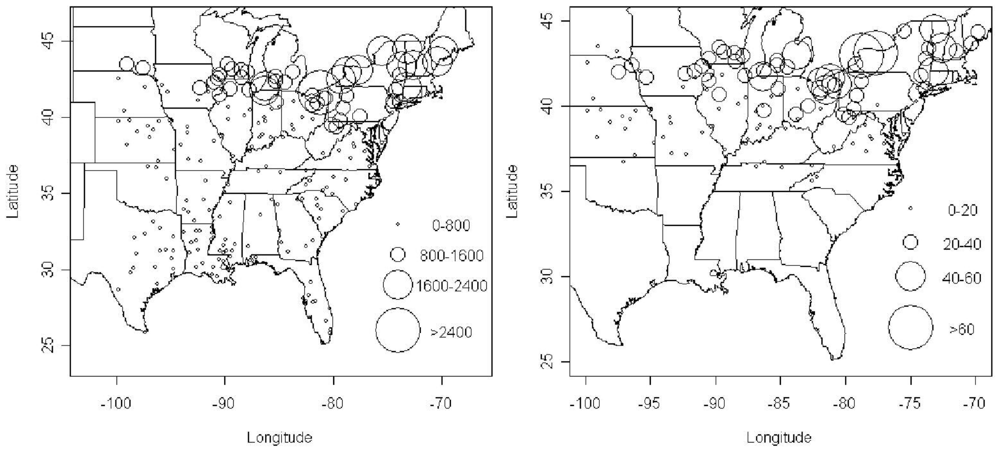


Figure 1 Locations of stations with data provided by the NWS COOP in the eastern U.S.



(a) (b)

Figure 2 Mean values of mean seasonal maximum temperature (a) and maximum temperature on precipitation days (b), both in degrees Fahrenheit.



(a) (b)

Figure 3 Mean values of total seasonal snowfall in mm (a) and number of snow days (b).

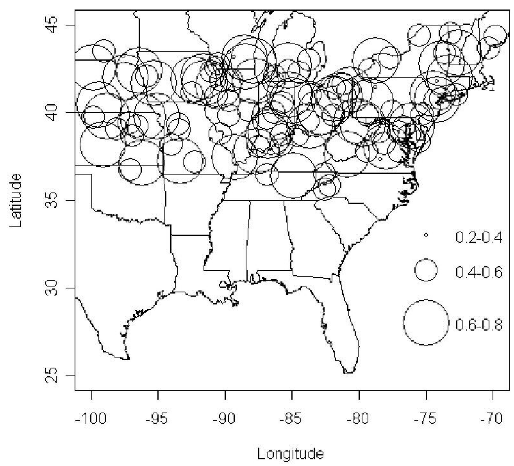
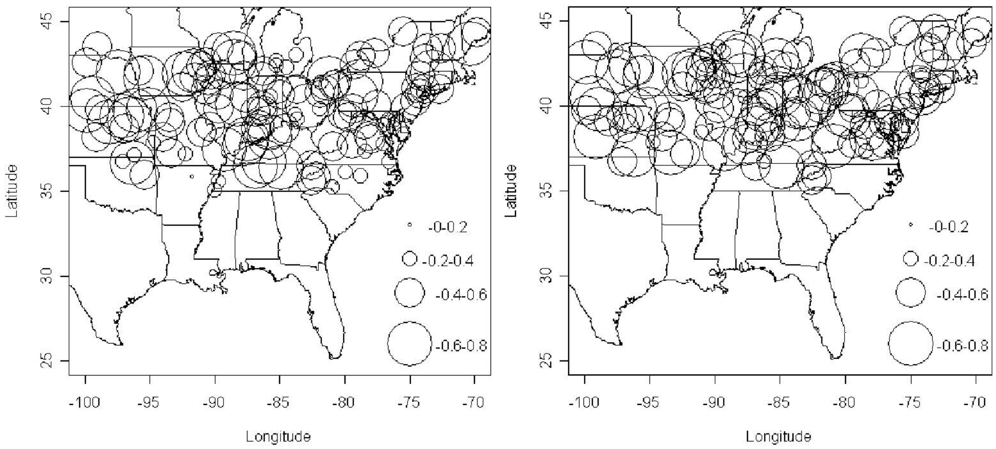


Figure 4 Correlations between total seasonal snowfall and number of snow days; values higher than 0.191 are statistically significant. All correlations are positive, and the size of the symbol indicates the magnitude of the correlation.



