The Association between Extremes in North American Snow Cover Extent and United States Temperatures

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(Manuscript received 10 August 1992, in final form 24 December 1992)

ABSTRACT

The association between satellite-derived North American snow cover extent and United States winter (December, January, February) temperature is examined. The results indicate that winter months evidencing extreme positive (negative) values of North American snow cover extent are associated with below- (above) normal temperatures across the majority of the United States. The area evidencing the largest temperature departures during both positive and negative North American snow cover extremes is located across the central United States, roughly from the Dakotas south through the southern plains, and from the Rocky Mountains east to the Mississippi Valley. This area is collocated with the largest variations in snow cover frequency. No consistently strong association is indicated east of the Appalachians or west of the Rocky Mountains.

During December, strong 500-mb height anomalies are collocated with the area of maximum snow cover frequency deviations and the largest temperature departures. This is not the case in January and February. During these months the snow cover frequency and temperature anomaly fields are not in close proximity to strong areas of 500-mb deviations.

Evidence is presented to suggest that continental snow cover anomalies produce remote temperature perturbations away from the area of local snow cover variations, through the large-scale modification of air masses. In addition, a brief climatology of North American snow cover is presented.

1. 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. 1982; Heim and Dewey 1984; Walsh et al. 1985; Namias 1985) and throughout the Northern Hemisphere (Foster et al. 1983; Ross and Walsh 1986; Walsh and Ross 1988). Several investigations have suggested a relationship between Eurasian snow cover and the magnitude and timing of Indian monsoon rainfall (Hahn and Shukla 1976; Dey and Kumar 1983; Dickson 1984; Ropelewski et al. 1984). 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; Barnett et al. 1989; Gutzler and Rosen 1992) as well as local temperature forecast errors (Dewey 1977), cyclone frequencies and intensities (Ross and Walsh 1986; Dewey 1987), and even outbreaks of severe weather (Dewey 1987).

In climate change research, snow cover is currently being monitored on regional scales (Robinson 1987, 1991; Cerveny and Balling 1992) and on hemispheric scales (Barry 1985; Schlesinger 1986; Robinson and Dewey 1990) as a potential indicator of global environmental fluctuations. Several studies have used general circulation models (GCMs) in an effort to understand the role of snow cover in potential large-scale climate change and climate dynamics in general (Spar 1973; Williams 1975; Roads 1981; Yeh et al. 1983; Walsh and Ross 1988; Cohen and Rind 1991).

The purpose of this paper is to document the association between extremes in North American snow cover extent and the magnitude and spatial distribution of temperature anomalies across the coterminous United States. During the winter months (December, January, February; DJF), snow cover variations across the United States are almost entirely responsible for extremes in North American snow cover extent. Initially we present a brief climatology of satellite-derived North American snow cover extent, illustrating some

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basic characteristics of large-scale snow cover over the continent. We then present a compositing analysis that explores the association between extremes in North American snow cover extent and temperature anomalies throughout the United States. In addition, 500-mb height composites, based on snow cover extremes, are presented in order to better understand midtropospheric circulation patterns that are associated with snow cover anomalies. This study differs from efforts cited above (e.g., Walsh et al. 1982; Heim and Dewey 1984) because of its use of weekly gridded satellite-derived snow cover data and the use of the divisional temperature network (NOAA 1983). Both of these datasets possess a relatively fine spatial resolution, a feature absent in previous studies. Moreover, the present analysis uses compositing techniques to explore conditions during snow cover extremes as opposed to correlation-based procedures used in previous studies (Walsh et al. 1982; Heim and Dewey 1984).

2. Data and methodology

A primary component of the ongoing snow cover monitoring effort is satellite observations of Northern Hemisphere snow cover. Visible satellite data are used in the production of NOAA weekly snow cover charts, which have been produced for Northern Hemisphere land areas for over two decades (Weisnet and Matson 1979; Dewey and Heim 1982; Matson et al. 1986). Although the snow cover over Northern Hemisphere areas has been charted since 1966, it is recognized that early observations underestimated the snow cover extent (Kukla and Robinson 1981; Ropelewski 1985). The deployment of the Very High Resolution Radiometer (VHRR) on board NOAA satellites beginning in 1972 enhanced the accuracy of snow cover estimates. Using the more accurate VHRR and Advanced VHRR (AVHRR) data, weekly Northern Hemisphere snow cover area values for a continuous 20-year period, 1972 through 1991, are currently available. In this work we use weekly gridded snow cover data and monthly snow cover area estimates for the Northern Hemisphere, calculated using the Rutgers routine developed by Robinson (1992). The Rutgers routine calculates monthly snow cover extents by first deriving weekly areas from the NOAA digitized snow cover product. 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. In addition, the Rutgers routine employs an updated land mask, used for identifying land cells for snow cover extent calculations, which differs from those used in previous studies. For more information on the production of the weekly snow charts and the calculation of the snow cover areas, the reader is directed to Robinson (1992). The monthly snow cover extent values for the winter season are standardized by month and stratified into positive and negative extreme categories for an individual month. All winter months with standardized snow cover values of greater or less than 0.75 standard deviations are chosen as snow cover extremes (Table 1). This value is subjectively chosen as a cutoff because it represents large changes in snow cover extent across the continent while allowing for an acceptable sample size in the subsequent compositing analysis.

