Interannual Variability of Wintertime Snow Cover across the Northern Hemisphere

DAVID S. GUTZLER AND RICHARD D. ROSEN

Atmospheric and Environmental Research, Inc., Cambridge, Massachusetts

(Manuscript received 9 May 1991, in final form 26 February 1992)

ABSTRACT

Digitized maps of Northern Hemisphere snow cover derived from visible satellite imagery are examined to assess the interannual variability of snow cover in winter months for years 1972–90. The secular trend of winter snow cover over the landmasses of Eurasia and North America during this period is extremely small in December and January. A decreasing trend of somewhat larger magnitude is observed in Eurasian snow cover in February. Fluctuations of detrended interannual snow-cover anomalies averaged over the Eurasian and North American continents are positively correlated. By subdividing the continents into longitudinal sectors it is determined that this intercontinental relationship is due to high correlations between European and North American sectors. The relationship of snow-cover fluctuations to large-scale circulation anomalies is described using time series of teleconnection pattern indices derived from monthly mean geopotential height fields. A pattern of height anomalies resembling the North Atlantic Oscillation is correlated with snow-cover anomalies in North America and Europe. The Pacific–North American teleconnection pattern is highly correlated with snow-cover anomalies in western North America but has limited influence on intercontinental snow-cover fluctuations.

1. Introduction

Snow cover is an important component of the coupled atmosphere–land climate system. The sensitivity of climate to snow cover has been well established through modeling studies, but relatively little documentation of snow-cover variability has been carried out for lack of comprehensive data. This paper describes an observational study of interannual variability of Northern Hemisphere snow cover and the relationship between snow cover and large-scale circulation anomalies, using a satellite-based dataset of monthly mean snow cover. Aspects of the seasonal cycle, frequency, secular trends, and persistence of snow cover depicted in this dataset have been documented in previous studies (Dewey and Heim 1982; Matson et al. 1986; Robinson et al. 1991, hereafter denoted RKD; Iwasaki 1991).

The purposes of this paper are to document wintertime, interannual variability of snow cover on subcontinental scales and to compare fluctuations of snow cover and the large-scale atmospheric circulation. Interannual circulation anomalies have been studied intensively during the past decade and provide a basis for assessing snow-cover fluctuations on scales smaller than the hemispheric average. In this study we present statistics of interannual variability for the winter months of December, January, and February, when snow cover is most extensive and atmospheric teleconnection patterns are particularly pronounced. Analysis of other months would yield a somewhat different perspective on snow-cover fluctuations; for example, the largest interannual variability of hemispheric snow cover is observed in the autumn months, the period of greatest snow accumulation (RKD).

Following a discussion of data-quality issues pertinent to the snow-cover maps, we present statistics describing the mean and interannual variability of the snow-covered area of large sectors of the two Northern Hemisphere landmasses. We then correlate interannual snow-cover fluctuations with time series of several prominent teleconnection patterns of monthly mean geopotential heights in the wintertime Northern Hemisphere.

2. Data

Digitized maps of Northern Hemisphere snow cover are analyzed and archived each week by NOAA/NESDIS. The maps are subjectively analyzed from visible imagery (Matson and Wiesnet 1981; Dewey and Heim 1982) to produce charts indicating the presence or absence of snow in each cell of an 89 × 89 grid covering a polar stereographic projection of the Northern Hemisphere. We have formed monthly means by assigning each weekly chart to the month in which the fifth day of the chart week occurs, since RKD found the weekly charts to be most representative of that day. Snow is considered present for each grid cell in the monthly mean if the cell is snow covered for half or more of the weeks in the month. In this study we show

Corresponding author address: Dr. David Gutzler, Aeronomy Lab, NOAA/ERL, R/E/AL3, 325 Broadway, Boulder, CO 80303.

results derived from December data for years 1972–1989 (18 years), and from January and February data for years 1972–1990 (19 years).

