A Regional Analysis of North American Snow Cover Extent
Climatic and Synoptic Associations from November through March

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ABSTRACT

Satellite-derived observations of North American snow cover extent from November through March between 1972 and 1994 are examined. Principal components, multiple regression, and correlation analyses are used to identify and analyze geographic regions within which snow cover fluctuates in a coherent manner. We find that between one and four regional signals per month predominate, and explain between 63% and 88% of the North American snow cover signal. To analyze associations between regional snow extent and other variables, we utilize a number of additional datasets, including: observations of snow depth and temperature; mid-tropospheric geopotential heights; Daily Weather Maps; and surface cyclone locations. We find seasonally dependent associations indicative of the persistence of daily synoptic patterns that are conducive to the deposition and maintenance of surface snow. These results are useful for improving snow cover climatology, validating climate model simulations, reconstructing historical snow cover and tropospheric circulation, and detecting climate change.

Key words: climate, snow, North America

INTRODUCTION

Snow cover is an important climatic and hydrologic variable, affecting global and regional radiative and thermal energy budgets (Barry 1985; Shine et al. 1990). It also affects air mass formation and weather systems, as well as thermal regimes in underlying soil and permafrost (Berry 1981). With regards to climate change, it is believed that a decrease of snow extent in response to an increase of high latitude temperatures can initiate a positive feedback that will enhance the boreal warming. Since snow cover maintenance is associated with atmospheric dynamics and thermodynamics, and high latitudes are believed to be especially sensitive to global warming due to cryospheric feedbacks, snow cover fluctuations can be used as an indicator of global climate change. Snow cover is also a critical source of both drinking and irrigation water. Thus, a temporally and spatially complete and accurate record of snow cover extent, and an understanding of the interactions between snow cover and the atmosphere, are critical for recognizing and understanding global climate fluctuations.

Seasonal and interannual variations of snow extent across the Northern Hemisphere have been derived in a consistent manner from visible satellite imagery since the early 1970s (Matson et al. 1986; Robinson et al. 1994; Robinson 1996 this volume). The geographic extent of snow cover over North American lands is highly variable seasonally, reaching a maximum of approximately 15 million square kilometers in January and February, with a minimum of about 2 million square kilometers (mostly over Greenland) in August. Interannual fluctuations, though much smaller than seasonal ones, are sufficiently large to have substantial impacts on regional hydrology and radiative regimes.

Several continental scale studies of Northern Hemisphere snow cover extent have been performed previously. For example, Robinson et al. (1991), Robinson & Leathers (1993), Karl et al. (1993), and Groisman et al. (1994b) investigated snow / temperature relationships. Other investigators have used multivariate techniques to identify regions of coherent snow cover fluctuations directly from snow cover

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observations (Iwasaki 1991; Frei & Robinson 1995a; Brown & Goodison 1996).

We extend these earlier studies by extracting regional signals from observations of areal snow cover extent for the entire Northern Hemisphere using monthly observations from November through March. We focus on North American fluctuations during those months because the availability of a highly quality-controlled dataset of station observations allows us to estimate historic snow cover fluctuations (Hughes et al. 1996 this volume). In sections 2 and 3 we describe the datasets and the statistical methods used in this analysis. In section 4 we discuss the results of our regional analysis, including: identifying areas of "active" snow cover fluctuation; identifying regions of "coherent" snow cover fluctuation; and using regional information to estimate continental-scale snow cover extent. In section 5 we explore associations between regional snow cover extent, surface climatological variables, and synoptic scale circulation. In section 6 we explore the utility of these results toward improving our spatial and temporal perspective on historic snow cover, understanding interactions between snow cover and other elements of the climate system, assessing climate model simulations, and monitoring climate change.

DATA

Charts of Northern Hemisphere snow cover extent, produced by the National Oceanic and Atmospheric Administration (NOAA) (Matson et al. 1986), from January 1972 through December 1994 (Robinson et al. 1994) are used for the principal components analysis. These are produced by analysis of visible satellite imagery by trained observers. Potential inaccuracies exist due to problems in observing snow cover under cloud cover, forests, and other problems. However, this data-set is adequate for monthly-averaged climatological analysis (Kukla & Robinson 1981). For analyzing surface and synoptic climatological associations, several other datasets are employed: the Historical Daily Climate Dataset (HDCD), which includes temperature and snow depth observations from over 1100 cooperative meteorological stations (Hughes et al. 1996, this volume); monthly average 500-mb geopotential heights from the National Meteorological Center (NMC) on a 2.5° latitude x 2.5° longitude grid from 30°N to 70°N latitude, and from 160°W to 50°W longitude; and Daily Weather Maps, produced by the U.S. Department of Commerce. Information on surface cyclones and storm tracks has been derived from the NMC octagonal grid using twice-daily sea level pressure arrays (Mark Serreze pers. comm.).