Snow cover frequency anomaly maps are constructed for each extreme category for each winter month (DJF) to illustrate where the snow anomalies are located within the United States during times of anomalous North American snow cover. The mean snow cover frequency for a given cell and month is calculated by summing the number of weeks classified as snow covered for a cell, during the period 1972 through 1991, and expressing this number as a percentage of the total number of weeks possible in that month during the 20-year period. The snow cover frequency anomaly maps are produced by calculating a snow cover frequency for each extreme snow cover category, in the same way that the mean frequencies are calculated. Subsequently, the mean snow cover frequency, based on the 20-year period, is subtracted from

TABLE 1. Months with snow cover values greater than or less than 0.75 standard deviation from the mean. Table includes monthly snow cover extent values in 10^6 km^2 and standardized snow cover values in parentheses.

>0.75 std dev			<0.75 std dev		
December					
1972	17.1	(0.75)	1979	14.8	(−1.77)
1978	17.5	(1.21)	1980	14.5	(−2.06)
1983	18.0	(1.73)	1986	15.6	(−0.90)
1985	17.9	(1.10)	1988	15.6	(−0.92)
1989	17.4	(1.10)*			
mean = 17.58			mean = 15.13		
std dev = 0.33			std dev = 0.49		
January					
1978	18.2	(1.09)	1972	16.6	(−1.10)
1979	18.5	(1.42)	1973	16.7	(−1.04)
1982	18.5	(1.38)	1981	16.0	(−1.96)
1984	18.3	(1.17)	1989	16.6	(−1.11)*
1988	18.1	(0.90)	1990	16.7	(−0.93)*
mean = 18.38			mean = 16.52		
std dev = 0.20			std dev = 0.26		
February					
1978	18.9	(2.00)	1977	15.9	(−1.48)
1979	18.7	(1.83)	1981	15.6	(−1.58)
1980	18.1	(1.05)	1987	16.3	(−0.95)
1982	17.9	(0.87)	1990	16.5	(−0.75)*
1985	18.2	(1.16)			
mean = 18.36			mean = 16.10		
std dev = 0.38			std dev = 0.35		

* Months not used in temperature compositing analysis.

the extreme values for each cell, yielding anomaly values.

Monthly temperature values for the winter season are collected for 344 climate divisions across the coterminous United States (NOAA 1983) for the period 1972 through 1988. The monthly temperature values are derived from a network of 5000 first-order and cooperative stations distributed across the country. For each month and snow cover extreme category (greater than 0.75 std dev or less than 0.75 std dev) temperature anomalies are derived by calculating the average of the divisional temperatures for all months in the extreme category and subtracting the monthly mean for the 17-year period from this value. Although a longer mean could have been obtained for the divisional data (data are available from 1895 through 1989) it is more appropriate to represent temperature anomalies using years that overlap between the snow cover and temperature datasets. The Student's t-test for the difference of means is used to determine the significance of the difference between the mean monthly divisional temperature and the composited temperature for each extreme category. All divisions evidencing means that are significantly different at the 95% level are marked with an asterisk in Figs. 3 through 5.

Finally, Northern Hemisphere 500-mb heights, derived from National Meteorological Center (NMC) octagonal grids (Jenne 1975), are used to construct height anomaly maps for each snow cover extreme category. This is done in order to document the atmospheric circulation during the extreme months, and understand the potential influence of midtropospheric circulation on United States temperature perturbations. These maps are produced by calculating the average of the 500-mb heights during the extreme snow cover categories for each month and subtracting the monthly mean of the 17-year period from these values (see discussion on temperature anomaly maps above). The 500-mb level was chosen because it is unlikely to be directly affected by large-scale thermal anomalies resulting from snow cover variations (Namias 1985; Walsh and Ross 1988). The Student's t-test is used to judge the local significance of the 500-mb anomalies. Asterisks denote those 500-mb grid points where anomalies are judged significant at the 95% level. No 500-mb patterns are judged significant at the 95% level using the field significance tests of Livezey and Chen (1983). In addition to the significance tests, the 500-mb field for each month included in a composite map was inspected in an effort to completely understand the make up of the composite pattern.

3. North American snow cover

Over the course of the annual cycle, average monthly snow cover across the North American continent (including Greenland) changes dramatically from greater than 17×10^6 km^2 in January to approximately 3×10^6 km^2 in August (Fig. 1a). The annual cycle is characterized by a relatively rapid establishment of continental snow cover during October and November and a gradual ablation of the snowpack during the spring and early summer months (Fig. 1a).

The coefficient of variation (standard deviation/mean) of North American snow cover extent also shows a distinct annual cycle (Fig. 1b), with the largest values occurring during the relatively snow-free summer and early autumn months and smaller values during the winter and spring seasons. Although the relative variation of North American snow cover is greatest during the summer and early autumn, the variability at this time of year is unlikely to be associated with large-scale climate anomalies because of the small area covered by snow.