We have incorporated several adjustments to the original NOAA/NESDIS grids suggested by RKD to remove temporal inconsistencies in the archiving procedure. Despite our adoption of these adjustments, our calculations of monthly mean snow-cover area differ from those presented by RKD in three respects. First, RKD calculate snow-cover areas directly from the weekly digitized grids, then average the weekly areas to form monthly areas. Our procedure (calculating an area from a monthly averaged digitized grid) tends to produce larger values of monthly mean area. Second, the areas assigned to the grid cells by NOAA/NESDIS (and used by RKD) inexplicably differ from those we calculated independently, resulting in slightly larger grid-cell areas in middle latitudes in our calculation. Third, RKD employ a weighting scheme that distributes the weekly mean snow cover of a week that spans two calendar months into the statistics for both months, whereas we have adopted the methodology outlined above of assigning each week to a single month, similar to the NOAA/NESDIS practice. These differences, which should not have a major qualitative effect on the conclusions of our study or those of RKD, are nevertheless representative of ambiguities that should be kept in mind when interpreting analyses from these snow-cover data.

From the gridded maps for each month we have calculated the land area covered by snow in seven longitudinal sectors of the Northern Hemisphere (Fig. 1). Sectors 1 and 2 cover the North American continent, sectors 3 and 4 cover Europe, and sectors 5–7 cover Asia. The sector boundaries, though subjective, are not entirely arbitrary. The boundary between sectors 1 and 2 follows the eastern edge of the Rockies, and that between sectors 4 and 5 is the approximate longitude of the Ural Mountains. The longitudinal extent of sector 5 corresponds to the western Asia maximum in the interannual variance of near-surface temperature (Gutzler et al. 1988). No attempt has been made to optimize this choice of sector boundaries empirically, for example with respect to some variance maximization criterion such as in a cluster analysis.

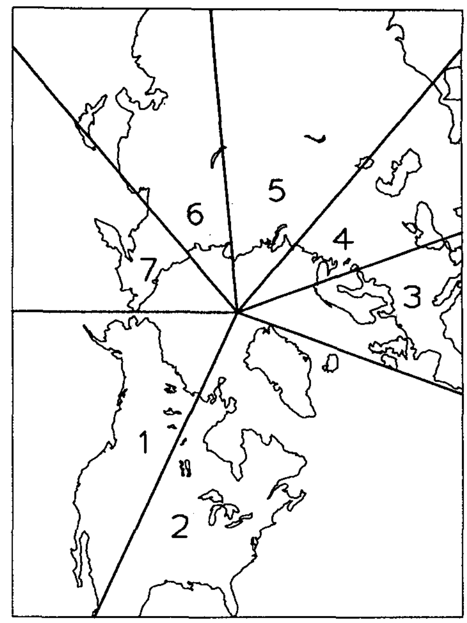

FIG. 1. Sector boundaries for snow-cover calculations. Sectors 1 and 2 together span North America; sectors 3–7 span Eurasia; and the sum of sectors 1–7 is the entire Northern Hemisphere.

3. Results

Table 1 shows the climatological mean and interannual variability of the snow-covered area in each of the seven longitudinal sectors, the North American and Eurasian landmasses, and the entire hemisphere. Mean and secular (linear) trend statistics are derived from the time series of monthly mean areas for each winter month. The mean and trend for each sector and month are then removed, and the standard deviation and coefficient of variation statistics in the right-hand columns of Table 1 (and the correlation statistics to be discussed presently) are derived from detrended time series of snow-cover anomalies.

In the previous section we outlined several differences between our analysis of this dataset and others published in recent years. Relative to calculations derived from the original NOAA/NESDIS grids (e.g., Matson et al. 1986), the mean January North American snow cover shown in Table 1 is larger by roughly 0.5 Mm^2 (1 $Mm^2 \equiv 1$ million km^2), and Eurasian snow cover is smaller by about 0.4 Mm^2. Most of these differences are due to the changes in the land/sea mask recommended by RKD that we have adopted. Relative to RKD, our hemispheric values are systematically larger by 1–2 Mm^2 and exhibit greater interannual variability, principally due to the different schemes used to derive monthly mean areas from weekly digitized grids.

