Characteristics of Snowfall over the Eastern Half of the United States and Relationships with Principal Modes of Low-Frequency Atmospheric Variability

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ABSTRACT

Monthly data from 206 stations for the period 1947–93 are used to examine characteristics of snowfall over the eastern half of the United States and relationships with precipitation and the maximum temperature on precipitation days. Linkages between snowfall and modes of low-frequency circulation variability are diagnosed through composite analyses, based on results from a rotated Principal Component Analysis (PCA) of monthly 500-hPa geopotential height. Results are examined for the 2-month windows of November–December, January–February, and March–April. The three dominant PCAs for each window capture regional components of the Pacific–North American (PNA), Tropical-Northern Hemisphere (TNH), and east Pacific (EP) teleconnection patterns.

Two general snowfall regimes are identified: 1) the dry and cold upper midwest, Nebraska and Kansas, where snowfall is strongly a function of precipitation; and 2) the Midwest, southeast, and northeast, where snowfall is more closely tied to the mean maximum temperature on precipitation days. The PNA (the dominant circulation mode) and the EP pattern are both associated with strong snowfall signals, best expressed for November–December and January–February. Snowfall for the PNA over the southeast, midwest, and mid-Atlantic states increases (decreases) under positive (negative) extremes, when the eastern United States is dominated by a strong 500-hPa trough (zonal flow or weak ridge) with associated lower (higher) precipitation-day temperatures. Snowfall signals are more extensive under positive PNA extremes where the lower temperatures have a greater impact on precipitation phase. An opposing precipitation-controlled snowfall signal is found over the upper Midwest. The positive phase of the EP pattern, describing a western ridge–eastern trough, is associated with negative snowfall signals clustered over the midwest and upper midwest. Opposing signals are found under the midwestern trough–eastern ridge pattern of the negative mode. These signals are primarily precipitation controlled, which for the Midwest are counter to the climatological control by temperature. TNH snowfall signals are fairly weak except for March–April, when significant differences are found for the upper Midwest and from Missouri northeast into New England. No coherent trends are observed in snowfall or in the strength of the circulation patterns derived from the PCA.

1. Introduction

Winter snowfall over the eastern half of the United States has clear economic impacts. In terms of snow removal, road salting, sanding, and disruption of ground and air transportation, heavy snowfall winters and large individual events have adverse impacts (Changnon 1979; Neal et al. 1988; Schmidlan 1993). Conversely, the winter sport industry is highly dependent on adequate snowfall. Numerous studies have examined the synoptic aspects of large snowfall events and the ability of numerical weather prediction models to accurately forecast them (e.g., Brown and Olson 1978; Salmon and Smith 1980; Bosart 1981; Bosart and Sanders 1986; Uccellini et al. 1984, 1995; Caplan 1995; Kocin et al. 1995). Kocin and Uccellini (1990) provide an excellent analysis of synoptic conditions associated with east coast U.S. snowstorms for the period 1955–85.

Changes in snowfall also influence local and large-scale climatic conditions. Snow cover suppresses low-level air temperatures (Lamb 1955; Namias 1985) both through the effects of increased albedo and energy used to warm and melt the snowpack. In heavy snow years subsequent increases in soil moisture may lead to these effects persisting well beyond the disappearance of the snowpack (Yeh et al. 1983). In a case study of the severe North American winter of 1976–77, Namias (1978) sug-

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gested that the cooling effect of the snow surface resulted in enhanced baroclinicity along the eastern seaboard, leading to stronger East Coast storms and reinforcement of the mean trough. Ross and Walsh (1986) subsequently demonstrated that anomalous eastern U.S. snow cover (100°–70°W) has a detectable influence on the location and intensity of synoptic-scale storm systems, with the association stronger for snow anomalies near the east coast (85°–70°W). In a recent modeling study, Walland and Simmonds (1997) conclude that changes in Northern Hemisphere snow cover have significant effects on atmospheric circulation. An increase in the areal extent of snow cover is associated with significant increases in sea level pressure over land areas. Cyclone activity is reduced over both North America and Eurasia and over the western sector of both the Atlantic and Pacific Ocean basins.

