4 POLAR FA 6.5

REGIONAL SIGNALS IN NORTHERN HEMISPHERE SNOW COVER DURING AUTUMN AND SPRING

Allan Frei and David A. Robinson

Rutgers University
New Brunswick, New Jersey

1. INTRODUCTION

Determination of whether observed global climate fluctuations of the last century result from anthropogenic causes, natural external forcing factors, or natural variability inherent in the climate system remains elusive. The continued warming predicted by many scientists is expected to be enhanced in higher latitudes due to the feedback effects of sea ice and snow cover. Greater understanding of the dynamics of these quantities is critical for understanding climate fluctuations.

Empirical and modeling studies have shown that snow cover affects energy and mass exchange between the surface and the atmosphere (Cess et al., 1991; Baker et al., 1992) and atmospheric dynamics (Ross and Walsh, 1986). Recent work by Leathers and Robinson (1993) show that snow cover over North America affects air temperatures on regional and continental scales. Groisman et al. (1994) show that on a global scale the earth's radiative balance is most affected by snow cover during the spring. Snow can also have a lagged climatic effect, whereby early spring snow melt can result in low summer soil moisture. Additionally, due to its associations with temperature and other atmospheric variables, snow cover can be an indicator of climate fluctuations. In order to better understand these associations, improved information on the spatial and temporal dimensions of snow cover is required.

In this analysis we examine monthly snow cover variations in the fall and spring between 1972 and 1994. Special effort is given towards identifying regions exhibiting coherent inter-annual snow cover fluctuations during these seasons, which were chosen because of their high inter-annual variability compared with winter (Robinson et al., 1993).

2 DATA SET

National Oceanic and Atmospheric Administration (NOAA) weekly snow charts serve as the primary source of data in our study. NOAA has produced these charts for northern hemisphere lands since 1966. However, only since 1972, with the deployment of the Very High Resolution Radiometer on board NOAA satellites, is the charting considered sufficiently accurate for continental scale climate analysis (Wiesnet et al., 1987). This constitutes the longest running remotely sensed environmental record produced in a consistent manner. These weekly charts are generated by visual analysis of visible satellite data by trained analysts, and digitized using an 89x89 cell grid overlaying a polar stereographic projection. In this analysis we apply a routine developed at Rutgers (Robinson, 1993) to the weekly digitized NOAA charts to generate monthly averages of snow cover extent. The monthly value for each grid cell is expressed as the percentage of time the cell is snow covered during a given month. These values may be applied to known grid cell areas to produce estimates of snow cover area on regional to hemispheric scales.

3. METHODOLOGY

Principal Components Analysis (PCA) is used to identify regions of coherent snow cover: that is, regions within which grid points have snow cover fluctuations that are highly correlated to each other. The application of this technique to the NOAA observations is unique and has an advantage over previous regional analyses: regions are defined according to the snow cover observations themselves, rather than more subjective criteria based on other climate variables, physiography, or geographic coordinates. An orthogonal varimax rotation of the resulting components is performed to allow for more clear visualization (Richman, 1986). Such techniques are commonly used for climatological data, as in the analysis by Leathers et al. (1993) of snowfall records in the USA.

Only grid points having considerable year-to-year variability are analyzed in a given month; areas that are always snow covered or snow free are easily identifiable without PCA. Study cells must be between 10% and 90% snow covered in at least one third of the years. For example, the April time series has 23 years. Thus only cells with eight or more Aprils meeting this criterion are included in the analysis.