Secular trends in winter snow cover are insignificantly small for most sectors in all three months. The only linear trends in Table 1 that are different from zero at the 5% significance level describe decreasing snow cover in sectors 4 and 5 (central Eurasia) in February. The trends in these sectors exceed 0.5% yr^{-1}. Pan-Eurasian and Northern Hemisphere snow cover also exhibit decreasing trends in February, but these trends are not large enough, relative to higher-frequency interannual variability, to reject a null hypothesis of zero trend.

Eurasia accounts for more than 60% of the hemispheric snow-covered area in winter months, and the

TABLE 1. Climatological mean and interannual variability of snow cover in each sector (from Fig. 1) for the winter months of December, January, and February. Mean and secular trend are given in units 10^6 km^2 and 10^6 km^2 yr^{-1}. Trends different from zero at the 5% significance level are parenthesized. Standard deviation (10^6 km^2) and coefficient of variation (COV: standard deviation/mean) are derived from detrended anomalies (mean and secular trend removed).

Longitude boundaries	Sector	Month	Mean	Trend	Std. dev.	COV
170°W–105°W	1	Dec	7.2	0.009	0.62	.09
		Jan	7.6	0.016	0.41	.05
		Feb	7.6	0.024	0.37	.05
105°W–10°W	2	Dec	9.5	−0.007	0.56	.06
		Jan	10.2	−0.022	0.57	.06
		Feb	10.1	−0.017	0.67	.07
10°W–30°E	3	Dec	2.2	−0.005	0.68	.31
		Jan	3.0	−0.009	0.86	.29
		Feb	3.0	0.003	0.78	.26
30°E–60°E	4	Dec	4.5	−0.023	0.56	.13
		Jan	5.6	−0.029	0.60	.11
		Feb	5.6	(−0.036)	0.34	.06
60°E–105°E	5	Dec	10.0	0.007	0.79	.08
		Jan	10.8	0.011	0.86	.08
		Feb	10.8	(−0.083)	0.82	.08
105°E–140°E	6	Dec	6.8	0.021	0.50	.07
		Jan	7.1	0.008	0.35	.05
		Feb	7.1	−0.033	0.49	.07
140°E–170°W	7	Dec	3.1	0.009	0.07	.02
		Jan	3.1	0.003	0.05	.02
		Feb	3.2	0.003	0.04	.01
North America	Σ 1–2	Dec	16.7	0.001	0.96	.06
		Jan	17.8	−0.005	0.80	.05
		Feb	17.7	0.006	0.95	.05
Eurasia	Σ 3–7	Dec	26.5	0.007	1.80	.07
		Jan	29.5	−0.017	1.79	.06
		Feb	29.7	−0.146	1.68	.06
Northern Hemisphere	Σ 1–7	Dec	43.2	0.008	2.61	.06
		Jan	47.3	−0.022	2.38	.05
		Feb	47.4	−0.139	2.20	.05

detrended interannual standard deviation of snow cover over Eurasia is considerably larger than the North American value in each month. On both continents and for the hemispheric average, January and February are the winter months with the most extensive snow cover, but the largest variability occurs in December. In individual sectors January and February are also the months of most extensive mean snow cover, but interannual variability shows no general monthly maximum. Sectors 3 and 5, covering western Europe and western Asia, exhibit the largest interannual variability, about 0.8 Mm^2 in January and February.