(a) (b)

Figure 5 Correlations between mean seasonal maximum temperature and total seasonal snowfall; values outside of +/- 0.195 are statistically significant (a) and mean seasonal maximum temperature and number of snow days; values outside of +/- 0.191 are statistically significant (b). All correlations are negative.

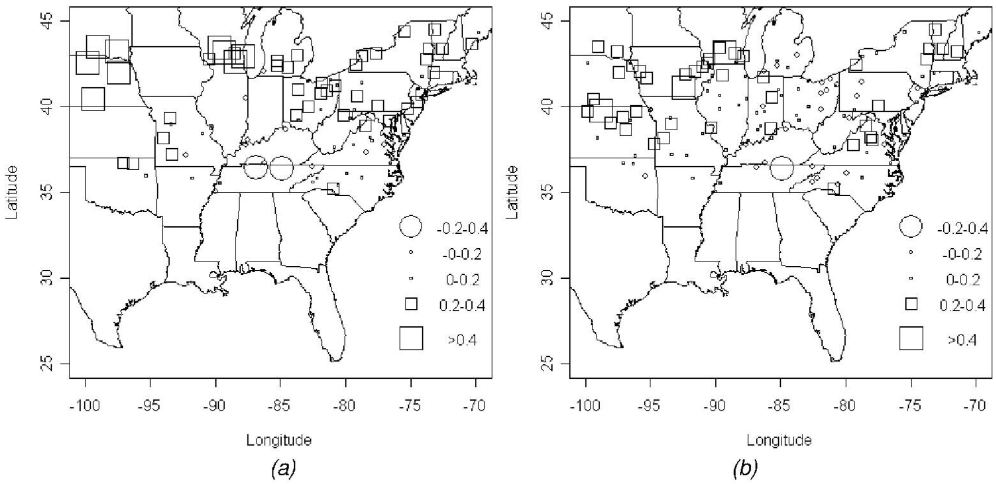


Figure 6 Correlations between total seasonal precipitation and total seasonal snowfall; values outside of +/-0.233 are statistically significant (a) and total seasonal precipitation and number of snow days; values outside of +/- 0.189 are statistically significant (b). Circles symbolize negative values and squares represent positive values.

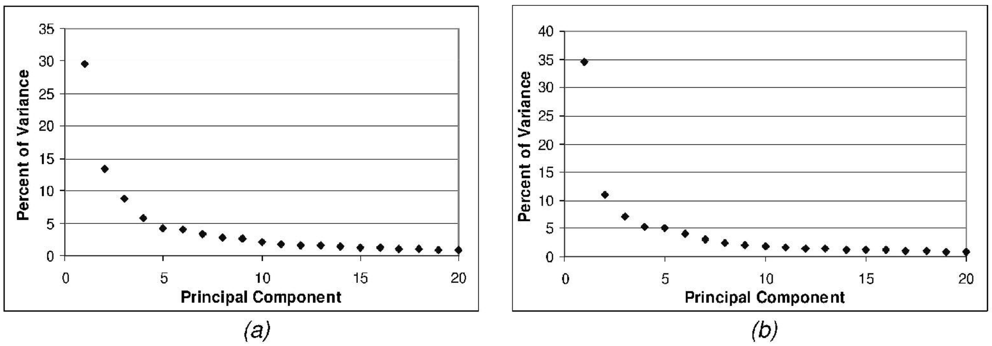


Figure 7 Percent of Variance Explained for First 20 PCs for Total Snowfall (a) and Number of Snow Days (b).