The annual cycle of month-to-month persistence of snow cover anomalies is presented in Fig. 1c. These values represent the correlation between snow cover anomalies of a given month and the month directly following, providing an estimate of the persistence of snow cover anomalies during a given portion of the annual cycle. Month-to-month correlations are relatively high during the winter and spring seasons, suggesting that North American snow cover deviations are relatively persistent during this time of the year. During the summer, the month-to-month correlation values peak, suggesting that anomalies have a tendency to be very persistent during this season. However, the high correlation values during the summer may be related to the persistent cloud cover that often exists over the snow-covered areas during this portion of the year, making detection of small snow cover changes difficult. The smallest month-to-month correlations occur during the autumn months when the rapid establishment of the snow cover pack takes place. This implies that rapid variations in snow cover extent are common during this season as changes in atmospheric circulation patterns bring an increase in snow cover extent.

A time series of the standardized monthly snow cover values (Fig. 1d) indicates no unidirectional trend in snow cover extent. However, there have been rather persistent periods of above-normal North American snow cover during the late 1970s and the mid-1980s and persistent below-normal anomalies during the early 1980s and particularly over the last four years of the period.

4. Results

The purpose of the present study is to explore the association between extremes in satellite-derived North American snow cover extent and concomitant temperature anomalies across the coterminous United States for the winter season.

The gross relationship between North American snow cover extent and United States temperature can be seen in Fig. 2. This figure shows scatterplots of the

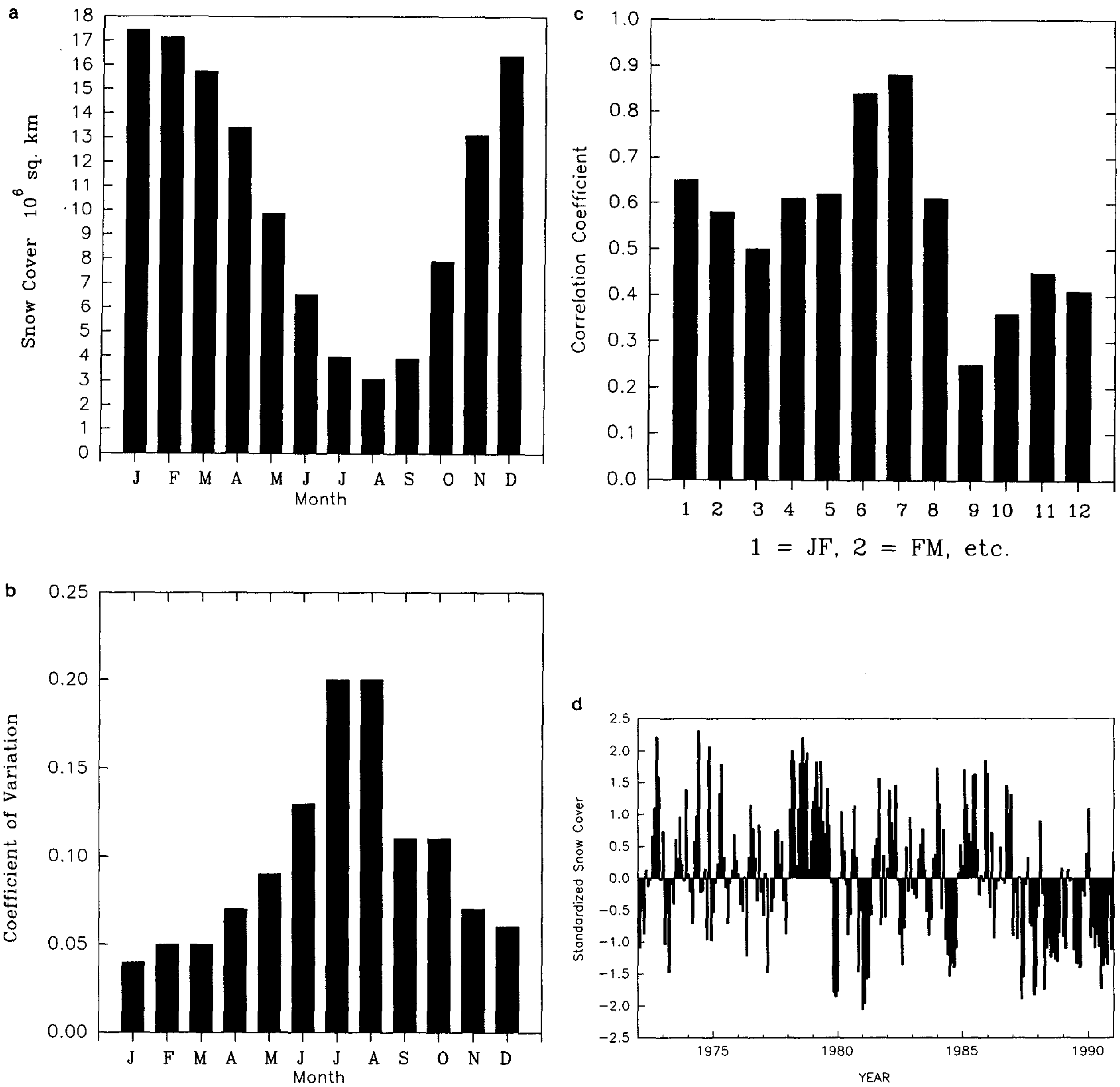

FIG. 1. Annual cycle of (a) North American snow cover, (b) coefficient of variation, (c) month-to-month persistence, and (d) time series of standardized snow cover.