Recognition of the climatic and economic significance of snow has fostered a large body of literature regarding snow cover variability and trends, based on analysis of station records and satellite-derived archives. Leathers et al. (1993) examined U.S. snowfall from 1945 to 85 and found positive trends in the Great Lakes–upper midwest region for December–February. Using snowfall records (1951–91) and weekly National Oceanic and Atmospheric Administration (NOAA) charts of snow extent (1973–90), Karl et al. (1993) find decreases in North American snow extent, consistent with observed surface temperature increases. Over the contiguous United States, there has been an increase in total precipitation as well as the variance of the frozen to total precipitation ratio. Groisman and Easterling (1994) argue for increased U.S. snowfall over the last century, largest over the north-central and northeast sectors. From the work of Leathers and Ellis (1996), it appears that this is in part due to an increased frequency of lake-effect synoptic types and a decreased frequency of cyclone synoptic types. Leathers and Robinson (1993) find strong inverse associations between surface temperature and snow extent over most of the United States, particularly across the central states from the Dakotas south through the southern Plains and from the Rocky Mountains east to the Mississippi valley. This area is in turn collocated with large variations in snow cover frequency.

Less attention has been paid to the response of eastern U.S. snowfall to low-frequency variability in atmospheric circulation. Namias (1960) demonstrated that heavy snow years over the eastern United States are associated with an enhanced eastern U.S. trough, with the large-scale situation similar to what is now termed the Pacific–North American (PNA) teleconnection pattern (Wallace and Gutzler 1981). Leathers et al. (1991) showed that positive PNA events (strong Aleutian low, upper-air ridge along the west coast of Canada, and a concurrent strong trough over the southeast United States) are associated with a general pattern of negative (positive) temperature anomalies over the eastern (northwestern) United States for most months. Precipitation anomalies are less coherent, but, in general, positive PNA events tend to be associated with reduced precipitation in the Ohio valley in winter. In the Great Lakes region, Assel (1992) shows that both air temperatures and ice cover are related to the PNA pattern but finds no association with snowfall.

The present study examines the characteristics of eastern U.S. snowfall and linkages with dominant modes of low-frequency atmospheric variability. Because the surface climate is often sensitive to minor shifts in large-scale atmospheric patterns (e.g., Yarnal and Diaz 1986), we select a relatively small spatial window in order to isolate the characteristics of atmospheric variability specific to the eastern United States. Our analyses are based on rotated Principal Component Analysis (PCA) of monthly 500-hPa height data and snowfall, precipitation and temperature data from 206 stations in the eastern half of the United States. Circulation linkages are examined with respect to attendant changes in precipitation and the maximum temperature on precipitation days. Analyses are performed separately for 2-month windows (November–December, January–February, and March–April) to assess seasonalities in snowfall responses.

2. Datasets

a. Historical daily climatic dataset

The Historical Daily Climatic Dataset (HDCD) (Robinson 1993) is an archive of daily surface records from over 1000 National Weather Service cooperative climate observing stations. The HDCD includes observations of precipitation, snowfall, snow depth on the ground, and maximum and minimum temperature. We use monthly records assembled from the daily data for 1947–93, although shorter time series are available for some stations. Quality control of the dataset, outlined by Robinson (1993), includes checks for outliers by examining multiple variables from the day in question and the previous day along with limit checks developed for each state (see the appendix).

Of the 720 stations available for the 30 states in the study region, 206 were initially retained for analysis (Fig. 1). Each have 10% or fewer missing winter months. A month is considered missing if more than two daily observations were either originally absent or coded as missing based on error checks. Despite the generally high quality of the stations records selected, none had an entirely complete time series. Consequently, we developed a routine to fill missing months. Correlations were determined between annual snowfall at each station and neighboring stations within a 160-km radius. The neighboring station with the highest correlation exceeding 0.70 was then identified. In determining the correlations, a square root transform was performed on the station totals to create a more Gaussian

