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Spatial and Temporal Variability of North American Snow Cover, 1971–1992

R.D. BROWN[1]

ABSTRACT

Principal Component (PC) analysis was applied to the NOAA weekly snow cover dataset to identify coherent regions of seasonal snow cover variability across North America (NA). The results revealed that regional-scale variability dominated the fall (SON) season, with the winter (DJF) characterized by a clear east-west division. Spring (MAM) was the only season exhibiting continental-scale coherent variations in snow cover. Correlation of the dominant PCs with atmospheric circulation indices indicated that the Pacific-North American pattern (PNA) was closely linked to snow cover variability over western regions of North America in all seasons. The North Atlantic Oscillation (NAO) was found to be most strongly associated with winter snow cover variability over the eastern United States and southern Ontario and Québec. Correlation of PCs with large-scale temperature anomalies revealed that the western interior of the continent was the main snow cover-temperature sensitive region of North America. The sensitivity of annual snow cover to changes in North American air temperature ranged from -30 to -60 days/°C across this region. It is proposed that the elevated temperature sensitivity of this region is related to the PNA pattern which strongly influences temperature and precipitation in the area east of the Rockies.

Key words: Snow cover, North America, principal component analysis, atmospheric circulation, temperature-sensitivity

INTRODUCTION

Snow cover is an important component of the climate and hydrological systems, particulary over the continental interior of North America where agricultural production is frequently constrained by levels of available moisture. For example, snow makes up only 30% of the average total precipitation over the Canadian Prairies, but snow melt accounts for over 80% of the annual runoff. Model simulations of the global climate under doubled levels of CO_2 suggest a large northward retreat in snow cover over the continental interior of North America, which would have far-reaching implications for water resource-based industries such as agriculture and hydroelectricity. Over the last 20 years, snow cover has in fact exhibited a clear trend toward earlier disappearance in the spring period over much of North America (Brown and Goodison, 1993).

Reliable satellite-based data of weekly snow cover over Northern Hemisphere land areas are available from the early 1970s. These data are too short to determine whether recent decreases in snow cover are part of the "normal" climate variability. However, they are a unique data set for investigating the spatial and temporal variability of snow cover over shorter time-scales over the Northern Hemisphere. Such knowledge is important for a number of applications such as validation of global climate models (GCMs), objective analysis of snow cover for input to numerical weather prediction models, and optimum design of data collection networks. Longer time-series of snow cover have been developed recently to look at the climate change

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[1] Climate Processes and Earth Observation Division, Atmospheric Environment Service, 2121 Trans Canada Highway, Dorval, QC, H9P IJ3, e-mail: rbrown@cmc.doe.ca

detection question (e.g. Hughes and Robinson, 1993; Brown et al., 1995), but these are confined to specific regions.

The goal of this paper is to provide further insight into the spatial and temporal variability in seasonal snow cover over North America during the post-1970 period of reliable satellite data. Specific objectives are: (1) to document regions which display coherent variations in seasonal snow cover variability; and (2) to examine the role of atmospheric teleconnection patterns and large-scale air temperature anomalies in the interannual variability of snow cover within these regions.

DATA

The snow cover data used in this study were the NOAA digitized weekly charts of snow cover derived from visual interpretation of satellite imagery by trained meteorologists. The charts are digitized onto an 89 x 89 polar stereographic grid over the Northern Hemisphere, with a grid spacing of 190.5 km at 60°N. The data is binary in format with grid cells interpreted to be at least 50% snow covered represented by a "1". The data set was obtained from D. Robinson (pers. comm.) and contained the corrections recommended by Robinson et al. (1991). Seasonal snow cover information at each grid point was derived by attributing a full week of snow cover to each occurrence of a "1". The Rutgers weighting scheme (Robinson, 1993) was used to correctly partition the weekly charts into appropriate months. The snow cover year was defined to extend from August to July, with three month seasons defined as: Fall (September-November), Winter (December-February) and Spring (March-May). A summer season was not included in the analysis as the area of snow cover involved is small. The weekly charts go back to 1966 (Matson et al., 1986), but only data starting in the 1971/72 snow cover season were included in this analysis as the earlier data are considered to underestimate snow extent (Robinson et al., 1993). Linear interpolation was used to account for a missing chart in week 51 of 1972.

