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Associations Between Snow Cover Extent and Surface Air Temperature Over North America

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ABSTRACT

We find significant associations between regional snow-cover extent and surface air temperature across North America. In a large majority of cases when the extent of snow cover is above normal, temperature departures are negative. Conversely, negative snow departures are almost always associated with above normal temperatures. Regional correlations are highest in seasons when snow cover is most variable. The largest temperature departures are associated with anomalies of snow cover over the central portion of the continent. An examination of 500-mb heights across North America suggests that -- though circulation anomalies doubtlessly contribute to the temperature departures observed in regions of anomalous snow -- the presence or absence of snow strongly influences temperatures. This relationship is most apparent in situations of above average snow extent. Results of this investigation should be of interest to those studying middle and high-latitude climate dynamics and climate change from both empirical and modeling perspectives.

INTRODUCTION

In recent years the presumed interaction between snow cover and atmospheric variables has garnered substantial attention from scientists investigating topics in climate diagnostics and climate change. In the realm of climate diagnostics, empirical studies have explored the potential influence of anomalous snow cover on temperature anomalies across the United States (Walsh et al. 1985, Namias 1985), and throughout the Northern Hemisphere (Foster et al. 1983, Walsh and Ross 1988). Moreover, snow cover, or the lack thereof, has been shown to be associated with large-scale circulation anomalies (Namias 1978, Walsh et al. 1982, Heim and Dewey 1984) as well as local temperature forecast errors (Dewey 1977), cyclone frequencies and intensities (Walsh and Ross 1986) and even outbreaks of severe weather (Dewey 1987).

In climate change research, snow cover is currently being monitored on regional scales (Robinson 1987, Hughes and Robinson 1993) and on hemispheric scales (Gutzler and Rosen 1992, Robinson et al. 1993) as a potential indicator of global environmental fluctuations. Several studies have used general circulation models in efforts to understand the role of snow cover in potential large-scale climate change and climate dynamics in general (Yeh et al. 1983, Barnett et al. 1989, Cess et al. 1991).

The purpose of this paper is to examine associations between snow cover and surface air temperature across North America. Monthly temperature and snow cover anomalies are compared within 5° latitude x 5° longitude cells for the period 1972-1992. Correlation coefficients are generated and tested for statistical significance and composites of anomalies of both variables are calculated for extreme snow conditions. In addition, 500-mb height composites are generated for the extreme monthly situations to better understand mid-tropospheric circulation patterns that are associated with snow-cover anomalies and whether they may or may not be influencing temperature departures. This study differs from earlier ones because of its use of weekly gridded satellite-derived snow cover data and the temperature data of Jones et al. (1986), and is a natural continuation of a recent study of ours (Leathers and Robinson 1993) in which compositing techniques were used to explore snow/temperature associations over the contiguous United States.

DATA AND METHODOLOGY

Northern Hemisphere weekly snow charts produced by NOAA are used in this investigation. This product is generated by a manual analysis of visible satellite imagery by trained observers (Wiesnet and Matson 1979, Matson et al. 1986). Charts have been produced since 1966, although it is recognized that early observations underestimated snow extent (Kukla and Robinson 1981). The deployment of the Very High Resolution Radiometer on board NOAA satellites beginning in 1972 improved the accuracy of snow cover estimates. The snow charts are digitized using the NMC Limited-Area Fine Mesh grid, which divides a polar stereographic chart into 7921 grid cells ranging in area from 16,000 km^2 to 42,000 km^2.

Monthly snow-cover areas for the twenty-six 5° x 5° cells selected for study (Figure 1) are calculated using the Rutgers Routine developed by Robinson (1993). All snow grid cells centered within a selected 5° cell are used to generate snow areas. The Rutgers Routine calculates monthly snow-cover area by first deriving weekly snow-cover areas. In the aggregation to monthly snow-cover values, the weekly areas are weighted according to the number of days of a week that fall within a given month. Monthly snow anomalies are calculated from 1972-1992 means.