The nonuniformity of areas makes it difficult to compare snow-cover variability in different sectors directly. For this purpose a normalized measure of variability, the coefficient of variation (standard deviation/mean), is shown in the right-hand column of Table 1. The coefficients of variation for the continents and the entire hemisphere are 5%–7% for winter months. Several individual longitudinal sectors on the Eurasian continent, however, exhibit much larger relative variability. Fluctuations over western Europe (sector 3) are particularly pronounced; the standard deviation of snow cover in that sector exceeds 25% of the climatological mean in each winter month. Coefficients of variation in eastern Europe (sector 4) exceed 10% in December and January.

Table 2 shows correlation coefficients between detrended interannual fluctuations of sector snow cover for the month of January. The nominal 5% nonzero significance threshold is 0.45, derived from a two-tailed t test assuming that each of the 19 monthly means is independent. All correlations involving adjacent sectors (near the diagonal in Table 2) are positive, indicating that snow-cover anomalies are often of large scale. Several of these correlations are low, however; the correlation between western and eastern North American sectors is only 0.27, and correlations between adjacent Asian sectors, while positive, are not significantly different from zero. Snow-cover anomalies in sector 6 are

TABLE 2. Correlation coefficients among interannual fluctuations of detrended January snow-cover anomalies in longitudinal sectors, North American and Eurasian landmasses, and the entire Northern Hemisphere. Correlations between independent areas exceeding 0.45 in magnitude are nonzero at the 5% significance level and are shown in underlined bold type. Sector numbers refer to Fig. 1.

1	1.00									
2	0.27	1.00								
3	**0.53**	**0.55**	1.00							
4	**0.60**	0.34	**0.46**	1.00						
5	0.27	0.36	0.07	**0.66**	1.00					
6	−0.40	−0.09	−0.04	−0.10	0.26	1.00				
7	**−0.49**	−0.03	−0.33	**−0.65**	−0.38	0.19	1.00			
Σ 1–2 North America	0.72	0.87	**0.68**	**0.56**	0.40	−0.27	−0.27	1.00		
Σ 3–7 Eurasia	**0.49**	**0.53**	0.65	0.83	0.77	0.27	−0.49	**0.64**	1.00	
Σ 1–7 Northern Hemisphere	0.61	0.69	0.71	0.81	0.71	0.12	−0.46	0.82	0.97	1.00
Sector	1	2	3	4	5	6	7	Σ 1–2	Σ 3–7	Σ 1–7

not significantly correlated with anomalies in any other sector. Anomalies in sector 7, the easternmost part of Siberia, are negatively correlated with anomalies in western North America and eastern Europe.

Both North American sectors are significantly correlated with pan-Eurasian snow cover, with the higher correlation between eastern North America and Eurasia (0.53). Conversely, snow cover in each of the North American sectors is significantly positively correlated with the snow cover in western Europe (sector 3), resulting in a high correlation of 0.68 between snow cover in western Europe and the North American continent. Snow cover in sector 4 is also significantly correlated with that over North America, but the correlation with North American snow cover decreases to insignificant values moving eastward through sectors 5–7. The net result is a highly significant correlation of 0.64 between North America and Eurasia. The large intercontinental correlation we find is consistent with the empirical orthogonal function analysis of winter snow anomalies carried out by Iwasaki (1991) in which the first mode describes continent-scale anomalies of the same sign across North America and Eurasia.

Table 3 displays a summary of snow-cover correlations for all three winter months to assess the reproducibility of the January interannual correlations just described. The entries in the table indicate which correlations among independent areas are significantly different from zero. All significant correlations in the December and February data are positive, so there is no need to indicate the signs of the correlations in Table 3. The three most robust correlations (significant in all three months) are between sectors 2 and 3 (eastern North America and western Europe), sector 3 and pan-North America, and North America and Eurasia. The bottom two rows in the table suggest that correlations between North American sectors and Eurasian snow cover, or between Eurasian sectors and North American snow cover, are most extensive in December and least extensive in February.