United States national temperature (NCDC 1991, 1992) as a function of North American snow cover extent for the three winter months over the 20-year period. For each month, the correlation between the snow cover extent and the temperature is significant at the 99% level, with extensive (restricted) snow cover associated with relatively cold (warm) United States national temperature. It is clear from these plots that North American snow cover and United States temperature are rather closely associated. However, the question as to which regions of the country are strongly associated with the continental snow cover is not answered by this analysis. To understand the spatial nature of the relationship, the compositing technique described above is employed.

a. December

Decembers falling in the extreme positive snow cover category have average snow cover extents 1.2×10^6 km^2 above the 20-year mean (1972 through 1991). During the same months, large temperature anomalies

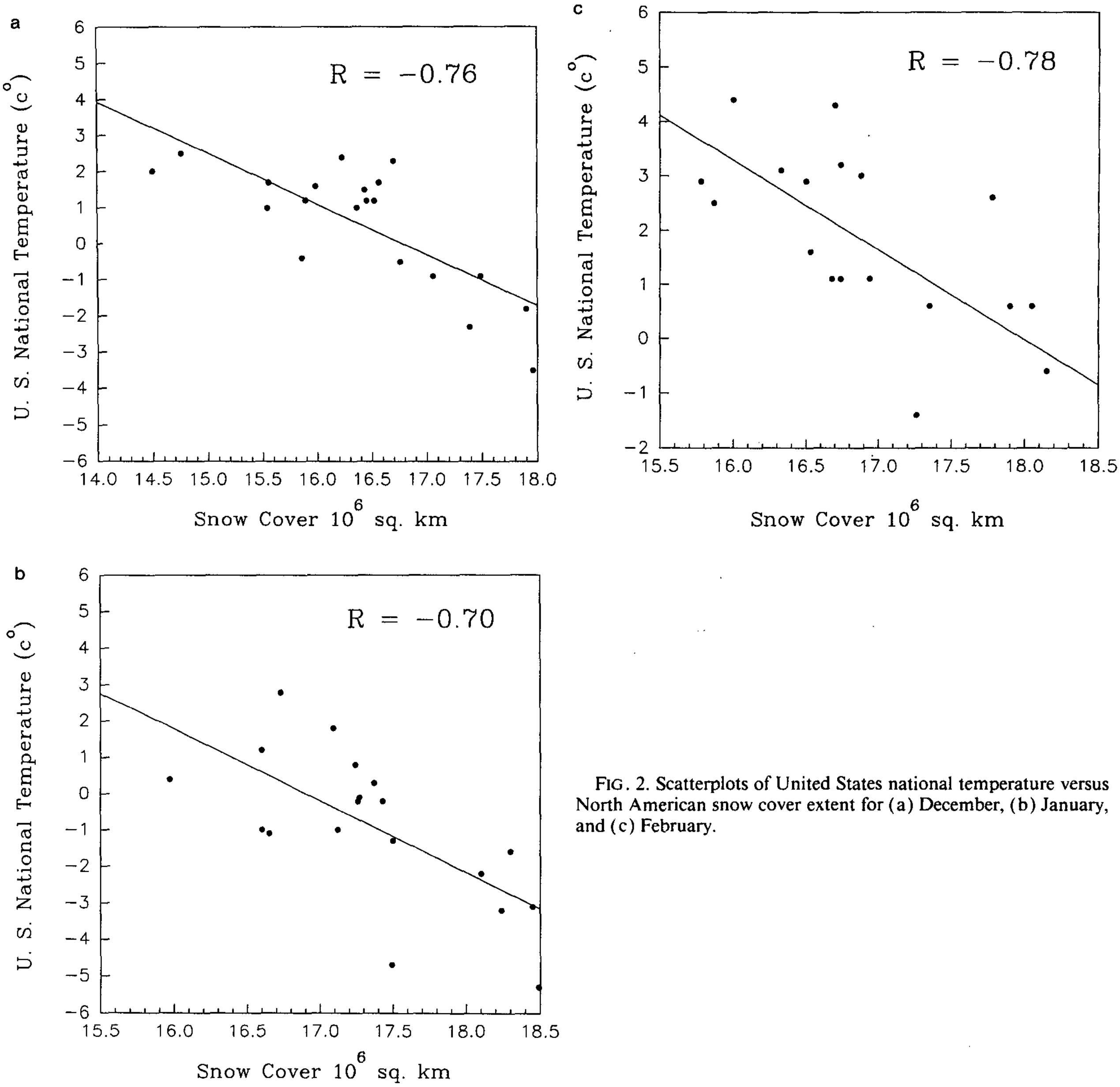

FIG. 2. Scatterplots of United States national temperature versus North American snow cover extent for (a) December, (b) January, and (c) February.