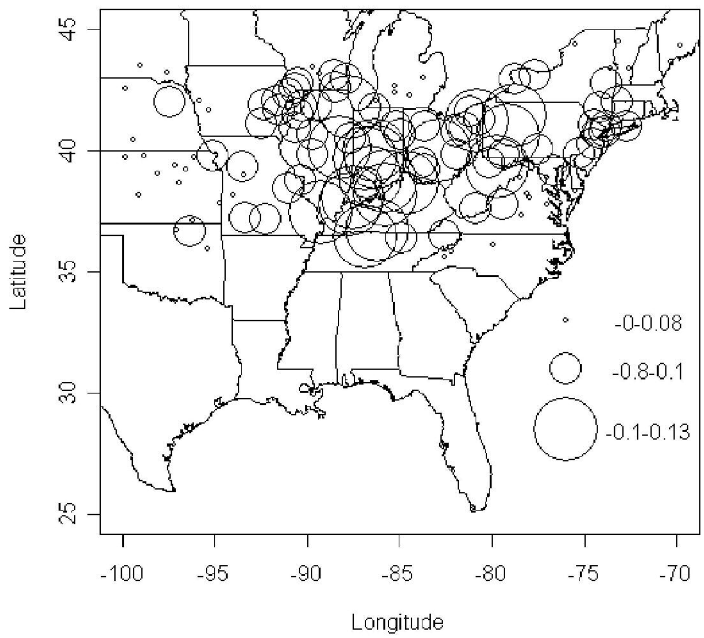
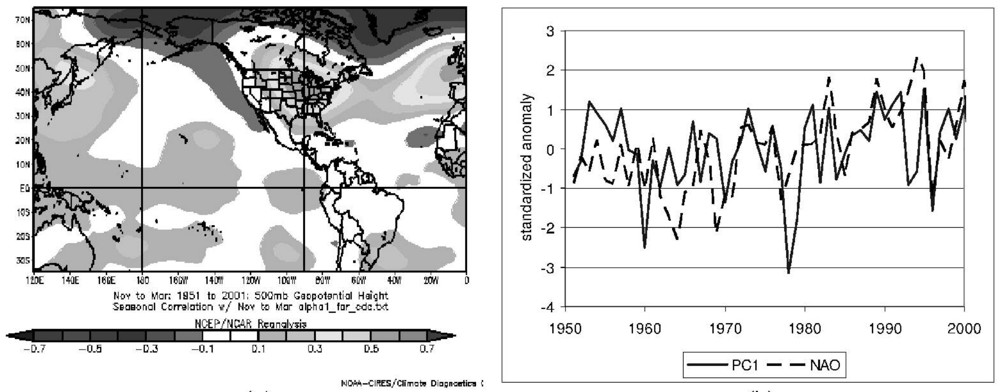


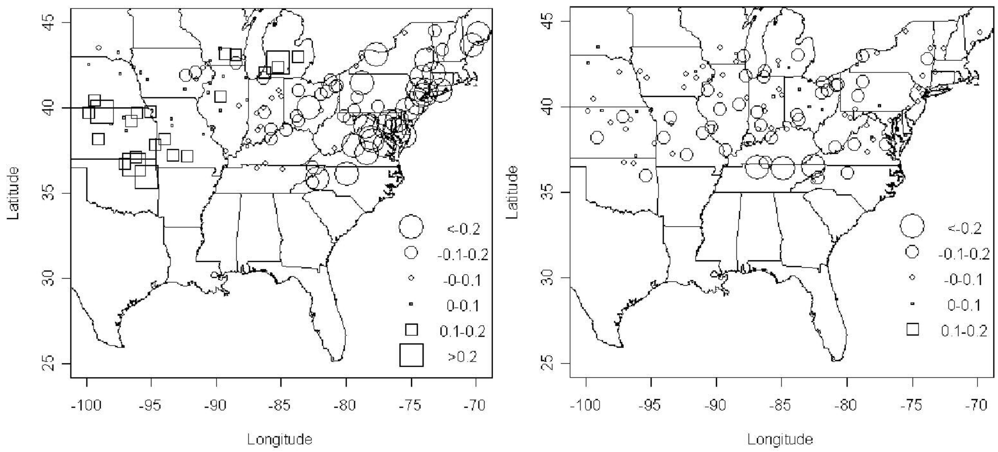
Figure 8 Spatial Pattern of EOF1 of Total Snowfall. All values are negative.



(a) *(b)*

Figure 9 PC1 of total snowfall time-series correlation with geopotential height @ 500mb (a), and PC1 of total snowfall time-series and NAO index, Nov.-March (b).