The relationship between interannual fluctuations of snow cover and the large-scale circulation is examined by correlating anomalies of snow cover with time series of prominent teleconnection patterns. Such patterns have been identified and defined in slightly different ways by many investigators. The particular

TABLE 3. Summary of significant correlation coefficients among interannual fluctuations of detrended snow-cover anomalies. Capital letters D, J, and F denote correlations significantly different from zero at the 5% significance level for months of December, January, and February; dashes denote correlations not significantly different from zero. Asterisks are shown for nonindependent areas.

2	– –F							
3	–J–	DJF						
4	DJ–	D– –	–J–					
5	D– –	—	—	DJ–				
6	D– –	—	—	—	D–F			
7	–J–	—	—	–J–	—	—		
Σ 1–2	*	*	DJF	DJ–	D– –	D– –	—	DJF
Σ 3–7	DJ–	DJ–	*	*	*	*	*	*
Sector	1	2	3	4	5	6	7	Σ 3–7
	North American sectors				Eurasian sectors			Eurasia

patterns used for our calculation were derived from monthly mean 700-mb heights for the period 1950–1991 using the rotated principal component pattern definition technique described by Barnston and Livezey (1987). This updated set of patterns and their associated time series were kindly provided to us by T. Barnston. We examined the first 10 modes of interannual variability derived separately for December, January, and February. Fluctuations of two patterns were found to exhibit significant correlations with snow cover in one or more sectors that were reproducible in at least two of the winter months.

The Pacific–North American (PNA) pattern of height anomalies (Wallace and Gutzler 1981) has centers over the central Pacific Ocean, northwestern North America, and the southeastern United States. Figure 2a shows the January PNA pattern, which is the third rotated mode in the January analysis. The PNA pattern is readily identifiable as the fourth mode in December and the first mode in February. Fluctuations of PNA are highly correlated with those of snow cover in the western (but not the eastern) North American sector (Table 4), such that the positive phase of PNA, characterized by ridging over western North America, is associated with a deficit of snow cover in sector 1. This result is consistent with the positive near-surface temperature and thickness anomalies across northwestern North America that are associated with the positive phase of PNA (Wallace and Gutzler 1981; Gutzler et al. 1988). The PNA height pattern is also significantly correlated with sector-6 snow cover in January, although this relationship is not reproducible in other months. The influence of the PNA pattern on snow cover thus seems to be confined mainly to western North America.

The other pattern that exhibits fairly robust relationships with interannual snow-cover fluctuations is one that contains elements of several well-known patterns influencing the circulation over the North Atlantic that have been described at length in previous studies. Its January manifestation, mode 4 of the updated analysis, is shown in Fig. 2b. It includes a northern center on the Greenwich meridian near latitude 65°N, the sign of which we use to define the phase of the pattern. Height anomaly centers of the opposite sign are located in the central Atlantic near 30°N, 40°W and over the central United States between 90°W and 100°W. The United States center is the least stable in the three monthly analyses; its latitude varies from near 45°N in December to about 30°N in February, with the January pattern in Fig. 2b an intermediate example. Patterns with these characteristics are the ninth mode in the December analysis and the fourth mode in the February analysis. In some respects this pattern resembles the North Atlantic Oscillation (NAO) (Walker and Bliss 1932; van Loon and Rogers 1978) and the Eastern Atlantic pattern defined by Wallace and Gutzler (1981), although other modes in the sets of 10 for