4. RESULTS

Regional signals are found to be dominant over continent-wide signals. Components that explain at

* *Corresponding author address:* A. Frei, Dept. of Geography, Rutgers Univ., New Brunswick, NJ 08903

Proceedings Fourth Conference on Polar Meteorology and Oceanography, American Meteorological Society, Dallas, 127-131, 1995

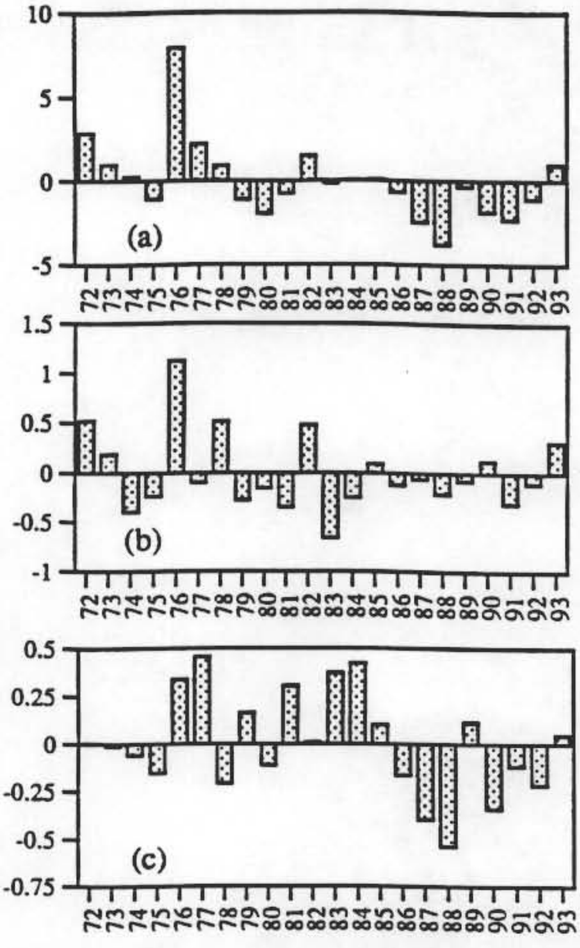

Fig 3: October time series for (a) Eurasian snow cover (million square km); (b) the score time series of component 1 (C1, weighted); and (c) the sum of score time series for all other Eurasian components that explain at least 3.5% of the total variance (C2, 7, 8, 10, 11, 12) (weighted). Components are weighted by the percent of variance explained.

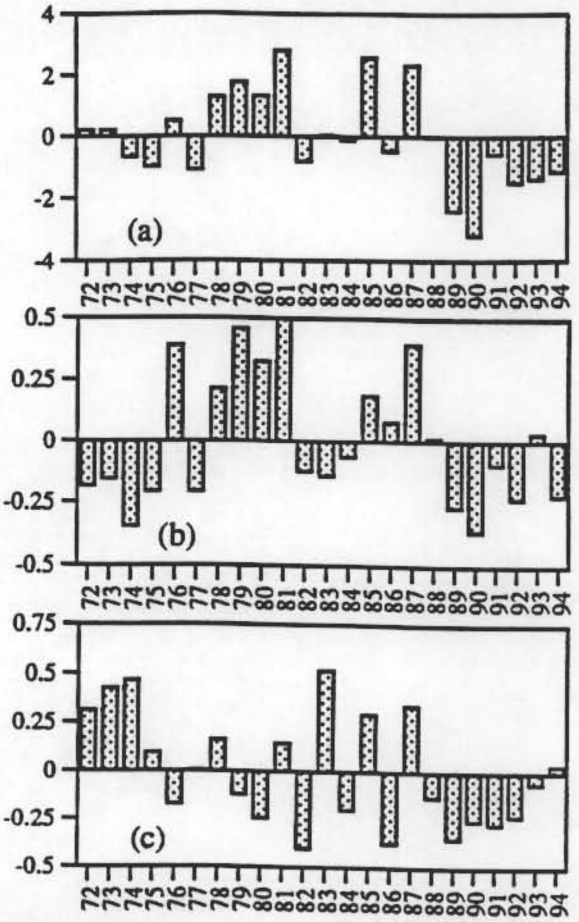

Fig 4: March time series for (a) Eurasian snow cover (million square km); (b) the score time series of component 1 (C1, weighted); and (c) the sum of score time series for all other Eurasian components that explain at least 3.5% of the total variance (C3, 4, 5, 6, 8, 9, 10) (weighted). Components are weighted by the percent of variance explained.

components are significantly correlated ($r^2 = 0.35$) to the hemispheric signal. Thus, in March one region consistently dominates inter-annual fluctuations, although compared to the earlier portion of the record, recent snow cover fluctuations have been more widespread.