Three teleconnection indices were used in the analysis of the relationship between snow cover variability and atmospheric circulation patterns: the North Atlantic Oscillation (NAO) which describes the "seesaw" in temperature between the west coast of Greenland and northern Europe, caused by an oscillation in pressure over a broad region of the North Atlantic (Rogers and van Loon, 1979); the Pacific-North American (PNA) index which measures the departure of the circulation over North America from normal i.e. positive PNA index values are associated with a more meridional wave train, while negative PNA values are associated with more zonal upper air circulation; and the Southern Oscillation index (SOI) which is a sea-level pressure manifestation of the cyclical variations in sea-surface temperatures which occur over the equatorial Pacific (the El Niño-Southern Oscillation or ENSO phenomenon). The NAO index used in this study was computed by Bonsal (1991) from gridded monthly 50 kPa height anomalies (Z) as $0.5*[Z(65°N,30°W)-Z(35°N,30°W)]$. Height anomalies were computed with respect to a 1947-87 mean. Monthly NAO data were available for the period 1947 to 1989. The monthly PNA index used in this study is documented in Leathers et al. (1991), and monthly index values covering the period 1948-1988 were obtained from Leathers (pers. comm). The SOI index used was monthly values of the standardized pressure difference between Tahiti and Darwin, which is available from the U.S. Climate Diagnostics Center from 1882 to date. A three-month running mean was applied to all three indices to remove high frequency variations prior to performing cross-correlation analysis with seasonal snow cover time series.

For the investigation of snow cover-temperature relationships, large scale seasonal temperature averages for North America (T_{NA}) were obtained from the 5° latitude by 10° longitude gridded monthly surface temperature data set of Jones et al. (1991). T_{NA} was computed over 30-70°N and 80-120°W. A hemispheric average (T_{NH}) was also derived over the same 30-70°N latitudinal band. A cosine weighting function was used to take account of the decreasing surface area at higher latitudes.

PC ANALYSIS

Principal Component (PC) analysis is a frequently used tool in meteorology for isolating the dominant modes of variability in complex fields (Richman, 1986). In this study, an "S-mode" PC analysis was performed where the matrix columns are the grid points, and the matrix rows are the seasonal snow cover values for each year from 1971/72 to 1992/93. In "S-mode" analysis, a plot of the PC loadings provides information on the spatial structure of the field (i.e. areas of coherent changes in seasonal snow cover), while a plot of the PC scores provides information on the temporal variability of seasonal snow cover within the defined coherent regions. PC analysis can be carried out using either the correlation or covariance matrix. A covariance matrix was used in this study as it weights individual points according to their contribution to the total variance (a correlation matrix applies equal weight to all points). An orthogonal varimax rotation was applied to the identified principal components (PCs) to avoid many of the problems of unrotated PCs discussed by Richman (1986). In order to reduce computational time, the PC analysis was only performed at grid points displaying considerable interannual variability in seasonal snow cover. A criterion was applied, following Frei and Robinson (1995), which restricted the analysis to grid points with at least one-third of seasonal snow cover values between 10 and 90% snow cover.

The PC analysis was carried out using IMSL routines CORVC to compute the covariance matrix, PRINC to compute the principal components, FROTA to apply the varimax rotation, FRVAR to compute the amount of variance accounted for by each rotated PC, and FCOEF and FSCOR to compute the standardized PC scores. A major challenge in PC analysis is deciding how many PCs to retain. There are numerous techniques ranging from rules of thumb (North et al., 1982) to Monte Carlo techniques (Overland and Preisendorfer, 1982). It was found that application of these objective methods to the seasonal snow cover data yielded a large number (~15-20) of significant eigenvalues, but subsequent plotting of the PC loadings revealed that many of these were not spatially coherent. In practice, a subjective restriction was applied which limited PCs to those explaining more than 5% of total variance. This resulted in 5-7 PCs per season, and nearly all the identified PCs covered relatively large spatial domains.