are found across a great expanse of the central portion of the United States (Fig. 3a). Temperature anomalies of greater than −4.5°C cover an area from Iowa west to Wyoming. In fact, significant temperature departures are found from Montana south through Texas and from the Rockies east to the Mississippi Valley. An inspection of the snow cover frequency anomaly map for this category (Fig. 3b) shows that the largest temperature anomalies are coincident with those areas that experience the greatest increase in snow cover frequency during the extreme months. However, the full magnitude of the anomalies may not be a result of the local effects of the snow cover. Figure 3c shows the 500-mb height departure map for this category. An area of below-normal 500-mb heights covers the majority of the United States during these months. The area of below-normal heights over North America may be associated with the anomalous snow cover through circulation perturbations and doubtlessly contributes to the temperature anomalies. However, the coincident nature of the maximum snow cover frequency and temperature perturbations would indicate that the snow cover is important, at least, in the amplification of the temperature anomalies. It is also interesting to note

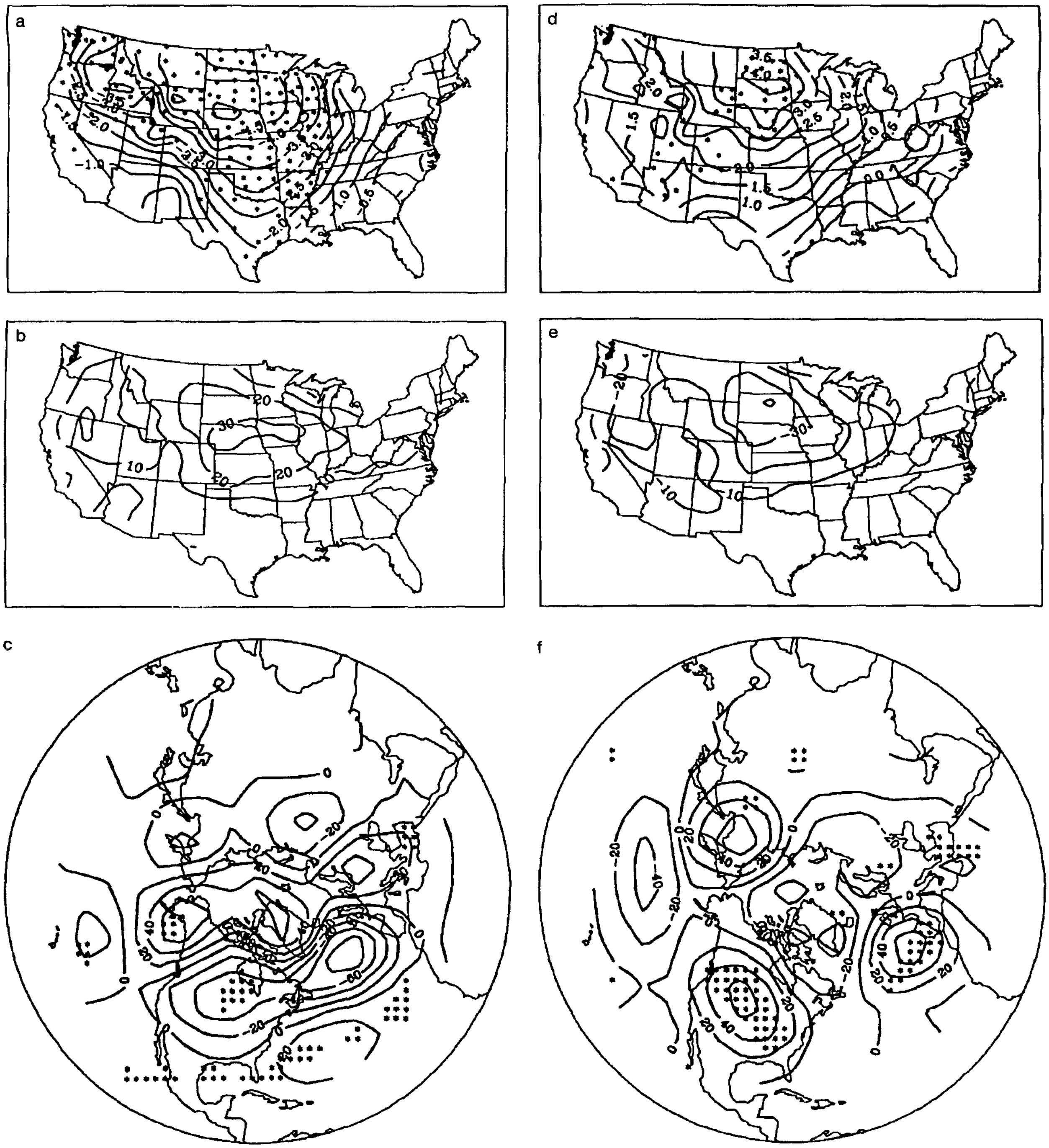

FIG. 3. (a) Temperature anomalies, (b) snow cover frequency anomalies, and (c) 500-mb height anomalies (gpm) for Decembers with positive snow cover extremes. (d) Temperature anomalies, (e) snow cover frequency anomalies, and (f) 500-mb height anomalies (gpm) for Decembers with negative snow cover extremes.

that the large temperature anomalies across the south central portion of the country are not associated with anomalous local snow cover. It is possible that the large snow cover extent across the continent is having a remote effect on temperatures in this region. As air masses move south out of Canada, over a predominantly snow-covered northern and central United States, they are modified little and reach the southern region of the United States with lower than normal temperatures. It is also likely that these temperature anomalies are due, at least in part, to advective effects associated with the anomalous 500-mb heights located over north-central North America.