METHODOLOGY

In this study we apply principal components, regression, and composite analyses to understand snow cover and climate fluctuations. Principal components analysis (PCA), performed for each month from November through March, is used to reduce the lengthy monthly dataset from several thousand grid cells (per month over the entire Northern Hemisphere) to a smaller number of regional signals that explain most of the variance in the original dataset.

For each month, grid cells that are consistently either snow-covered or snow-free are eliminated. This leaves an "active" area for each month that includes grid cells with snow cover frequencies between 10% and 90% for at least 8 of 23 years. Examining only the active area reduces the region to be analyzed from several thousand to several hundred grid cells. The application of PCA to datasets with a high ratio of variables to cases is common in climatological studies (i.e. Barnston & Livezey 1987) since long time series are often unavailable. For November, due to the impact of the large number of active grid cells on computer resources, a sample of five of every six grid cells is used for the PCA (solutions are stable with regard to minor changes in the selection of grid cells).

PCA with a Varimax rotation is applied to the cells comprising the active area for the entire hemisphere, obtaining a smaller set of principal components that explain much of the variance. Between 88% and 90% of the variance in hemispheric snow cover extent is explained by the first 16 components. The Varimax rotation forces the resulting score time series to be orthogonal, which is important for the subsequent regression analysis. We also performed the PCA with the non-orthogonal Oblimon rotation, which produced similar results, thus confirming the applicability of the Varimax rotation. PCs are identified numerically in descending order: that is, PC1 represents more of the variance in hemispheric snow cover than PC2, etc. For this regional analysis, only components with a PC loading factor of $r>0.7075$ ($r^2>0.5$) for at least three adjacent grid cells ("coherent regions") are retained for further analysis. Thus, grid cells within regions have at least 50% of their variance explained by a common time series, and coherent regions do not overlap. Interannual snow extent fluctuations within coherent regions are correlated, and are represented by their corresponding component score time series.

To determine how well regional snow cover fluctuations correspond to continental scale signals, least squares multiple regression analysis is employed for each month. The predictand is North American snow cover extent derived from the NOAA digitized dataset. The predictors are time series of snow cover extent for each region.

Composite analysis is used to determine associations of snow cover to snowfall, total precipitation, surface temperature, mid-tropospheric synoptic circulation, and surface cyclogenesis. For each region, snow cover extent for the 22 years from 1972 through 1993 (the period of overlap between the remotely-sensed and station-based datasets) is ranked. Then, observations of other climatic variables are composited by averaging together observations from the upper quartile (highest five years *of snow extent*) as well as from the lower quartile. In this way we determine if extreme values in snow cover extent are associated with extreme values in these other variables.

REGIONAL SIGNALS

PCA indicates that strong regional signals are prevalent and explain much of the variance in North American signals. In sections 4a and 4b monthly active areas and regions of coherent snow cover fluctuations are identified and discussed. The utility of regional signals for predicting continental scale snow cover fluctuations is discussed in section 4c.

Active Areas

Areas of "active" snow cover fluctuation, over which snow cover is transient on a monthly time scale, are identified for each month (figure 1). November has the largest active area, which extends well over 50°N latitude across most of Canada. From December through March large areas of North America north of 50°N latitude are almost always 100% snow covered, and therefore not considered active.

Regions of Coherent Snow Cover

PCA is used to identify regions of coherent snow cover within each month's active area (figure 1). Between 1 and 4 regions per month are identified over North America (table 1). During each month, a region is identified that dominates the signal over the central and/or western portion of the continent (November PC1, December PC1, January PC4, February PC1, March PC2). During three of the five months one region dominates the eastern North American signal (December PC5, January PC3, March PC7). February is the only month during which only one regional signal is identified over the continent.