Results:

The coherent regions of seasonal snow cover variability identified by the PC analysis are summarized in Figure 1. The identified PCs represent areas which are important "centres of action" (Groisman et al., 1994b) in snow cover variability. Groisman et al. (1994b) termed such areas "snow transient regions" or ***STRs***. In their analysis, they used the standard deviation to identify ***STRs***, which lumps all areas of high interannual variability together. The PC analysis represents a major refinement of this process by identifying areas of important snow cover variability where snow cover varies coherently. The percent variance attributed to each rotated PC is summarized in Table 1 below.

Table 1. Amount of variance (%) in North American seasonal snow cover variations over 1971-92 period accounted for by the rotated PCs plotted in Figure 1.

PC	Ann.	Fall	Winter	Spring
1	12.2	10.0	14.2	18.9
2	16.6	13.8	16.1	9.0
3	15.4	9.9	19.1	15.2
4	11.3	9.1	11.9	11.6
5	-	7.6	8.7	5.3
6	-	-	-	-
7	-	7.6	-	-

In the fall season (Fig. 1a) snow cover variability is not dominated by any single region, but is fairly evenly spread across the continent. This coincides with a rapid areal expansion of snow cover across North America during October. In the winter (Fig. 1b), snow cover variability is largely confined to the United States, and there is evidence of an east-west split in the variability around 95°W, a feature also observed by Gutzler and Rosen (1992). In contrast, the spring results (Fig. 1c) revealed the presence of continent-wide regions of coherent snow cover variability with PCs 1 and 3 together explained almost 35% of the total variance. These two adjacent bands, straddling much of the continent, reflect the northward migration of the snow line through the three month period starting in the south in March-April, and in the more northern area in April-May. The annual (August-July) results (Fig. 1d) represent a composite of the above seasonal patterns (including summer snow cover variability at high latitudes). The annual results also show evidence of an east-west division in snow cover variability over North America with PCs 1 and 2 confined to the southwest and northwest parts of the continent, and PCs 3 and 4 confined to the southeast and northeast. PC4 over the Canadian Arctic Archipelago was somewhat of a surprise as this area was not expected to exhibit significant interannual variability in snow cover due to the short snow-free period. It is possible that some of this variability may be attributed to the snow/cloud differentiation problem with NOAA snow cover charts noted by Wiesnet et al. (1987). However, PC analysis of seasonal snow cover derived from Canadian daily snow depth observations confirmed that this region was indeed an important contributor to North American annual snow cover variability.

There is little published material on PC analysis of snow cover over North America with which to compare these results. Iwasaki (1991) performed an empirical orthogonal function analysis of the NOAA snow cover data set over the Northern Hemisphere for the 1967-1978 period. However, by averaging the 89 by 89 grid down to an 8 by 8 grid, Iwasaki smoothed out much of the information content. Frei and Robinson (1995) carried out a detailed PC analysis of monthly snow cover variations over the Northern Hemisphere with the full NOAA data set for the 1972-1994 period. Their analysis was carried out on a monthly basis which meant that significant PCs were much smaller in spatial extent than this study where a three month seasonal average was used. Nevertheless, the two sets of results display strong similarities, particularly in the spring period.

LINKS TO ATMOSPHERIC VARIABILITY

Gutzler and Rosen (1992) observed significant correlations between North American winter (DJF) snow cover and the Pacific-North American (PNA) and North Atlantic Oscillation (NAO) indices. Previous studies (e.g. Ropelewski and Halpert, 1986) have also shown that ENSO events have important effects on the regional climate of North America. To examine the relationship of these indices to observed snow cover variability over North America, cross correlations were computed between these monthly indices, and the PC score time series which represent the temporal variability of snow cover within the areas shown in Figure 1. A summary of statistically significant (0.05 level) zero lag correlations is provided in Table 2.