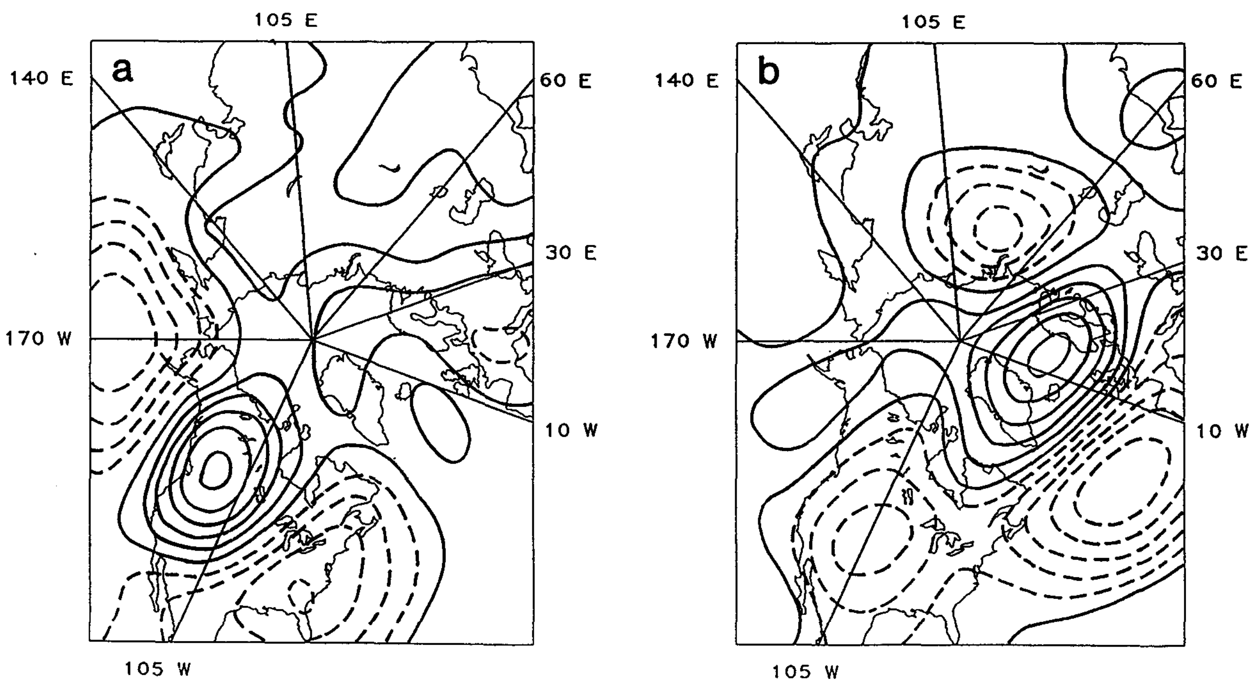

FIG. 2. (a) Positive phase of the PNA pattern of January monthly mean 700-mb geopotential height anomalies. This is the third mode of a rotated principal component analysis of interannual variability derived from 42 January monthly means (1950–91) carried out by T. Barnston. Contour interval is arbitrary; negative height contours are dashed. (b) Like (a) but for the positive phase of the NAO-like pattern, the fourth mode of the January analysis.

TABLE 4. Correlation coefficients between interannual (detrended) fluctuations of snow cover and fluctuations of two teleconnection patterns of the large-scale circulation. Correlations exceeding 0.45 in magnitude are nonzero at the 5% significance level and are shown in underlined bold type. See text and Fig. 2 for description of teleconnection patterns.

Longitude boundaries	Sector	Month	PNA	NAO-like
170°W–105°W	1	Dec	**−0.64**	0.28
		Jan	**−0.54**	0.31
		Feb	−0.39	0.09
105°W–10°W	2	Dec	−0.12	0.40
		Jan	0.35	0.10
		Feb	−0.03	**0.50**
10°W–30°E	3	Dec	−0.38	0.16
		Jan	0.04	**0.69**
		Feb	0.16	**0.58**
30°E–60°E	4	Dec	−0.12	**0.49**
		Jan	−0.15	0.31
		Feb	0.27	0.26
60°E–105°E	5	Dec	−0.11	0.13
		Jan	0.06	−0.03
		Feb	0.03	−0.09
105°E–140°E	6	Dec	−0.05	0.29
		Jan	**0.46**	0.23
		Feb	0.09	0.13
140°E–170°W	7	Dec	−0.06	−0.13
		Jan	0.18	−0.35
		Feb	0.08	**0.46**
North America	Σ 1–2	Dec	**−0.48**	0.41
		Jan	−0.02	0.23
		Feb	−0.17	0.39
Eurasia	Σ 3–7	Dec	−0.25	0.35
		Jan	0.09	**0.46**
		Feb	0.17	0.32
Northern Hemisphere	Σ 1–7	Dec	−0.34	0.39
		Jan	0.06	0.42
		Feb	0.06	0.40