Prediction of Continental Signals Using Regional Signals

Interannual fluctuations of snow cover within coherent regions can be used to predict a large portion of the variance in continental snow cover during most months. Least squares multiple regression analysis is employed for each month to predict North American snow cover extent (the predictands) from regional component score time series (the predictors). Regression results shown in table 1 indicate that much of the variance in continent-wide signals can be explained using observations from only a relatively small portion of the continent. Regional score time series explain between 63% and 88% of the interannual variance of monthly continental snow cover extent. In all cases, the observed and predicted continental time

Month	Number of Regions	Pearson Correlation (r)	% of Variance Explained	Spearman Correlation (S)
Nov	4	.91	82	.92
Dec	2	.86	73	.89
Jan	3	.79	63	.87
Feb	1	.94	88	.91
Mar	2	.90	81	.89

Table 1. Summary of PCA and multiple regression analysis results. Columns, from left to right, are: *Month*; *Number of Regions* number of coherent regions identified in PCA analysis; r Pearson Product Moment Correlation Coefficient between observed North American snow cover extent and prediction by multiple regression (all values shown are significant p= 0.05, 1-tailed); *% of Variance Explained* percent of variance in observed explained by predicted continental signal ($\%var = r^2 x 100$); S Spearman Rank Correlation Coefficient between observed and predicted continental signal (all values shown are significant p=0.05, 1-tailed, df=23).