Figure 9. PC1 of total snowfall time-series correlation with geopotential height @ 500mb (a), and PC1 of total snowfall time-series and NAO index, Nov.-March (b).



(a) (b)

Figure 10 Correlation of EOF1 of total snowfall with total precipitation; values of +/-0.196 are statistically significant (a), correlation of EOF1 of total snowfall with number of snow days; values of +/-0.201 are statistically significant (b). Circles symbolize negative values and squares represent positive values.

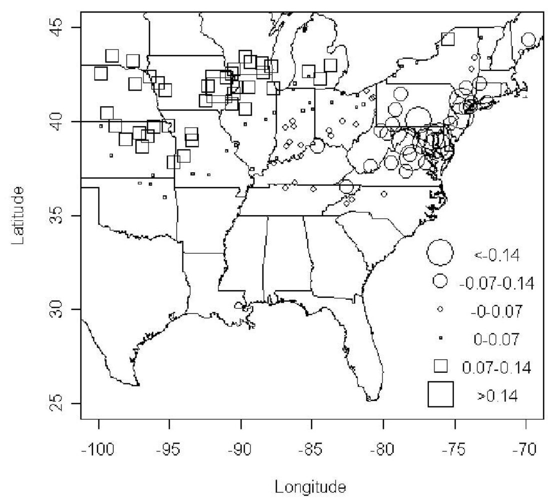
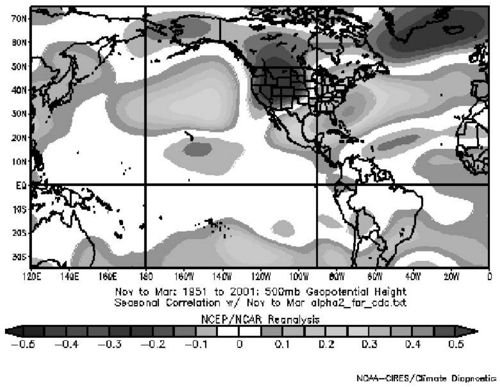
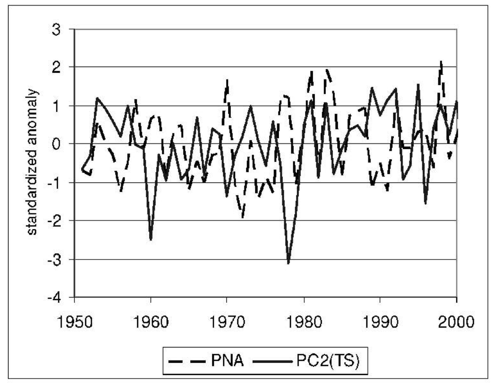


Figure 11 Spatial pattern of EOF2 of total snowfall. Circles symbolize negative values and squares represent positive values.



(a)



(b)

Figure 12 PC2 of total snowfall time-series correlation with geopotential height @ 500mb (a), and PC2 of total snowfall time-series and PNA index, Nov.-March (b).