The NAO pattern was observed to exhibit strong positive correlations with winter snow cover variations over the eastern United States (PC2) in agreement with Gutzler and Rosen (1992). This suggests that positive pressure anomalies over the north Atlantic (i.e. a weakened Icelandic Low and generally weak circulation over the Atlantic) are associated with above-average snow cover over the eastern United States and *vice versa*. Gutzler and Rosen (1992) also observed similar strong positive correlations between the NAO and snow cover over western Europe. These results are interpreted as being related to a southward expansion of cold air associated with a southward shift of pressure patterns by about 10° of latitude during periods of weak circulation over the north Atlantic (Rogers, 1990). The winter (Feb.) NAO pattern was also observed to exhibit a significant positive correlation with annual snow cover variability over the Canadian Arctic Archipelago (PC4). Marginally significant positive NAO correlations were also observed in the spring over the southwestern United States (PC2).

Table 2. Maximum significant (0.05 level) lag 0 correlations between snow cover variations in each PC-defined region, and atmospheric circulation indices.

	NAO	PNA	SOI
Ann.	PC4 0.54 Feb	PC2 -0.70 Nov	PC2 0.52 Mar
Fall	-	PC2 -0.79 Nov	PC7 -0.52 Nov
Win.	PC2 0.77 Dec	PC3 -0.56 Dec	PC3 0.52 Feb
Spr.	PC2 0.49 Mar	PC4 -0.67 Mar	PC4 0.64 Mar

The strongest lag 0 correlations were observed between the PNA teleconnection pattern and snow cover variability over the northern Great Plains and Canadian Prairies (PC2) during the fall season. This region of North America exhibited significant negative correlations with PNA across all seasons, confirming the conclusion of Gutzler and Rosen (1992) that the positive phase of the PNA, characterized by ridging over western North America, is associated with a deficit of snow cover in this region.

Positive relationships between SOI and snow cover were observed over the northern Great Plains and Canadian Prairies during the winter and spring. The positive relationship suggests that warm equatorial Pacific sea-surface temperature (SST) anomalies (El Niño) are associated with less snow cover over these regions, while negative SST anomalies (La Niña) are associated with more snow cover. A significant negative relationship was observed between SOI and snow cover variability over the Mackenzie Basin (PC7) in the fall, suggesting that snow cover in this region is established earlier during El Niño periods. Computation of correlations for a lag of one year

(SOI leading snow cover) revealed significant negative relationships in the winter season between SOI in the previous winter and snow cover variability over the southwestern United States (PCs 1 and 4). These results suggest a complex temporal and spatial evolution of the winter ENSO-snow cover signal over North America, in agreement with Groisman et al. (1994b). However, unlike Groisman et al. (1994b), the above results suggest the influence of ENSO is mainly confined to western regions of North America.

As a footnote to this section, it was interesting to note that in three seasons, the PNA and SOI were both significantly correlated with the same PCs, but with different signs. This is consistent with the observation of Leathers and Palecki (1992) that during warm (cold) events in the tropical Pacific, PNA index values have a tendency to be positive (negative).

SNOW COVER-TEMPERATURE RELATIONSHIP

Understanding the interaction of snow cover and temperature is important in areas such as climate diagnostics, climate modelling (e.g. model verification) and climate change detection. Groisman et al. (1994a) clearly demonstrated that snow cover results in negative forcing in the Earth's radiative balance, particularly during the spring season. Karl et al. (1993) documented significant negative correlations between annual (October-September) snow cover variations over North America for the 1972-90 period, and large-scale air temperature anomalies over North America (r = -0.80) and the Northern Hemisphere (r = -0.73). Karl et al. (1993) also provided information on the location of their so-called "temperature-sensitive snow cover regions", or ***TSRs***, over North America by constructing maps of snow cover change between ensembles of cold and warm years. ***TSRs*** are regions where "the transient effects of climate forcing may be especially prominent, and where snow cover should be monitored closely" (Groisman et al., 1994b).