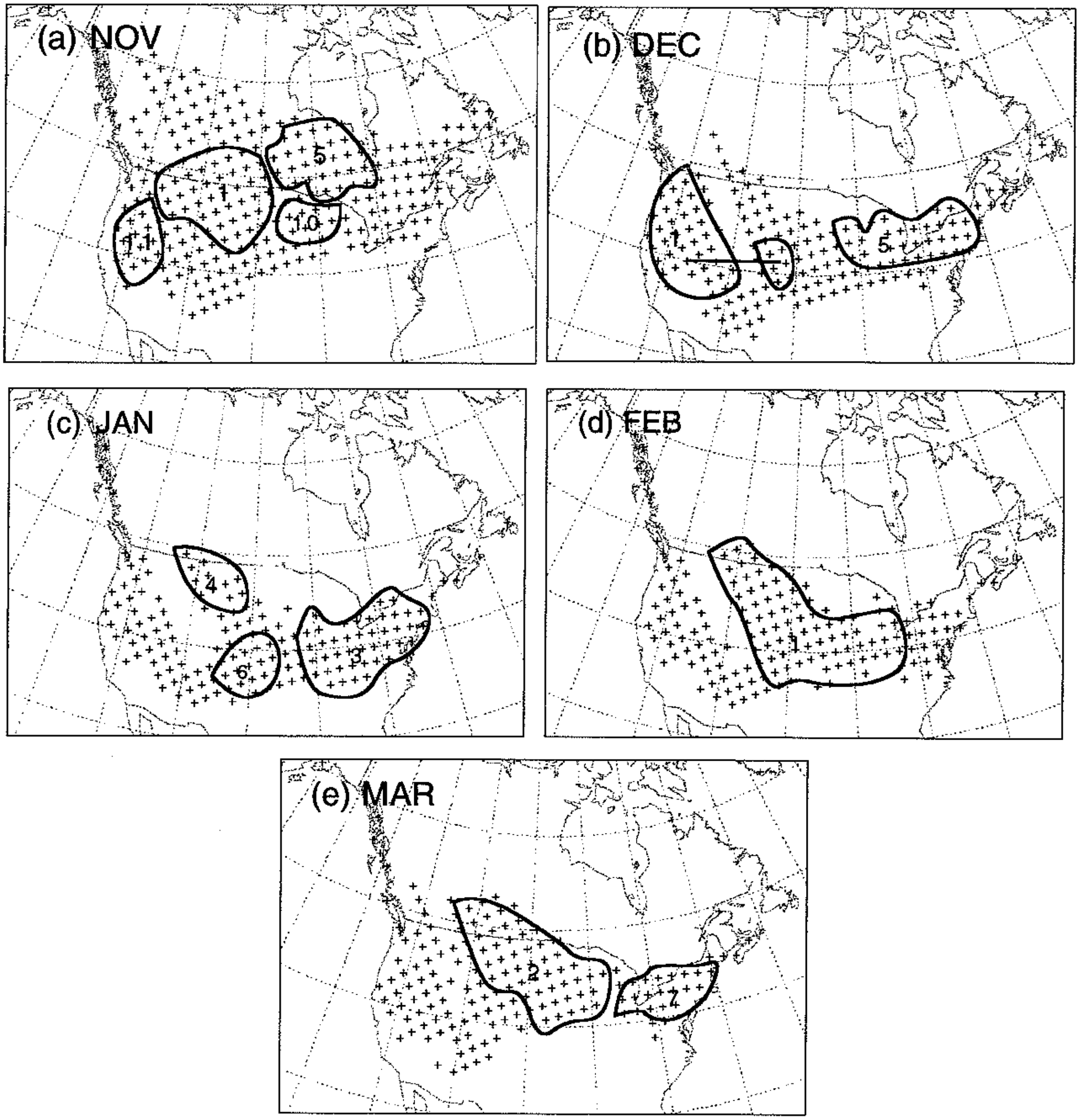

Figure 1. Areas of "active" snow cover for each month from (a) November through (e) March are identified with crosses. Thick lines indicate regions of coherent snow cover fluctuation (0.71 PCA loading contours). Numbers identify the component associated with each region. See text for further explanation.

series are positively and significantly correlated (p=0.05, df=21, 1-tailed).

Considering the short record length (23 years) we corroborate these results with a non-parametric correlation analysis. Table 1 shows Spearman Rank Correlation coefficients between actual and predicted time series for each month. Results from this non-parametric test are similar to those from the Pearson Correlation analysis, indicating that assumptions of normality are not influencing our conclusions.

CLIMATIC AND SYNOPTIC ASSOCIATIONS

Climatic and synoptic conditions associated with extreme values of monthly snow cover extent are identified using composite analysis. Observations of snowfall, surface temperature, total precipitation, mid-tropospheric geopotential heights, and cyclogenesis over each region are examined. We find that interannual fluctuations of all variables, with the exception of total precipitation, are associated with extremes in snow cover extent. These associations are seasonally dependent, the weakest occurring during periods of snow ablation.

Composite analyses for two sample regions are discussed in detail in this section. The first, PC1 of November, is found in the central / western portion of the continent during a period of snow accumulation. The second, PC7 of March, is located on the eastern side of the continent during a period of snow ablation. Other regional results are presented more generally in the discussion section.

Extreme values of snow cover extent over November PC1 tend to also have extreme values of snowfall and temperature (table 2a). The five highest months of snow cover extent over this region coincide with four of the five highest snowfall years, the five lowest maximum-temperature years, and four of the five lowest minimum-temperature years. Associations also exist in this region, although appear to be weaker, for the five lowest snow extent months. These are associated with three of the five lowest snowfalls, four of the five highest maximum-temperatures, and two of the five highest minimum-temperatures. The association between snow cover extent and total precipitation is weak over November PC1.

Figure 2a shows the difference in November 500-mb geopotential heights over North America between composited highest and composited lowest snow cover years. The difference map shows an area of anomalously low heights over central / western North America (directly over PC1), and high heights over the eastern Pacific Ocean and Gulf of Alaska, during years of high snow cover extent. This represents a deepening and westward shift of the climatological ridge. The ridge axis, normally found over western North America, is located during years of high snow cover extent over the eastern Pacific. Another way to interpret this is an excursion of the circumpolar vortex further south over the continent, and a retreat of the vortex to the north over the eastern Pacific, when November PC1 has high snow cover extent.