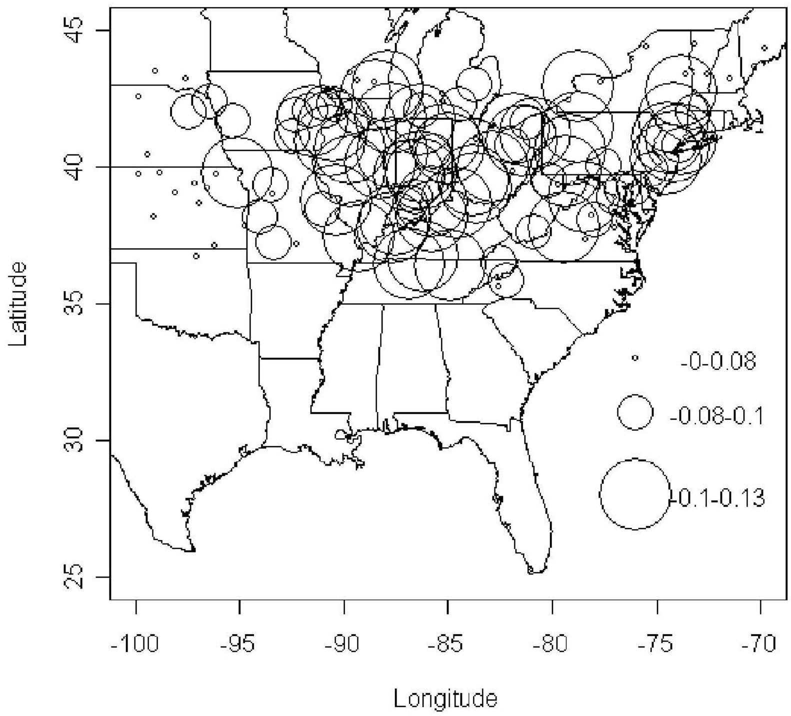
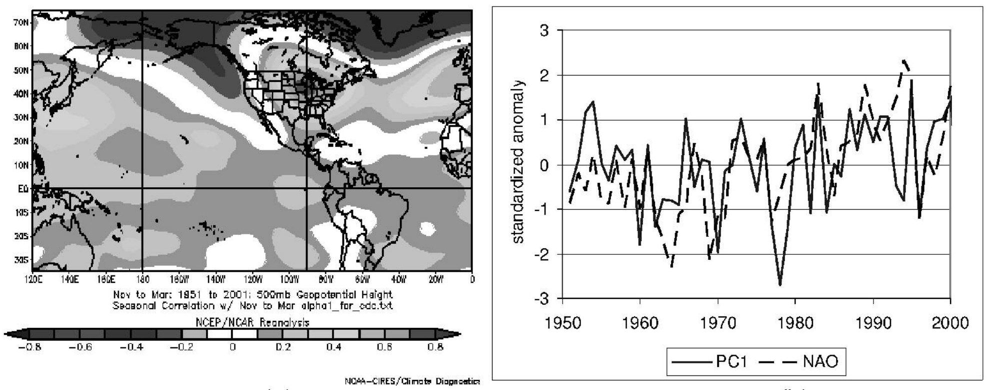


Figure 13 Spatial pattern of EOF1 of NSD. All values are negative.



(a) (b)

Figure 14 PC1 of number of snow days time-series correlation with geopotential height @ 500mb (a), and PC1 of number of snow days time series and NAO index, Nov.-March (b)

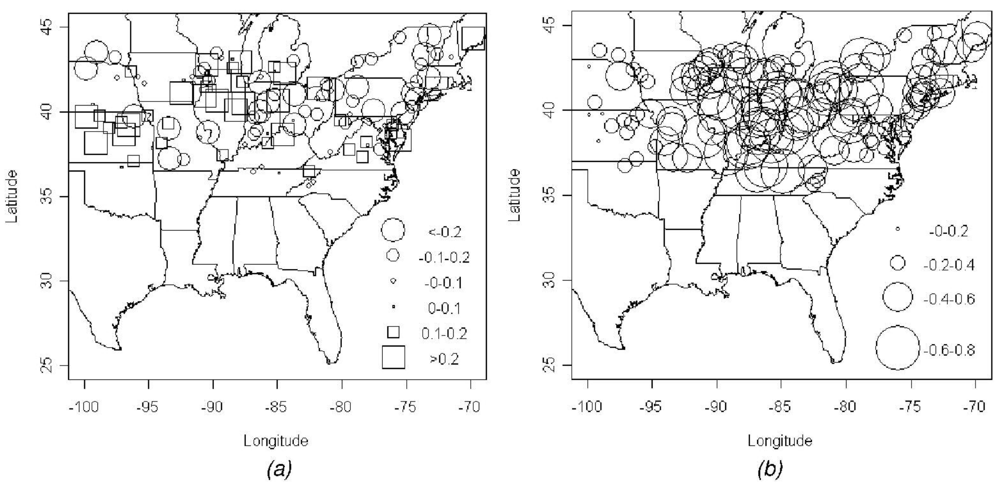


Figure 15 Correlation of EOF1 of NSD with total precipitation; values of +/-0.200 are statistically significant (a), correlation of EOF1 of NSD with total snowfall; values of +/-0.206 are statistically significant (b). Circles symbolize negative values and squares represent positive values.