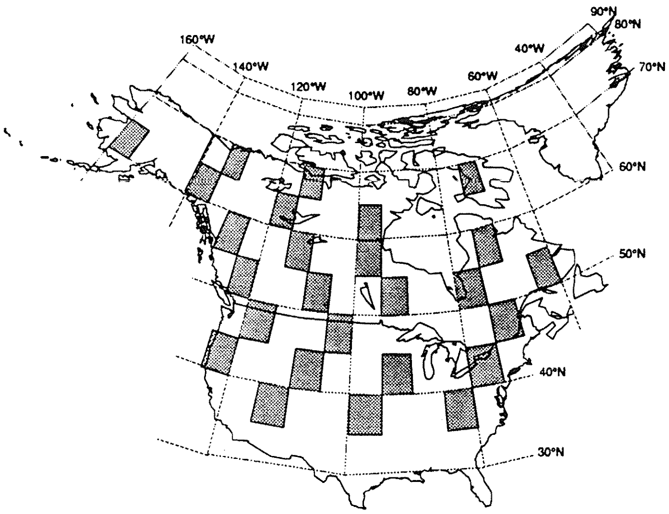

Figure 1. Location of the 5° x 5° cells (stippled) used in this study.

Monthly surface air temperature anomalies used in this study are from the dataset of Jones et al. (1986 and personal communication). Anomalies in North America are produced for 5° x 5° cells using land-based stations and fixed-position weather ships. Temperatures in the Jones set are presented as departures from 1951-1970 means. For this study monthly anomalies are adjusted to represent departures from 1972-1992 means.

Associations between snow cover and temperature for each 5° cell are first explored by applying a simple linear regression to scatter plots of the two variables for selected months. The correlation coefficients of the regression are subject to the Students T test to determine the significance of any association between the two variables. Only months when the cell was partly snow covered (i.e. 1-99% snow covered) for at least two-thirds of the study years are used in this analysis.

Next, for each cell we composite average the temperature and snow-cover departures from the five most extensive and five least extensive snow years for the month having the highest correlation between the two variables. For these cases, 500-mb heights are examined to document the atmospheric circulation during the extreme months and to understand its possible influence on the temperature perturbations. Northern Hemisphere 500-mb heights, derived from NMC octagonal grids (Jenne, 1975), are used to construct anomaly maps. These maps are produced by calculating the composite average of the 500-mb heights during the extreme snow-cover categories for each month and subtracting the mean of the 1972-1989 period. Because the upper air data do not cover the entire period of record, only four years of 500-mb data are used in five cases and three years in three other cases. The 500-mb level is chosen because it is unlikely to be affected by large-scale thermal anomalies resulting from snow cover variations (Namias 1985; Walsh and Ross 1988).

RESULTS

Snow/temperature correlations

The number of months meeting the two-thirds partial-cover criterion vary from one to eight among the study cells (Table 1). Most cells south of 55°N have three to five months where in at least 15 of the 21 study years the cell is partly snow covered. Exceptions occur in the mountainous West with six to eight months and only two months in the 45-50°N cell in eastern Canada. Three cells from 55-60°N have four months that qualify, with the easternmost cell again having only two such months. Poleward of 60°N one or two cells meet the criterion, the

Table 1. Correlation coefficients from simple linear regressions of scatter plots of snow cover and temperature departures over North American study cells. Only months where the cell was partly snow covered for at least 15 of the 21 study years qualify for analysis. Cells are listed by the coordinates (latitude N.longitude W) at their lower left corner. Coefficients that are significant at the 99% level (Students T test) are shown in bold print.

CELL	MONTH									
	S	O	N	D	J	F	M	A	M	J
35.115			-.21	**-.51**	**-.55**	-.33	-.37	-.35		
35.100				**-.67**	**-.61**	**-.67**				
35.85				**-.80**	**-.87**	**-.83**				
40.125			**-.59**	-.48	-.02	-.44	-.23	-.42		
40.110		-.32	-.41	**-.79**	-.49	**-.72**	**-.57**	-.14	-.36	
40.95			-.37	**-.71**	**-.84**	**-.78**	**-.64**			
40.80			-.27	**-.67**	**-.70**	-.21	**-.56**			
45.120		-.31	**-.63**	**-.65**	-.42	**-.68**	-.39	-.25	-.03	
45.105			**-.67**	**-.69**	**-.57**	**-.86**	**-.79**			
45.75			**-.56**					**-.64**	-.23	
50.125	-.29	-.24	**-.57**					-.39	-.16	-.44
50.110			-.72				-.73	**-.68**		
50.95			**-.56**					**-.82**	**-.73**	
50.80		**-.59**	-.26						**-.54**	
50.65		**-.70**	-.50						**-.51**	
55.130		-.44	-.46						-.41	**-.60**
55.115		**-.54**	**-.62**					-.75	**-.57**	
55.100		**-.65**	-.45						**-.66**	-.35
55.75		-.52								-.23
60.160		**-.57**							**-.61**	
60.140		-.35							**-.51**	-.38
60.120		**-.66**							**-.52**	
60.100		**-.55**								-.43
65.135										-.44
65.115	-.39									**-.60**
65.75	**-.64**									