each month more closely resemble those particular patterns. Barnston and Livezey (1987, Fig. 16a) alluded to this pattern as "unclassified, but NAO-like."

Correlations between the time series of this pattern and sector snow-cover anomalies are shown in the right-hand column of Table 4. Significant positive correlations are found for sector 3 (western Europe) in January and February; thus excessive snow cover is associated with anomalously high pressure west of Scandinavia. In December the sector 3 correlation is insignificant, but there is positive correlation with snow cover to the east in sector 4. Several other correlations in Table 4 exceed the nominal significance level, including positive correlation with sectors 2 and 7 in February and with pan-Eurasian snow cover in January. Numerous correlations lie just below the 0.45 threshold for significance, most notably those involving continental and hemispheric snow cover. It is tempting to think of this NAO-like circulation anomaly pattern as perhaps one of central importance for wintertime snow-cover anomalies. This conclusion is very tentative, however, considering the somewhat nebulous nature of this mode relative to more familiar teleconnection patterns and the caution that must be used in interpreting even statistically significant correlations in time series with as few degrees of freedom as are present here.

4. Concluding remarks

The principal result of this study is the description of significant positive correlation between interannual fluctuations of wintertime snow cover on the North American and Eurasian landmasses. The trends observable in 19 years of snow-cover data are generally insignificant during winter months, and the intercontinental snow-cover correlations documented here are manifestations of year-to-year fluctuations distinct from long-term trends. The general absence of significant secular trends found here does not conflict with recent results of RKD, who documented substantial snow-cover trends but principally in the other three seasons. It is not known whether this apparent seasonality in snow-cover trend represents seasonal differences in recent global warming, seasonality in the temperature–snow cover relationship suggested by RKD, or simply uncertainties in the snow-cover data. In any case, seasonal discrimination should be an important consideration for monitoring snow cover as an indicator of climate change.

Examination of subcontinental snow-cover variability reveals that snow cover over Europe is exceptionally variable on interannual time scales, and the best intercontinental correlations are between European and North American sectors. Continent-averaged North American and Eurasian snow-cover anomalies are significantly correlated in all three winter months, as are sector-averaged anomalies in sectors 2 (eastern North America) and 3 (western Europe). Intercontinental snow-cover correlations tend to be stronger in December and January than in February.

The emphasis upon European snow cover and its variability derived from this analysis is rather different from most previous studies of snow cover and short-term climate change, which usually focus on Asia (e.g., Barnett et al. 1989). Positive intercontinental correlation is also observed in interannual fluctuations of near-surface temperature (Barnett 1978; Gutzler et al. 1988), but here again the principal center of variability on the Eurasian landmass is in western Asia, not Europe.

The highest correlations between anomalies of snow cover and fluctuations of the large-scale circulation (defined from time series of teleconnection patterns) are associated with the PNA pattern, which is significantly correlated with snow cover over western North

America. Correlations between fluctuations of PNA and Eurasian, or hemisphere-averaged, snow cover are generally small, however, so the intercontinental snow-cover relationship does not seem to be associated with the PNA pattern.

The only height teleconnection pattern exhibiting appreciable correlations with snow-cover anomalies on continental or hemispheric scales is an NAO-like pattern. The correlations are not large or robust enough to be thoroughly conclusive, however, and this particular height pattern is not among the most prominent modes of large-scale circulation variability. We therefore consider this result to be tentative pending further investigation.