5. SUMMARY AND CONCLUSIONS

Both regional and continent-wide snow cover signals are observed in the northern hemisphere during fall and spring. Regions are identified that have coherent, persistent snow cover fluctuations during several months of the year. Regional analyses, such as presented here, are necessary to understand these observations. For example, during the recent period of low Eurasian snow cover during October and March, a shift is observed in the nature of snow cover dynamics. Prior to the mid-1980s snow cover fluctuations were dominated by one particular region in each month. More recently a continent-wide signal emerges that is dominant in October, but remains weaker than the regional signal in March.

This study is the first time that PCA has been used to analyze the remotely sensed hemispheric snow cover record. These results, which are being expanded to include all months and regions, are being applied to other climatic studies, including: analysis of regional fluctuations to identify potential climatic teleconnections; the application of this procedure to climate model results to aid in model evaluation; comparison to other snow cover observations; and improved climate change monitoring, detection, and prediction.

least three to four percent of the variance for the entire hemisphere usually load onto regions that are clearly bounded spatially. "Strong" regional signals are defined as components that explain at least 50% of the signal in a portion of a region; "weak" regional signals explain 20% to 50% of the variance. The geographic extent of regions are defined according to the strong component unless otherwise stated. Components are numbered such that lower numbers (e.g. C1) explain more of the hemispheric snow cover variance for that month than higher numbers (e.g. C10). An "active" region for a particular month is one in which the grid points are included in the analysis.

4.1 Identifying Regions of Coherent Snow Cover

Regions having coherent snow cover fluctuations are mapped in figure 1. Of the 25 regions identified, 11 have coherent snow cover signals in at least two months. Regions with signals in more than one month are outlined using the outer boundaries of all relevant monthly signals. The absence of coherent signals on a hemispheric scale is clearly indicated by the size and number of regions. No components have even weak signals covering diverse portions of both continents. Figure 2 shows the active areas for October and March overlaid by contour plots of the top component loadings. Figure 2a shows components 1 and 2 (C1, C2) for October, which together explain 29.7% of the variance; figure 2b shows C1 and C2 for March, which together explain 25.7% of the variance. The time series for these months are discussed in section 4.2.

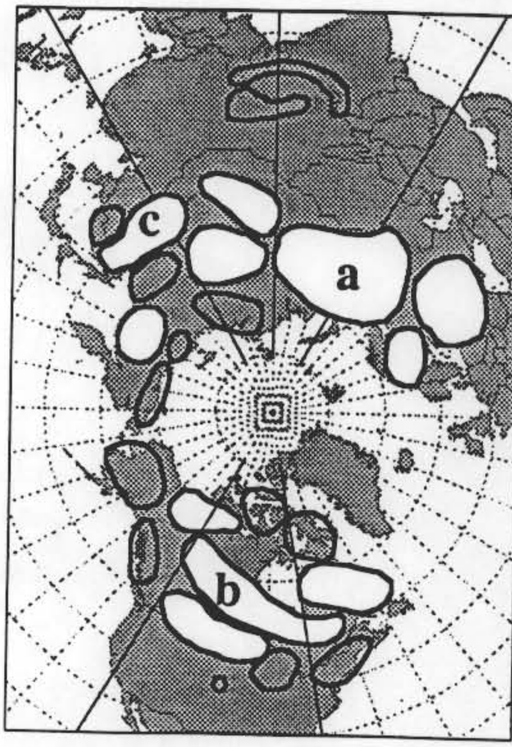

Fig 1: Results of regional analysis of northern hemisphere snow cover fluctuations during fall and spring. Continental regions in white have coherent snow cover fluctuations in at least two months; all others in only one month. The three most persistent regions are: (a) the Eastern European / Western Siberian Plains; (b) the Canadian Shield; and (c) the East Asian Highlands.