exception being the mountainous cell in the Yukon with three months.

Correlation coefficients from the regression analyses of monthly snow-extent and temperature anomalies are presented in Table 1. Of the 97 monthly values calculated, 54 show a significant association between the two variables at the 99% level, and 19 more are significant at the 95% level. Over 50% of the variance is explained in 15 cases (r > -.71), these occurring in cells between 35 and 55°N. An examination of the cells from south to north shows the strongest association at 35-40°N in the cell encompassing most of the Appalachian Mountains and central Ohio Valley (Figure 1). This occurs in January and has the highest correlation of all 97 cases. The strongest associations continue during the winter months in cells located between 40-45°N, except in the westernmost cell centered in western Oregon. The strongest correlation within this latitudinal zone occurs in January at the midwestern cell centered over Iowa. In the western cell the correlation is highest in November, and January shows the weakest association of any month at any cell (r = -.02). Between 45 and 50°N the second highest correlation of all cases is found in February at the cell centered over western North Dakota (Figure 2).

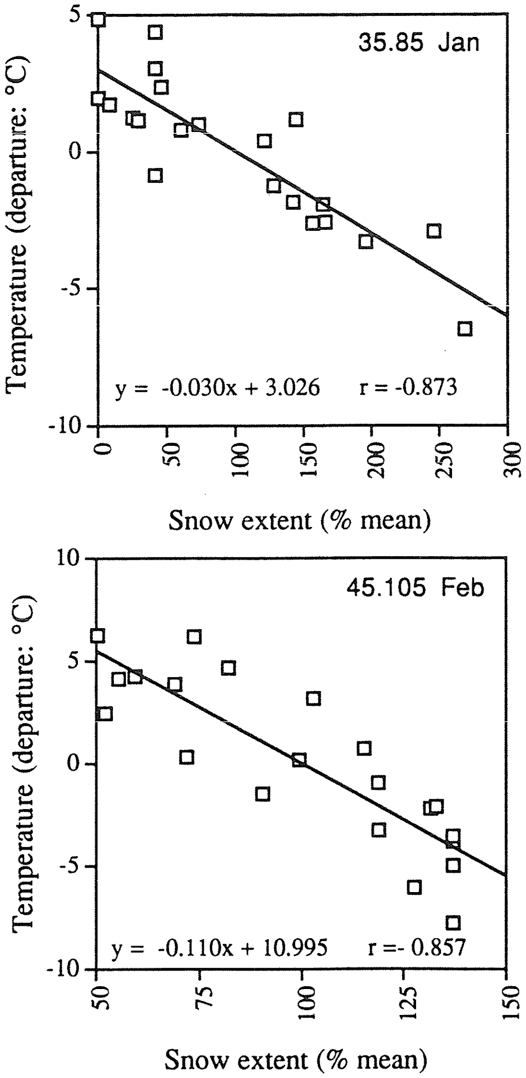

Figure 2. Scatter diagrams of snow extent anomalies and associated temperature departures from 1972-1992 at study cells situated (Top) between 35-40°N and 80-85°W for January, and (Bottom) between 45-50°N and 100-105°W for February. Snow anomalies are expressed as a percentage of the 1972-1992 mean, temperature departures as differences from the 1972-1992 mean (in °C). The regression line, equation and r value are also shown for each cell.