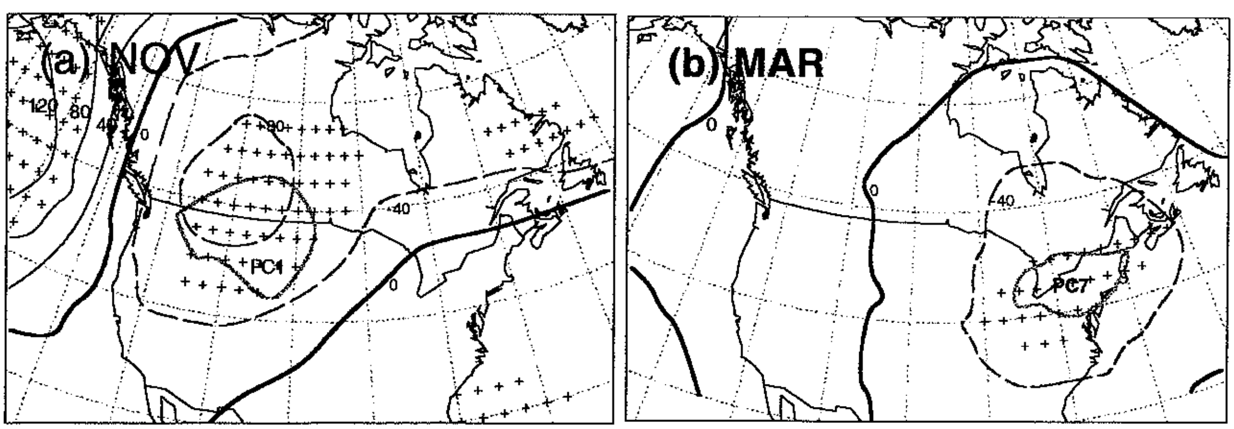

Figure 2. Difference in 500-mb heights (meters) between composited high snow cover years and composited low snow cover years for (a) November PC1 and (b) March PC7. Negative contours are dashed. Grid points significant at ≥95% (2-tailed t-test) are identified with crosses.

a. November PC1: Central/Western North America

	yr	snow extent rank	snowfall rank	Tmax rank	Tmin rank	precipitation rank
HIGH	73	22	**21**	**2**	**4**	**22**
	78	20	**20**	**3**	**2**	17
	85	19	**22**	**1**	**1**	**19**
	86	21	**19**	**5**	6	**20**
	93	18	17	**4**	**3**	**5**
LOW	74	3	**2**	**18**	16	11
	79	5	7	10	9	**1**
	80	2	**5**	**20**	**21**	7
	87	1	**1**	**21**	**20**	**3**
	90	4	8	**19**	15	10

b. March PC7: Northeastern U.S.

	yr	snow extent rank	snowfall rank	Tmax rank	Tmin rank	precipitation rank
HIGH	78	22	11	**2**	**2**	**4**
	80	18	17	6	**5**	**20**
	82	19	16	8	7	7
	84	20	**21**	**1**	**1**	11
	93	21	**22**	**3**	**3**	17
LOW	76	4	15	**20**	**18**	14
	87	5	6	**19**	14	**5**
	89	3	9	11	9	10
	90	1.5	**3**	17	16	**3**
	91	1.5	**4**	15	**20**	16

Table 2. Association of snow cover extent with station-based observations during high / low snow cover months in (a) November PC1 and (b) March PC7. Ranks, in ascending order (1=lowest, 22=highest), of snowfall, maximum temperature, minimum temperature, and total precipitation for the upper and lower quartile (i.e. the five highest and five lowest) snow cover extent years between 1972 and 1993. Snowfall, temperature, and precipitation ranks that fall in either the upper or lower quartile of their distributions are shown in bold. Values in parentheses are column means.

We also apply composite analysis to centers of cyclonic activity for high and low snow cover years. Figure 3a shows four boxes, representing a northwestern, southwestern, northeastern, and southeastern sector. For the four regions combined, the average number of cyclones is 50% higher during high snow cover years. The figure also shows the relative difference in spatial distribution of cyclones between high and low years. These numbers indicate a southwestward shift of storm tracks during years of high snow cover extent in November PC1.

The second composite analysis we show here is for March PC7, which is located over the northeastern U.S. In comparison to November PC1, associations between snow extent and the other surface observations are relatively weak, although high snow cover extent maintains a strong association with temperature (table 2b). Of the five highest snow covered months for this region, only two are associated with extreme snowfall, three with extreme maximum temperature, and four with extreme minimum temperature. Of the five lowest snow covered months, two are associated with extreme snowfall, two with extreme maximum temperature, and two with extreme minimum temperature.

A relatively weak relationship between snow extent and synoptic scale tropospheric circulation for March PC7 is also apparent, as seen in the 500-mb height composite differences (figure 2b). Although lower heights are observed over March PC7 during high snow cover years, the maximum difference contour is only 40 meters, and outside of the immediate region no differences are found. There is, however, a difference in cyclonic activity between high and