Three key regions are recognized, each of which has strong coherent signals during all months of their accumulation and melt seasons, are described below. The largest, covering Northern Europe and Western Siberia, is identified in October (C1), November (C5), April (C1), and May (C3). In October, a signal is identified from the Finish border all the way into the Siberian highlands (cf. figure 2a). This is the largest component identified in any one month of either season. In November as the snow season progresses, the active zone shifts southward and the signal concentrates westward: C5 of November lies over the Russian plains west of the Urals. As the melt season begins in April this region is again identified as C1 and covers a large area, stretching from 40° to almost 80° E. In May a signal is identified in the northern European Plains from the Finish border to the Urals, although the weak portion of the signal extends over the Urals into the west Siberian plains. This region is the only one identified as the first component in more than one month.

The most persistent North American region (C5 of October, C3 of November, C4 of April, and C1 of May) is found across the Canadian Shield between the boreal forests of the Northwest Territories and southern Quebec. In October, the onset of the snow season for most of Canada, the region covers the western and southern Canadian Shield from Great Slave Lake to just southeast of Hudson Bay. The signal is concentrated farther southeast across the southern shield in November, from Lake Winnipeg to south of James Bay. In April, as the melt season begins in southern Canada, the signal stretches from central Saskatchewan to southern Quebec. This signal in May covers its largest area of any month, from the Northwest Territories to southern Quebec (70°-115° W).

The third key region, the East Asian Highlands, is centered over the Manchurian plains and the highlands to their north. Strong signals are observed in October (C10), November (C2), April (C3), and May (C2). During November and May, snow cover fluctuations are linked to fluctuations in the central Asian highlands. October coherent signals are found only in the northern