To investigate the connection between snow cover variability and large-scale variations in air temperature, a correlation analysis was carried out between the time-series of snow cover variations in each identified PC region, and North American and Hemispheric temperature anomaly series. Significant (0.05 level) correlations are summarized below in Table 3.

Table 3. Significant (0.05 level) correlations between snow cover variations in each PC region, and large-scale air temperature anomaly series over the 1971-89 period.

Season	T_{NA}	T_{NH}
Annual	PC2 -0.65	PC2 -0.55
Fall	PC4 -0.54	none significant
Winter	PC3 -0.64	PC3 -0.65
Spring	PC1 -0.60	none significant

The correlation analysis revealed that the ***TSRs*** were confined to only a few specific regions in each season. The only regions exhibiting a significant correlation to both continental and hemispheric temperature anomalies were PC2 (Prairies and Alberta) and PC3 (Great Plains/southern Prairies). The enhanced winter snow cover-temperature sensitivity of the Prairie-Great Plains region is consistent with the findings of Leathers and Robinson (1993) that this area experiences the largest temperature departures during positive and negative North American snow cover extremes. The fact that few of the ***STRs*** identified by the PC analysis were ***TSRs*** indicates that regional-scale variations in temperature and precipitation are more important than large-scale temperature anomalies in the interannual variability of snow cover over much of North America.

Regression analysis was used to obtain greater insight into the spatial variability in the relationship between snow cover interannual variability and continental-scale air temperature anomalies over North America. An advantage of regression analysis is that the results provide an estimate of snow cover-temperature sensitivity for use in climate change scenarios, and for validating GCMs. Regression analysis also uses all the data, unlike the cold-warm composite approach of Karl et al. (1993) which used only 8 years (4 warmest and 4 coldest). The regression analysis was carried out between seasonal snow cover at individual NOAA grid point locations over North America, and corresponding seasonally-averaged values of North American (T_{NA}) air temperature, as previously defined. The analysis was performed over the 1971-89 period of common snow cover and temperature data, and was restricted to grid-points where at least one-half of the snow cover values lay between 0 and 100% snow cover.

The spatial variation in the regression coefficient, dS/dT_{NA}, for the fall, winter and spring seasons is shown in Figure 2. Negative snow cover-temperature relationships were observed across large spatially coherent regions of North America in all seasons. Computation of "Student's" t-statistic (not shown) indicated that values of dS/dT_{NA} less than about -6 days/°C were locally significant (i.e. ignoring spatial autocorrelation) at the 0.05 level for the fall, winter and spring seasons. Values less than about -20 days/°C were locally significant in the annual period. Only a few scattered locally significant positive values of dS/dT_{NA} were observed. The fall pattern (Fig. 2a) was characterized by a broad band of locally significant negative values of dS/dT_{NA} stretching across southern Canada between 50-60°N, with a prominent maxima located over Alberta. The winter pattern (Fig. 2b) was concentrated over the southern interior of the continent with the area of significant negative values of dS/dT_{NA} confined to a northeast-southwest band running from southern Alberta down into the Great Plains. This region corresponds closely to PC3 which was previously determined to be a ***TSR***, and where winter snow cover variability is significantly correlated to the PNA pattern. The spring pattern (Fig. 2c) was characterized by the largest area of significant negative regression coefficients extending across most of the continent between 45-55°N, with the maximum located over the southern Prairies and adjacent northern Great Plains. The larger spatial domain of the spring pattern fits in with the observation of Groisman et al. (1994a) that the snow cover-temperature feedback is largest in the spring season. Analysis of seasonal snow cover changes over the 1971-94 period (not shown) revealed that significant decreases in snow cover were concentrated in the spring season, and to areas in the lee of the Rocky mountains. This corresponds closely to PC4 which was also observed to be significantly correlated with the PNA pattern. The annual results (Fig. 2d) are similar to the winter pattern, with a prominent maxima located over the northern Great Plains. Areas of high snow cover sensitivity to continental temperature anomalies were also observed over the Canadian Rockies and eastern Alaska.