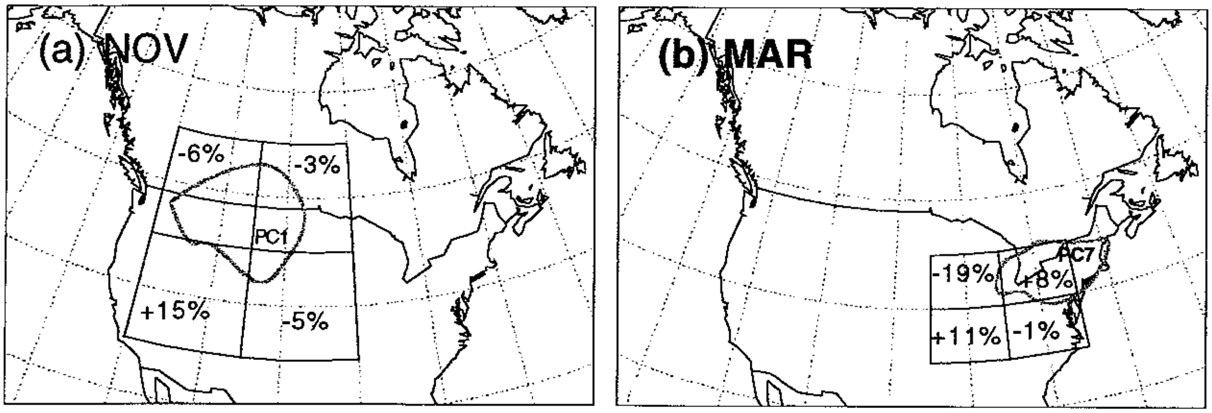

Figure 3. Difference in storm track locations between composited high snow cover years and composited low snow cover years for (a) November PC1 and (b) March PC7. The number shown in each of the four sectors indicates the difference between the percent of the cyclones that occurred between high and low years. High snow extent years in November PC1 (March PC7) are associated with 50% (11%) more cyclones than low snow extent years.

low years. High snow extent is associated with an 11% increase in the total number of cyclones, as well as a shift in storm track locations: northwestern cyclones decrease, while southwestern and northeastern cyclones increase (figure 3b).

DISCUSSION

The two regions analyzed in section 5 are examples of a western and an eastern region, one during a period of snow accumulation and one during a period of ablation. The results shown are indicative of those for other months over North America. In general, during periods of snow accumulation, there are strong associations on the monthly time scale between regional snow cover extent and snowfall, temperature, mid-tropospheric circulation, and storm tracks. In contrast, during periods of snow ablation (e.g. March) the association with temperature is maintained while the association to snowfall is weakened (table 3).

Hints of similar seasonality are observed in the synoptic associations to snow extent. Over western / central regions (i.e. November PC1, December PC1, and January PC4) high snow cover extent is generally associated with a westward shift of the climatological 500-mb ridge from over western North America to the eastern Pacific Ocean and up into the Gulf of Alaska; lower heights over the region in question; an increase in the number of cyclones between 15% and 100%; and a southwestward shift of storm tracks. For March PC2 these associations are weaker. Over this region, 500-mb height composite differences between high and low snow extent months are not as great as during other months (although there is a strong signal over northern Hudson Bay); and there is no change in the total number of cyclones or storm track locations.

In the east, we find stronger associations between snow extent and tropospheric activity during December (PC5) and January (PC3) in comparison to March (PC7). Strong mid-tropospheric height differences between high and low snow extent are observed during December and January, and in January they span across much of the continent. These are in direct contrast to March PC7, when a weaker tropospheric signal is detected. Cyclonic activity is also found to be associated with snow extent in these regions. In December, January, and March we find an eastward shift in storm tracks during periods of high snow extent in the east. In December (March) we find a 15% (11%) increase in the total number of cyclones, while in January no change in total cyclonic activity is noted.

The monthly synoptic patterns identified here are a result of the increased persistence of particular daily synoptic conditions that are associated with snowfall and the maintenance of snow cover (i.e. low temperatures). During months with extensive snow cover, we find circulation to be more meridional. Strong mid-tropospheric ridging centered in the eastern Pacific Ocean, or over the Gulf of Alaska, and troughing centered over Hudson Bay, possibly combined with enhanced ridging over Bermuda, tend to bring cold air masses and strong jet winds southward from the polar regions. Short-wave disturbances migrating through these long-waves tend to produce snowfall, which is then maintained on the surface by the associated cold air masses (and by thermal and radiative feedbacks of the snow cover itself). Troughs are generally found over a broader longitudinal range during high snow cover periods in the west, but are more confined over eastern North America during high snow cover periods in that region. Persistent synoptic patterns during low snow cover months are characterized by weak, zonal, or sometimes split flow across the continent, with above average 500-mb heights over much of the continent. These contrasting synoptic situations can, in essence, be seen as an indication of the position of the circumpolar vortex. During high snow cover months over western North America, the vortex extends farther south over the continent but retreats to the north over the eastern Pacific; while in low years the vortex experiences a general retreat to the north.