Poleward of 50°N only some fall and spring months meet the analysis criterion. Cells in the center of the continent from 50-60°N tend to have the month with the highest snow/temperature correlation in spring and those in the East have highest values in fall. Between 50-55°N the strongest association occurs in April over the western Ontario cell. At 55-60°N the northeastern Alberta cell has the highest correlation, again in April. The cell between 60-65°N with the strongest association, this occurring in October, is centered between Great Slave and Great Bear lakes. Among the three cells from 65-70°N, the highest correlation occurs over Baffin Island in September. In this zone, only June qualifies for analysis at the cell between 135 and 130°W, and the correlation is not significant at the 95% level. This is the only cell not to have at least one month significant at the 99% level.

Composites for extreme snow conditions

Composites of monthly departures of snow cover and temperature for the five most extensive and five least extensive snow years in each cell are shown in Table 2 for the month having the highest correlation coefficient. Departures for the extensive snow composites range from 117 to 296% of normal and for the less extensive snow groupings from 0 to 75% of normal. These vary broadly owing to seasonal and regional differences in the year-to-year variability of snow cover.

Composites of temperature departures are all negative for the maximum snow cases, ranging from -0.6 to -4.4°C. Only 17 of the 130 composited maximum months (26 cases x 5 years) have positive temperature departures, and only four cases have as many as two positive departure months. Temperature departures exceed -3.0°C in most cells centered over the contiguous United States, exceptions being the two westernmost cells between 35-45°N, where departures are -1.0°C or less. Departures in the -1.0 to -2.0°C range are common in the Canadian and Alaskan cells.

Temperatures are all positive for minimum snow cover composites, ranging from +0.3 to +4.2°C. All but 19 of the 130 minimum months have positive departures and only four cases have as many as two negative departure months. The three cells with the largest departures are in the center of the continent between 40 and 55°N. They run from southeast (40-45°N/90-95°W; departure +3.9°C) to northwest (50-55°N/105-110°W; departure +3.9°C), and occur in January (southeast cell), February (45-50°N/100-105°W; departure +4.2°C), and March (northwest cell). Elsewhere departures are within several tenths of a degree of +2.0°C, except over the mountainous west and at higher latitudes where departures are closer to +1.0°C.

Table 2. Composite averages of monthly departures of snow cover and temperature for the five most extensive and the five least extensive snow years in each study cell for the month with the highest correlation coefficient (cf. Table 1). Snow departures (Snow_d) are expressed as a percentage of the 1972-1992 mean, temperature departures (Temp_d) as differences from the 1972-1992 mean (in °C). Cells are listed by the coordinates (latitude N/longitude W) at their lower left corner.

		Maximum Snow		*Minimum Snow*	
Cell	*Month*	Snow_d	Temp_d	Snow_d	Temp_d
35.115	Jan	154	-1.0	34	+0.9
35.100	Feb	296	-3.3	3	+2.5
35.85	Jan	208	-3.5	13	+2.2
40.125	Nov	237	-0.5	0	+0.7
40.110	Dec	142	-3.4	61	+2.1
40.95	Jan	135	-3.6	61	+3.9
40.80	Jan	130	-3.0	54	+1.8
45.120	Feb	117	-3.0	75	+1.6
45.105	Feb	136	-4.4	57	+4.2
45.75	Apr	132	-1.3	56	+0.7
50.125	Nov	130	-2.0	71	+1.8
50.110	Mar	123	-2.1	71	+3.9
50.95	Apr	124	-1.4	58	+2.6
50.80	Oct	273	-1.5	1	+0.8
50.65	Oct	246	-1.2	3	+0.3
55.130	Jun	160	-0.9	34	+0.8
55.115	Apr	133	-2.1	58	+2.3
55.100	May	161	-1.6	40	+1.0
55.75	Oct	188	-1.3	40	+0.6
60.160	May	155	-1.3	40	+1.3
60.140	May	141	-0.6	39	+1.0
60.120	Oct	170	-1.0	17	+2.3
60.100	Oct	139	-1.3	64	+2.1
65.135	Jun	222	-0.7	3	+1.0
65.115	Jun	131	-1.4	66	+1.2
65.75	Sep	178	-0.6	10	+0.7

Potential tropospheric influence on snow/temperature associations

The results presented to this point indicate a significant association between the regional coverage of snow and anomalies of surface air temperature. In principal, variations in snow cover are likely contributors to the temperature departures, however the full magnitude of these anomalies is not likely a result of the local effects of snow cover. To investigate the potential influence of mid-tropospheric circulation on these temperature anomalies, composites of 500-mb height anomalies are examined in each 5° latitudinal zone at the cell having the highest snow/temperature correlation. Results are presented here and discussed in the next section. For the minimum snow composites, centers of above normal 500-mb heights are situated either over or immediately to the east of the cells. Figure 3 exemplifies this, showing a strong ridge in February situated east of the northern Great Plains cell.