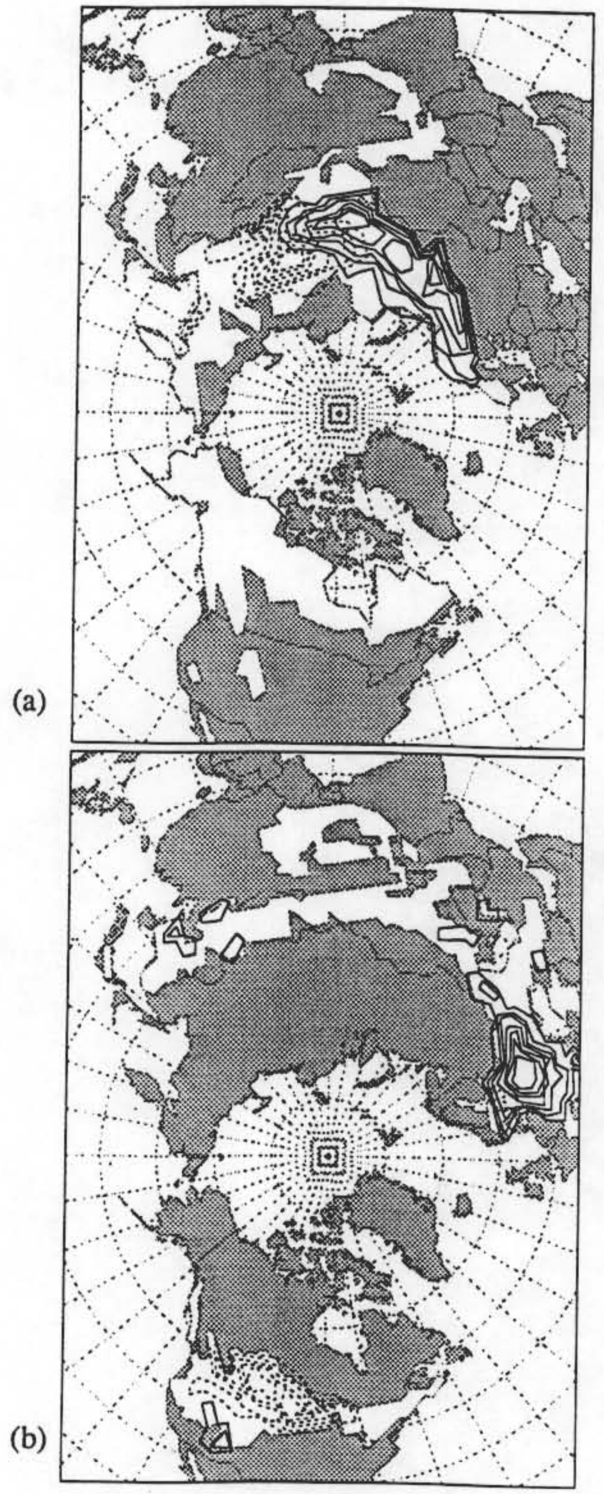

Fig 2: PCA results for October and March. Contours shown for first (C1, solid) and second (C2, dotted) components in (a) October and (b) March. Land areas shown in white are zones of accumulation / melt. Contours start at $r^2 = 0.2$, increment by 0.1. In October (March) C1 and C2 explain 19.8% (14.2%) and 9.9% (11.5%) of the hemispheric variance, respectively.

and eastern sections of this region, the remainder of the region falling outside the active zone. November snow cover fluctuations are coherent from the east Asian highlands into central Asia in a region stretching almost from the coast to Lake Baikal.

4.2 Regional Time Series

Previous analyses of snow cover time series have found evidence of coherent continental or hemispheric fluctuations. Global snow cover extent has been inversely related to global temperatures (Robinson and Dewey, 1990); and, positive correlations are found between snow cover fluctuations over widespread areas of the northern hemisphere (Gutzler and Rosen, 1992; Robinson et al., 1994). Examination of PCA results from two months shows that despite continental scale correlations, regional snow cover dynamics have shifted over time.

Figures 3 and 4 show Eurasian snow cover and PCA score time series for October and March. Both of these months have had below average snow cover since 1987. The first components of each of these months explain comparable percentages of the variance (19.8% and 14.2%, respectively). Yet, evaluation of time series reveals that C1 of October is much less correlated ($r^2 = 0.29$) (r = Spearman correlation coefficient) to the Eurasian snow cover signal than is C1 of March ($r^2 = 0.67$). Critical values of r^2 at the 0.01 (one-tailed) significance level are 0.26 for October (n=22) and 0.25 for March (n=23).

In light of observed pan-continental correlations, it is interesting to note changing regional dynamics. During October a change occurred during the mid 1980s, when continental scale fluctuations shifted from being primarily influenced by conditions in one particular region to a more continent-wide signal. Prior to 1987 the correlation between C1 and the hemispheric signal ($r^2 = 0.50$) is much greater than between the sum of other Eurasian components and the hemispheric signal ($r^2 = 0.05$). However, during the period 1987 through 1993, C1 correlates poorly to Eurasian snow cover ($r^2 = 0.29$) while the lesser components are highly correlated ($r^2 = 0.74$). Thus, we observe a fundamental shift in the regional dynamics of snow cover during October.

In March the regional dynamics also changed, but less dramatically. Eurasian snow cover fluctuations are highly correlated to the first component (Eastern Europe) for the entire period of record: $r^2 = 0.65$ prior to 1987, $r^2 = 0.74$ since 1987. The lesser Eurasian components, when combined, are uncorrelated to Eurasian snow cover prior to 1987 ($r^2 = 0.02$). For the period 1987 through 1994, however, the lesser