Temperature departures during periods of extreme negative December snow cover anomalies are shown in Fig. 3d. During these extreme months the average North American snow cover is 1.3×10^6 km^2 below the 20-year mean. The same general region of the country evidences the largest temperature departures during these months. However, the temperature anomaly signal is slightly weaker and far fewer climate divisions evidence significant departures. The area of maximum temperature anomalies is confined to the central and northern plains states where departures of greater than 4.0°C are found. The snow cover frequency anomaly map (Fig. 3e) indicates that the area of maximum temperature departure is coincident with the area of maximum snow cover frequency decrease. An anomalous pattern of 500-mb heights is evidenced during these extreme months (Fig. 3f). A large area of significant positive height departures covers North America from Alaska southeast through the Florida peninsula. This 500-mb pattern suggests that atmospheric conditions may inhibit the buildup of the normal snow extent and contribute to the temperature departures seen in Figure 3d. However, similar to the December positive extreme case, the coincident nature of the snow cover frequency departures and the temperature departures suggests at least an amplification of the temperature anomalies by the absence of snow cover in areas where it would usually be found.

b. January

The central United States continues to evidence the maximum temperature anomalies for positive snow cover extremes in January (Fig. 4a). Monthly departures of greater than −3.0°C cover an area from the Mississippi Valley north and west through the Dakotas and into Montana. These departures are associated with snow cover extents 1.0 million km^2 above the 20-year mean. Again, the area of greatest temperature anomalies is coincident with the area of largest snow cover frequency increases (Fig. 4b). The 500-mb height departures during this month are weak and likely contribute little to the snow cover distribution or the temperature anomalies (Fig. 4c). An inspection of the individual 500-mb fields (not shown) shows no consistent height pattern or advective effects that might contribute to the temperature anomalies.

With negative snow cover extremes in January, average snow cover anomalies of -0.9×10^6 km^2 are found across North America. However, temperature departures across the United States are small during these months. An area of departures with magnitudes of 1.5°C is found from the Mississippi Valley northwest through the Dakotas (Fig. 4d). No climate divisions evidence a statistically significant temperature departure during these months. The snow cover frequency map for this category shows the largest changes in snow cover in the same area as the largest temperature departures (Fig. 4e). The snow cover frequency anomalies are relatively small, possibly explaining the reason for the lack of significant temperature perturbations. The 500-mb height pattern over North America during these events is similarly weak in the composite sense (Fig. 4f). However, an inspection of the individual 500-mb fields indicates a tendency for anomalous southerly flow over the eastern two-thirds of the United States during four of the five extreme months. This doubtlessly contributes to the positive temperature anomalies in some measure.

c. February

During months falling into the extreme positive snow cover category for February, the majority of the eastern two-thirds of the United States is covered by significant temperature anomalies. During these months the average snow cover anomaly across the continent is 1.2×10^6 km^2 above the 20-year mean. The axis of greatest temperature anomalies runs zonally from Indiana through Kansas and Nebraska, where values of −4.0°C are found (Fig. 5a). However, significant temperature departures are found throughout the northern tier states south to the Gulf of Mexico and from the high plains east to the Atlantic Coast. The snow cover frequency anomaly map indicates that the axis of greatest snow cover anomalies (up to 40%) is coincident with the temperature anomalies discussed above (Fig. 5b). The 500-mb departure map for this category shows no strong anomalous features anywhere over North America (Fig. 5c) and the individual fields show no consistent pattern of 500-mb influence in either the local or advective sense. In fact, the only significant feature is an area of depressed heights in the North Atlantic. This suggests that anomalous positive snow cover in February is critically important to the distribution of temperature anomalies across the United States. The lack of a substantial atmospheric perturbation over North America during these extreme months suggests that the local effects of anomalous snow cover may be principally responsible for the temperature anomalies found across the country. It is also important to note that three of the five extreme Februarys are preceded by snow cover extremes in January (see Table 1). It is possible that anomalous January snow cover persisted into February, affecting the mean temperatures for several days or weeks, contributing to the February temperature anomalies. During Februarys with well below-average snow cover extents (-1.0×10^6 km^2), positive temperature departures across the United States are large from the northern plains south to Texas, with values exceeding 4.0°C