An association between temperature departures and 500-mb heights is more difficult to discern in the maximum snow-cover composites. For maximum snow composites height departures are weak over most of North America in five of the seven cases, with none exceeding ± 20 m within approximately

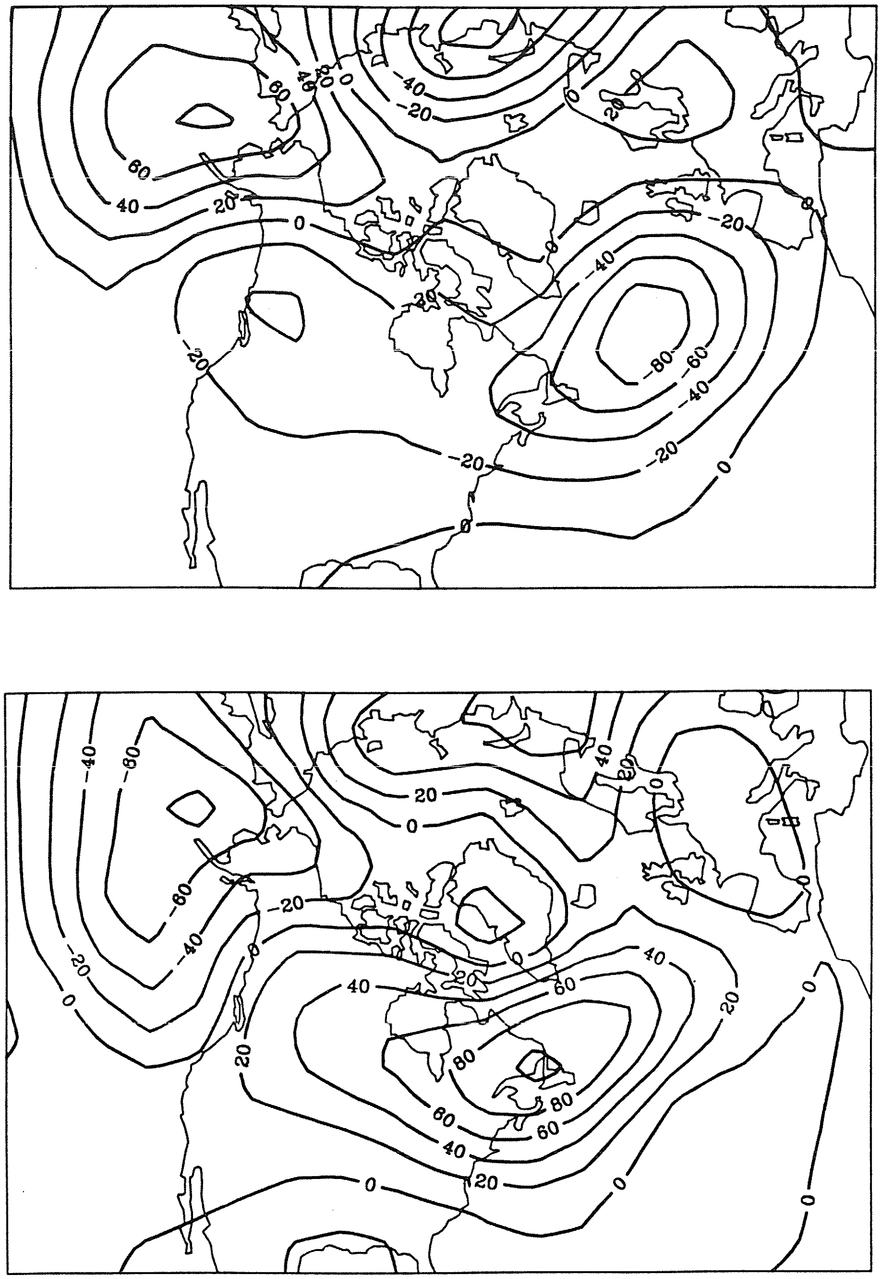

Figure 3. Composite averaged 500-mb height departures (in meters) for Februaries with positive (top) and negative (bottom) snow cover extremes at 45-50°N and 100-105°W. Positive snow years include 1972,75,78,79,82; negative years 1977, 81,83,84 (1992 is the fifth negative year, however 500-mb data are as yet unavailable).