The area east of the Rockies between 40°N and 60°N stands out in this analysis as an area where there is a strong negative relationship between snow cover and continental temperature anomalies: observed annual snow cover-temperature sensitivities in this region range from -30 to -60 days/°C. Isaac and Stuart (1992) showed that winter precipitation amount and temperature exhibited a close negative relationship in the area east of the Canadian Rockies. A southward continuation of this pattern over the Great Plains can be inferred from the air temperature-precipitation correlation results of Zhao and Khalil (1993). This regional precipitation-temperature response is attributed to the PNA teleconnection pattern which exerts a strong influence on the precipitation and temperature regime of western North America (Leathers et al., 1991). It is proposed that the observed strong snow cover-temperature sensitivity over the interior of the continent is a combination of the PNA pattern and an enhanced snow cover-temperature feedback over the interior of the continent documented by Leathers and Robinson (1993). These combine to produce a strong snow cover-temperature relationship where warm (cold) air temperatures are associated with less (more) snowfall, negative (positive) snow cover extent anomalies, which result in warmer (cooler) regional air temperatures and a positive feedback on snow cover extent. Snowfall frequency may also contribute to this positive feedback through its effect on surface albedo. Snowfall frequency was observed to be highly correlated with total snowfall across southern Canada (r = 0.9), which means that heavy snow cover years are associated with more frequent snowfall which helps to maintain a high surface albedo.

The above analysis is based on a rather short period of record (1971-89) which includes the warmest decade of the last century, and which may well not be typical of the modern climate record (Karl et al., 1993). This problem was investigated by Brown et al. (1995) who looked at the relationship between snow cover and large scale temperature fluctuations over the interior of North America for a much longer period (1900-1990). Their results suggested that the close negative relationship observed between hemispheric temperatures and snow cover variations over the western interior of North America during the past two decades was a relatively recent phenomenon. They also presented evidence of a major change in snowfall-temperature relationships over the Prairies around 1960, which coincided with a shift in the PNA pattern to more positive values (Leathers and Palecki, 1992). This result highlights the important role of atmospheric circulation in observed snow cover-climate sensitivity.

CONCLUSIONS

The above analysis has shown that seasonal snow cover variability over North America is closely associated with variations in atmospheric circulation patterns, in particular, the PNA pattern over western regions, and the NAO pattern for eastern regions. Analysis of the role of large-scale temperature anomalies in snow cover variability revealed that the temperature sensitive regions of North America were mainly confined to the area east of the Rockies over the Great Plains and western Prairies. This finding is consistent with a strong positive snow-cover temperature feedback in this region involving the PNA pattern where warm (cold) air temperatures are associated with less (more) snowfall, negative (positive) snow cover extent anomalies, which result in warmer (cooler) regional air temperatures and a positive feedback on snow cover extent. The results also pointed to a connection between ENSO events and the PNA pattern where warm Pacific SST anomalies are associated with a positive PNA pattern, resulting in warmer temperatures and reduced snow cover in the lee of the Rockies. Kumar et al. (1994) showed that much of the post-1980 spring warming observed over the Northern Hemisphere could be accounted for by an Atmospheric GCM forced with observed tropical Pacific SST anomalies. Their simulation results for North America clearly show a maximum warming east of the Rockies over the continental interior in response to warm Pacific SST anomalies. It is proposed that the above PNA-related snow cover-temperature feedback is contributing to this response. The high snow cover-temperature sensitivity of this region has major implications for water resource based industries should global temperatures continue to warm.