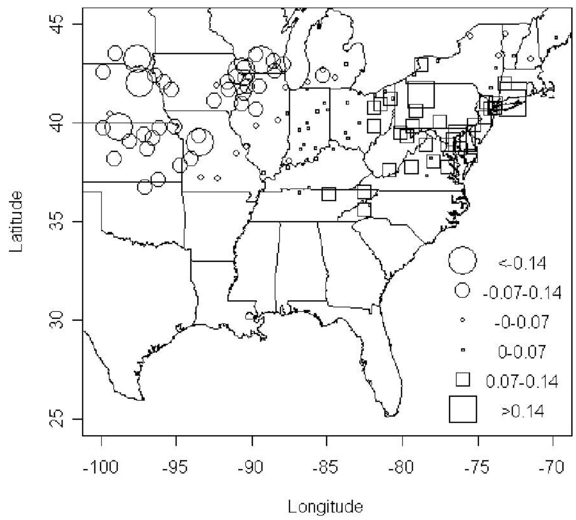


Figure 16 Spatial loading of EOF2 of number of snow days. Circles symbolize negative values and squares represent positive values.

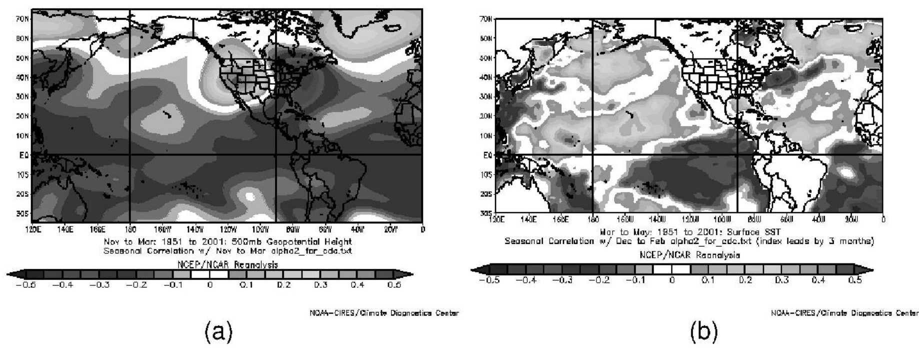


Figure 17 PC2 of number of snow days time-series correlation with geopotential height @ 500mb (a), PC2 of number of snow days time-series correlation with SST (b).

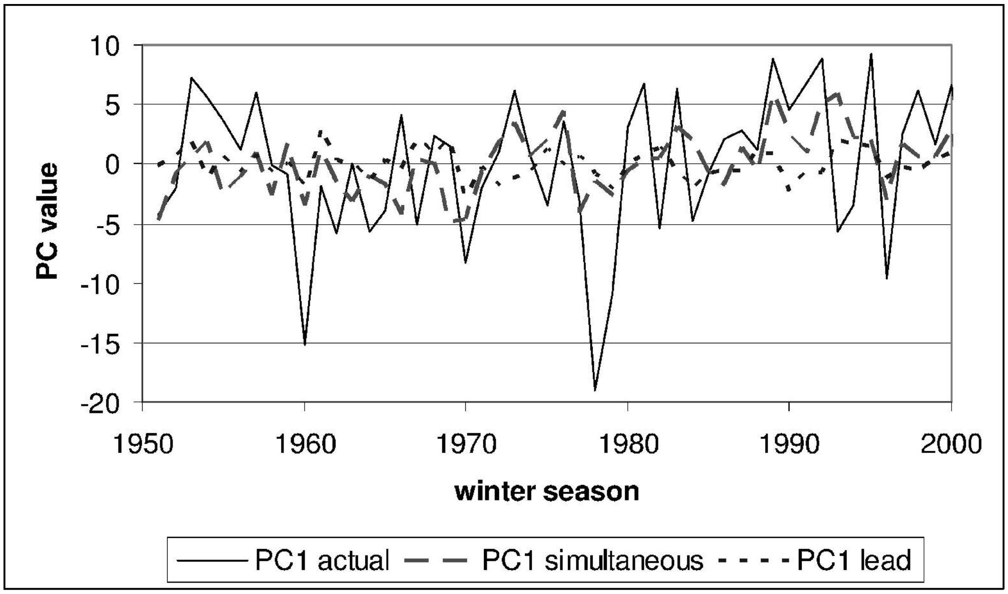


Figure 18 Model-based PC1 values for total seasonal snowfall.