The seasonality of these associations is most likely associated with the changing solar zenith angle and increased effect of the snow albedo feedback during spring. Robinson and Leathers (1993) and Leathers and Robinson (1993) found a strong snow/temperature feedback over the continental U.S. that is independent of synoptic conditions. As insolation increases and radiative energy fluxes become increasingly important, surface albedo plays a larger role in the regional energy balance. Groisman et al (1994a) determined that recent changes in spring snow cover extent are associated with regional and hemispheric temperatures, and that the snow cover - albedo - feedback effect is most significant during this season. Our results indicate that during spring, synoptic circulation is less important than during autumn or winter, and regional radiative forcing more important, for affecting snow cover.

CONCLUSIONS

The results of this analysis are useful for improving our understanding of snow cover climatology, as well as climate fluctuations in general. On the monthly time scale, we have defined areas of "active", or transient, snow cover fluctuation. Principal components analysis reveals that particular regions are the "centers of action" of snow cover extent, in the sense that fluctuations within these regions dominate the North American signal. Multiple regression analysis indicates that these regional signals explain 63% to 88% of the variation in continental snow cover extent. Composite analysis shows that snow cover fluctuations within these regions are strongly associated with the boundary layer climate (i.e. snowfall and temperature), and in the fall and winter to mid-tropospheric circulation patterns as well. These monthly averaged synoptic associations result from the persistence of particular daily synoptic patterns that maintain conditions that are conducive to frozen precipitation and to the maintenance of snow cover on the surface. These associations are being used for the assessment of climate models, the reconstruction of historical climate fluctuations, and the detection of future climate change.

	Correlations to Snowfall		Correlations to Tmax		Correlations to Tmin	
	west	east	west	east	west	east
Nov	.92	NA	-.86	NA	-.79	NA
Dec	.84	.90	-.90	-.82	-.72	-.68
Jan	.84	.86	-.82	-.89	-.56	-.88
Feb	.82		-.94		-.94	
Mar	.64	.74	-.90	-.71	-.83	-.76

Table 3. Pearson Product Moment Correlation Coefficient between snow cover extent and snowfall, maximum temperature, and minimum temperature, within western and eastern North American regions. Western regions are November PC1, December PC1, January PC4, and March PC2. Eastern regions include December PC5, January PC3, and March PC7. Only one region exists over North America during February (PC1), which dominates the snow cover signal across the entire continent.

Validating climate models is of critical importance to understanding climate change. Since we depend on these models for predictions of climate change, their reliability must be validated as much as possible. Being that snow cover is such an important climatic parameter, and that the current general circulation models (GCMs) predict a cryospheric response to anthropogenically-induced global warming that will enhance the boreal warming, the ability of models to simulate snow cover fluctuations must be evaluated. In an earlier study we examined 27 GCMs from the Atmospheric Model Intercomparison Project (AMIP) and found that on the continental scale, models are able to capture the mean snow cover extent over Northern Hemisphere land masses (Frei & Robinson 1995b). However, they are unable to simulate the observed variability of snow extent, or the response of snow extent to boundary conditions. The regional results discussed here are being used to assess the ability of GCMs to simulate regional associations.

The North American snow cover climatology can be reconstructed back to the early part of this century using station observations from the contiguous United States (Hughes et al. 1996 this volume) and Canada (Brown & Goodison 1996). The decreasing trend of winter snow cover extent observed during by satellites since 1972 must be evaluated in the context of longer-term fluctuations if conclusions are to be drawn regarding climate change. Changes in snow cover extent over that last century have occurred, and these are associated with identifiable changes in mid-tropospheric circulation. Snow extent over North America has been reconstructed back to 1910. Recent fluctuations observed by satellites are within the range of fluctuations seen over the last 90 years.

Recent debates regarding the nature of climate fluctuations to be expected during the coming decades, due to either natural or anthropogenic causes, have in part revolved around the issue of climate change detection. Our results are being used to establish the natural variability of snow cover over certain regions, as well as on the continental scale, over the last 90 years. In this way future observations can be evaluated in the context of historical fluctuations to determine if the climate system is exhibiting behavior outside of its natural variability.

Extensive sets of station-based observations are currently becoming available from Canada, the former Soviet Union, and China. This will enable us to extend this analysis to the autumn and spring seasons over both North America and Eurasia. Such an analysis will allow us to gain a more complete understanding of changes in snow cover and tropospheric circulation over the Northern Hemisphere.

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