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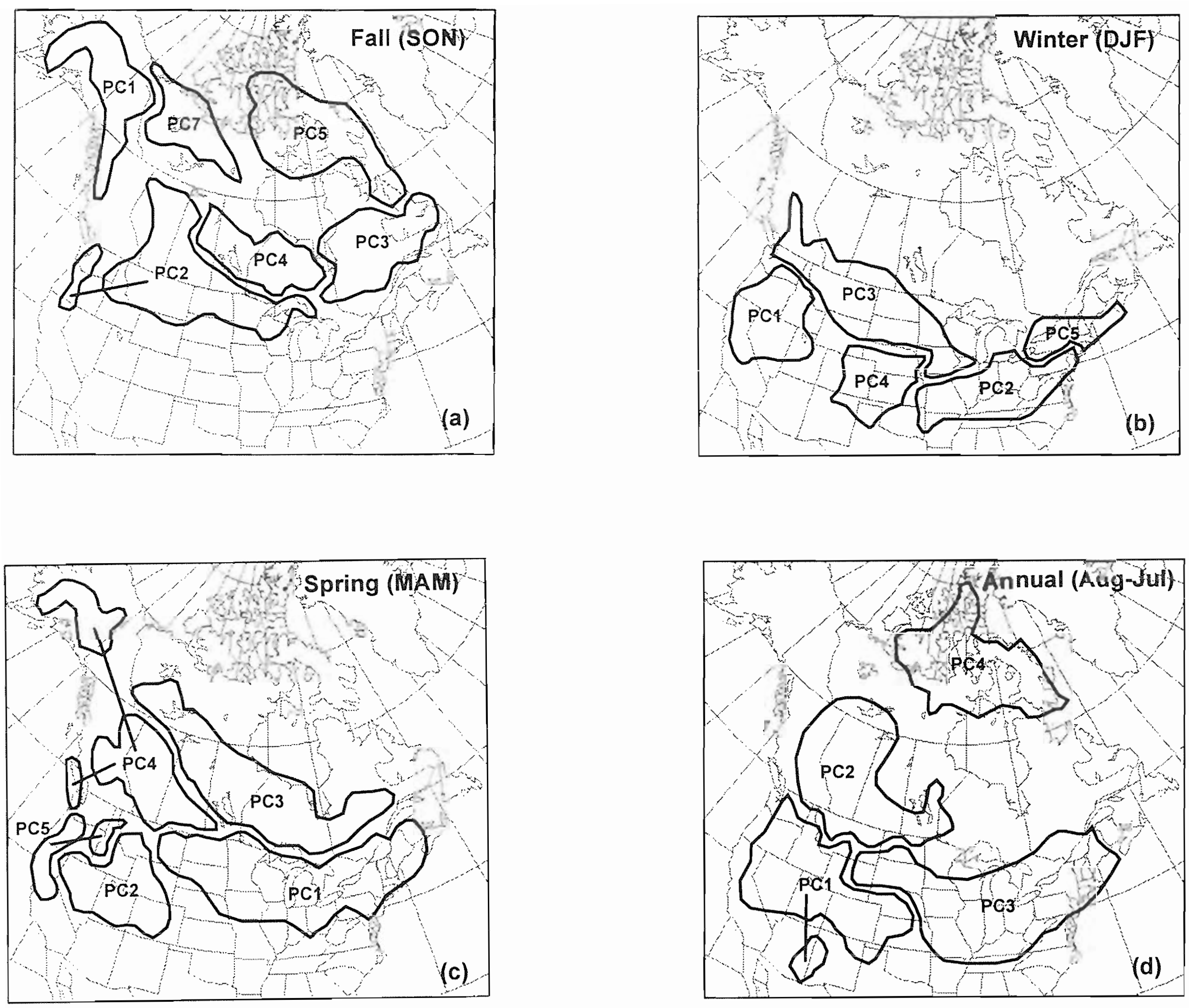

Figure 1: Spatial extent of PCs explaining > 5% of the variance in seasonal and annual snow cover variability over the 1971/72 to 1991/92 period. Lines correspond to PC loadings of ± 0.5.