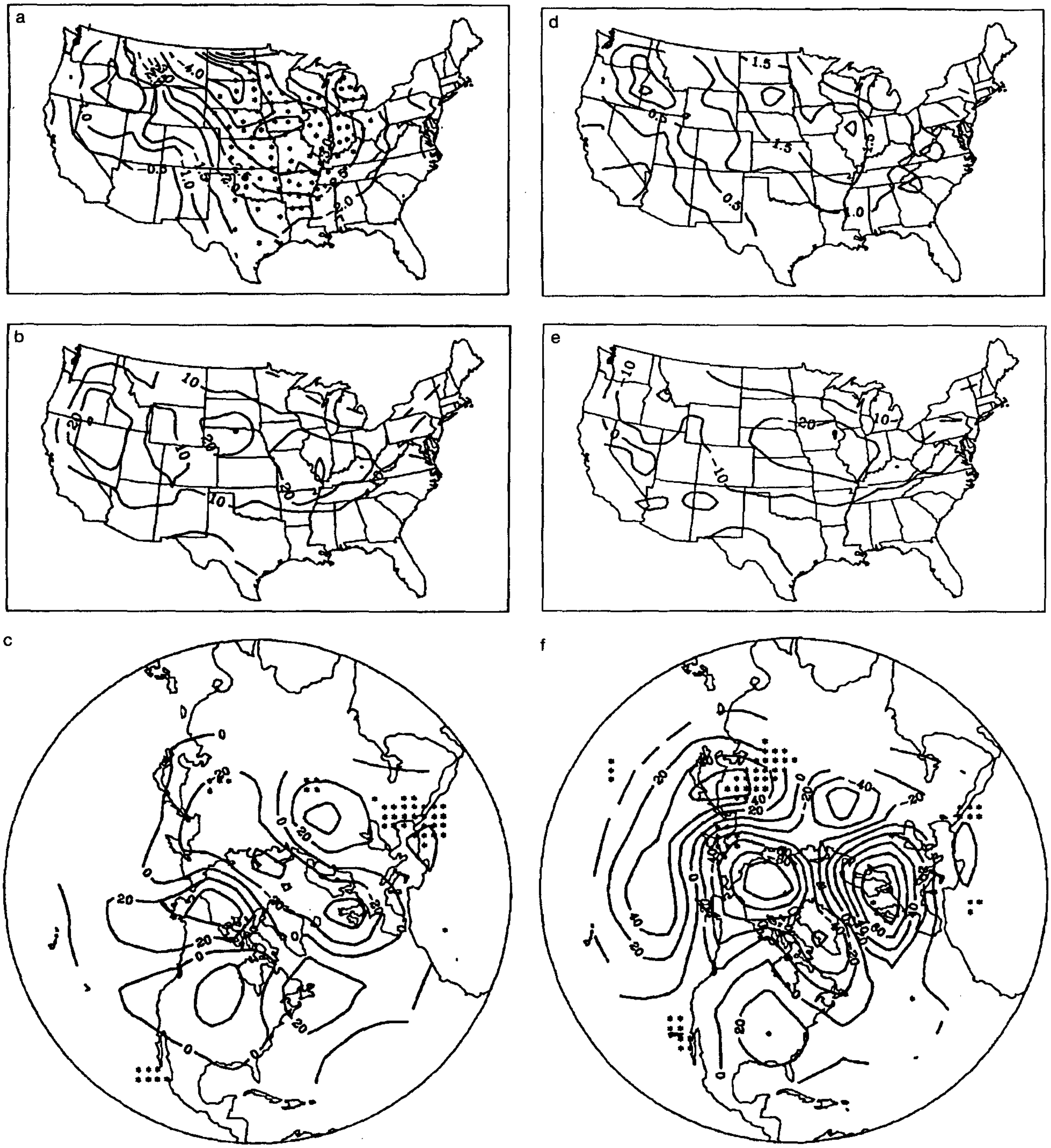

FIG. 4. Same as Figure 3 but for January.

across most of the northern plains (Fig. 5d). The snow cover frequency anomaly map for this category shows a close correspondence with the temperature departures (Fig. 5e). The 500-mb height departures evidence a tendency for above-normal heights across the entire North American continent, with strong anomalies over northeastern Canada (Fig. 5f). In addition, another area of strong height anomalies stretches from the area of the Aleutians west to northern Asia. However, the height anomalies in the area of the United States temperature perturbations are not large and no advective effects are evident. This suggests that the absence of