Previous studies have shown a clear correspondence between hemisphere-averaged, monthly mean snow cover and temperature fluctuations (Robinson and Dewey 1990; RKD), and continental regions are emphasized in the interannual variance of the near-surface temperature field in contrast to the oceanic maxima in height variance (Gutzler et al. 1988). The temperature anomaly field associated with the NAO-like teleconnection pattern has not been documented; the height pattern in Fig. 2b implies anomalous northerly flow and cold temperatures over Scandinavia and northeastern Europe. A systematic examination of regional-scale relationships between temperature and snow cover would provide results complementary to those reported here and may help to clarify the mechanisms responsible for the coupling between interannual fluctuations of winter snow cover over North America and Europe.

Acknowledgments. This material is based upon work supported by the National Science Foundation under Grant ATM-8911293. Most of the snow-cover data were obtained from the World Data Center A for Glaciology in Boulder, Colorado. Prof. David Robinson (Rutgers University) has been unstintingly helpful with many aspects of these data and provided us with unpublished results to facilitate comparisons of our analyses. Tony Barnston (NOAA/NMC/Climate Analysis Center) provided us with updated time series of teleconnection patterns. We thank David Salstein (AER) and Chet Ropelewski (Climate Analysis Center) for helpful comments. Most of the calculations described here were carried out at the computing facility of the National Center for Atmospheric Research, which is sponsored by the National Science Foundation.

REFERENCES

Barnett, T. P., 1978: Estimating variability of surface air temperature in the Northern Hemisphere. *Mon. Wea. Rev.,* **106,** 1353–1367.

——, L. Dümenil, U. Schlese, E. Roeckner, and M. Latif, 1989: The effect of Eurasian snow cover on regional and global climate variations. *J. Atmos. Sci.,* **46,** 661–685.

Barnston, A. G., and R. E. Livezey, 1987: Classification, seasonality and persistence of low-frequency atmospheric circulation patterns. *Mon. Wea. Rev.,* **115,** 1083–1126.

Dewey, K. F., and R. Heim, 1982: A digital archive of Northern Hemisphere snow cover, November 1966 through December 1980. *Bull. Amer. Meteor. Soc.,* **63,** 1132–1141.

Gutzler, D. S., R. D. Rosen, D. A. Salstein, and J. P. Peixoto, 1988: Patterns of interannual variability in the Northern Hemisphere wintertime 850 mb temperature field. *J. Climate,* **1,** 949–964.

Iwasaki, T., 1991: Year-to-year variation of snow cover area in the Northern Hemisphere. *J. Meteor. Soc. Japan,* **69,** 209–217.

Matson, M., and D. R. Wiesnet, 1981: New data base for climate studies. *Nature,* **289,** 451–456.

——, C. F. Ropelewski, and M. S. Varnadore, 1986: An atlas of satellite-derived Northern Hemispheric snow cover frequency. *NOAA Atlas,* 75 pp.

Robinson, D. A., and K. F. Dewey, 1990: Recent secular variations in the extent of Northern Hemisphere snow cover. *Geophys. Res. Lett.,* **17,** 1557–1560.

——, F. T. Keimig, and K. F. Dewey, 1991: Recent variations in Northern Hemisphere snow cover. *Proc. 15th Annual NOAA Climate Diagnostics Workshop,* Asheville, NC, 219–224.

van Loon, H., and J. C. Rogers, 1978: The seesaw in winter temperatures between Greenland and Northern Europe. Part I: General description. *Mon. Wea. Rev.,* **106,** 296–310.

Walker, G. T., and E. W. Bliss, 1932: World Weather V. *Mem. Roy. Meteor. Soc.,* **4,** 53–84.

Wallace, J. M., and D. S. Gutzler, 1981: Teleconnections in the geopotential height field during the Northern Hemisphere winter. *Mon. Wea. Rev.,* **109,** 784–812.