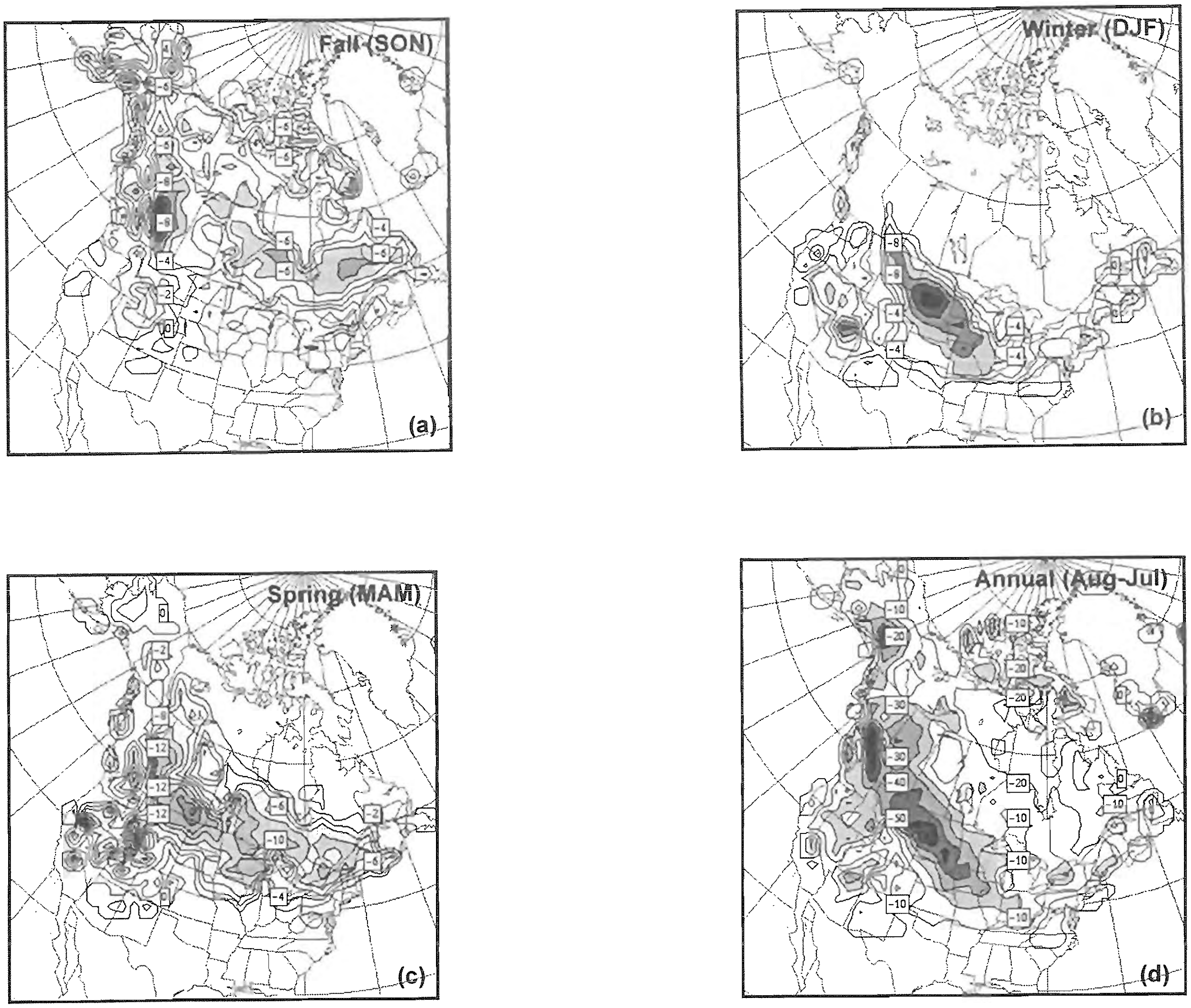

Figure 2: Spatial variation in the regression coefficient of seasonal and annual snow cover versus corresponding North American air temperature anomalies (dS/dT_{NA}). Locally significant values are shaded (see text for explanation). A contour interval of 2 days/°C is used in the fall, winter and spring plots, and 10 days/°C in the annual plot.