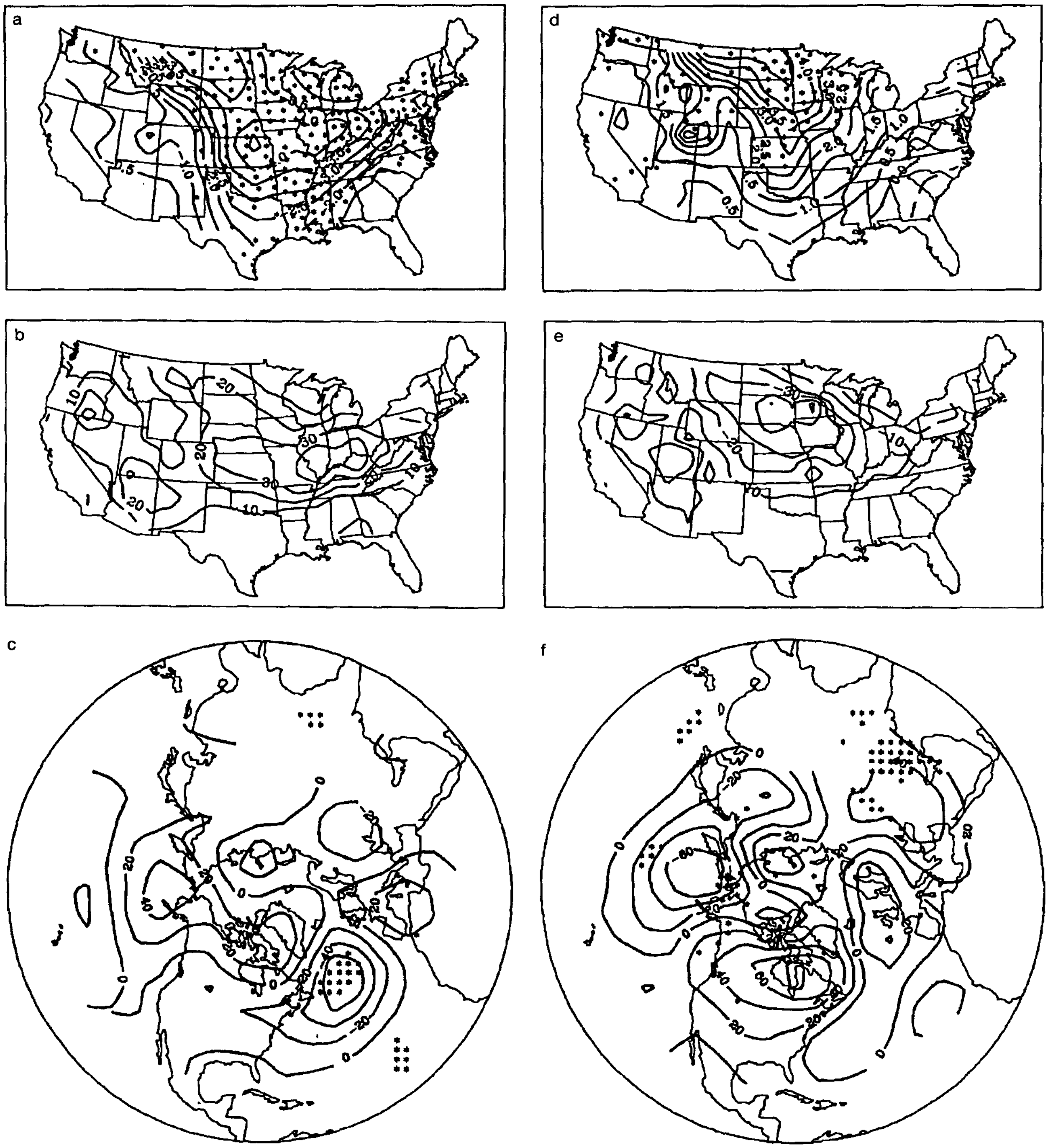

FIG. 5. Same as Figure 3 but for February.

"normal" snow cover is playing an important role in the temperature anomaly pattern.

5. Discussion and conclusions

This study has explored the relationship between the extent of snow cover on the North American continent and associated temperature anomalies across the coterminous United States. Results from this study indicate the following:

1) Winter months evidencing extreme positive (negative) values of North American snow cover extent are associated with below- (above) normal tempera-

tures across the major portion of the United States. These results are similar to those obtained by Heim and Dewey (1984).

2) The axis of maximum temperature departures associated with anomalous North American snow cover is located across the central United States, roughly from the Dakotas south through the central plains, and from the Rocky Mountains east to the Mississippi Valley. No consistent relationships are indicated east of the Appalachians or west of the Rockies. These results are similar to those obtained by Walsh et al. (1982) using a regression-based methodology.

3) During December, strong 500-mb height anomalies are collocated with the maximum snow cover frequency changes and largest temperature deviations. This suggests that atmospheric perturbations are likely to be influencing both the anomalous snow cover and the temperature anomalies during this month. Any 500-mb flow influence is much less apparent during January and February. During these months the snow cover frequency anomalies and temperature departure fields are not in close proximity to consistently strong or significant 500-mb deviations, suggesting that the snow cover anomalies and the temperature variations are not necessarily a result of large-scale, persistent atmospheric forcing.

4) United States temperature departures during extremes in North American snow extent are not limited to the immediate area of anomalous local snow cover. Instead, they extend far to the south, often as far as the Gulf of Mexico, suggesting that airmass modification may be involved in the temperature deviations in these areas. During months with above-normal snow cover, air masses moving south out of central Canada can reach the southern United States having undergone little modification, causing lower than normal temperatures in these areas. With negative snow cover extremes, continental polar air masses from central Canada may be less likely to move as far to the south and, when they do so, are likely to be greatly modified.

Acknowledgments. The authors wish to thank Mr. Alan Frei of the Department of Geography, Rutgers University, for his help in the generation of snow cover frequency values. In addition, the cartographic work of Mrs. Linda Parrish, Department of Geography, University of Delaware, is also gratefully acknowledged. A portion of this work was supported by NOAA Grant NA90AA-D-AC518, and the Geography and Regional Science Program of the National Science Foundation under Grant SES-9011869.

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