2000 km of a study cell (Figure 3). Only in the eastern U.S. cell between 35 and 40°N and in the northwestern Canadian cell between 60 and 65°N is there a suggestion that atmospheric circulation may be strongly contributing to the temperature departures. A deep trough is situated immediately to the east in the former composite and a ridge is located to the southwest over British Columbia in the latter case. Elsewhere circulation appears to be contributing little to the temperature anomalies.

DISCUSSION

Despite the clear association between anomalies of snow and temperature, the preceding results at 500 mb illustrate the difficulty in establishing whether the two are related, and if so, whether snow cover is directly affecting temperature or whether they are both responding to other factors. Our examination of 500-mb heights where significant above normal snow/below normal temperature correlations exist found a general lack of height anomalies over or near the correlation regions. This lack suggests that local tropospheric dynamics or advective influences are not contributing greatly to the temperature anomalies, and supports the contention that snow cover (or the lack thereof) is strongly influencing temperatures. This conclusion agrees with our earlier study (Leathers and Robinson 1993), where we also noted that large negative temperature anomalies across snowfree southern portions of the United States during the winter may in part be influenced by positive snow-cover anomalies further north. Air masses moving south across the anomalous snowpack just to the north would undergo little modification before reaching the snowfree southern areas.

It is also interesting to speculate whether above normal snow extents may in some areas indirectly contribute to negative temperature departures. In our study case over the Appalachians and central Ohio Valley it is noted that a strong 500-mb trough is centered over southern New England when snow is extensive and below normal temperatures are observed. Walsh and Ross (1986) found that more extensive than normal snow cover over eastern North America appears to enhance cyclogenesis and promote a southward displacement of storm tracks along the east coast of North America. Thus both the snow-influenced lower tropospheric heights and the local presence of snow might be contributing to the temperature departures.

In situations where snow cover is less extensive than normal and temperatures are above normal, the frequent presence of above normal 500-mb heights makes assessing the potential influence of snow anomalies on temperature more difficult than in the extensive snow-cover cases. The above normal heights, either over the area or to the east, doubtlessly contribute to the temperature anomalies. However, the coincident nature of the minimum snow-cover and temperature perturbations indicates that the snow cover seems to be important, at least, in the amplification of the temperature anomalies.

CONCLUSIONS

We have found significant associations between regional snow cover extent and surface air temperature across North America. In a large majority of cases, when the extent of snow cover is above normal, temperature departures are negative. Conversely, negative snow departures are almost always associated with above normal temperatures. In a large majority of cases, when the extent of snow cover is anomalously high (low) temperature departures are negative (positive). Regional correlations are highest in seasons when snow cover is most variable. These results agree with earlier studies of more limited spatial or temporal scales (e.g. Dewey 1977; Walsh et al. 1982; Namias 1985). The largest temperature departures are associated with anomalies of snow cover over the central portion of the continent. This finding agrees with an earlier study over the United States (Leathers and Robinson, 1993). In the present study we found that the magnitude of temperature anomalies decreases not only to the east and west of the central region but also toward the Pole.

An examination of 500-mb heights across North America suggests that, though circulation anomalies doubtlessly contribute to the temperature departures observed in regions of anomalous snow, the presence or absence of snow strongly influences temperatures. This snow influence is most apparent in situations of above-average snow extent.

We plan to continue analyzing snow cover in relation to temperature and other climatic variables in North America as well as in Eurasia using satellite and long-term station datasets (cf. Hughes and Robinson, 1993). Knowledge gained from studies to date and from future studies will continue to increase our understanding of snow/atmosphere dynamics, help improve short and medium range temperature forecasts, and contribute to the utilization of snow cover as an indicator of future climate change.

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