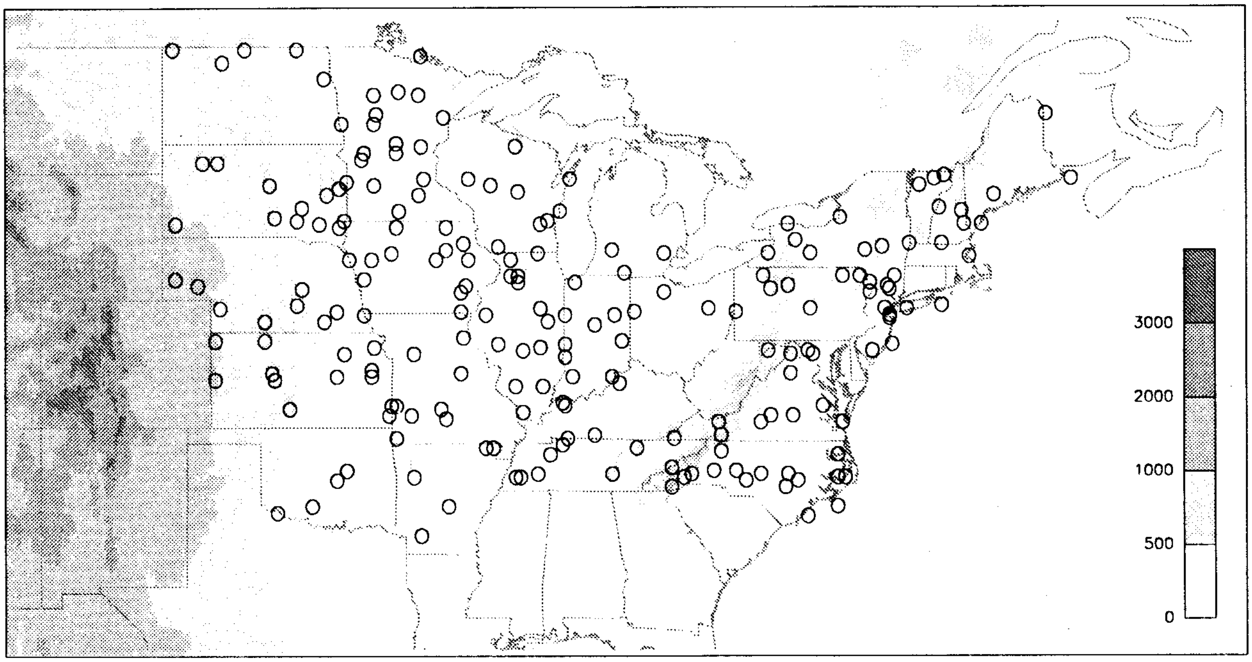

FIG. 1. Locations of the HDCD stations used in the study. Shading indicates elevation (in m).

distribution. This is especially necessary for the more southern stations, which may have zero values. The filling then proceeds by performing a linear regression on the transformed snowfall to obtain (a) the slope and (b) the intercept between the two stations. These results were then applied to the missing monthly snowfall totals (Y) as

$$Y = [(M/A)a + b(X)]^2, \quad (1)$$

where X is the square root of monthly snowfall for the surrogate station, M is the mean monthly snowfall for the primary station, and A is the annual snowfall for the primary station. Using this technique, the average percentage of missing months for all stations was reduced from 5.32% to 1.67%. Temperature and precipitation records are more complete than snowfall and no attempt was made to fill missing data, although, as with the snowfall, months are not considered if more than 2 days of data are missing. Snowfall data for most stations are missing for 1988. For all analyses, we require that for any variable or pairs of variables used, either on a monthly basis or for climatological or composite means, results be based on at least 30 yr of data. Depending on the analysis, this typically eliminates 10–20 stations.

No corrections are made for precipitation gauge biases. Precipitation gauges, which are generally unshielded, measure water equivalent of snowfall with large error (Karl et al. 1993; Groisman and Easterling 1994). The snowfall data used here represent ''stick'' measurements, which, while providing good linear measures of snowfall, provide no information on water equivalent. These factors should be kept in mind as we discuss snowfall–precipitation relationships.

b. Atmospheric circulation

Monthly 500-hPa fields (1946–93) from the National Centers for Environmental Prediction (formerly the National Meteorological Center) were obtained from the NOAA Climate Diagnostics Center at Boulder, Colorado.

3. General relationships

It is useful to first examine mean features of snowfall, precipitation, and temperature. Figure 2 provides climatological totals of snowfall and precipitation and average maximum temperature on precipitation days based on the months November–April, using stations with at least 30-yr records. Snowfall (Fig. 2a) displays a roughly zonal pattern, with amounts increasing to the north, but with the higher values over the northeast away from the coast. The highest totals (locally >300 cm) are found in the lake-effect regions east of Lakes Erie and Ontario. Precipitation (Fig. 2b) exhibits a more meridional pattern, with amounts increasing eastward (generally >40–60 cm) with higher local maxima over the southeast. This pattern reflects the combined effects of the more abundant atmospheric water vapor over the eastern part of the domain and frequent cyclone activity associated with the mean eastern U.S. tropospheric longwave trough.

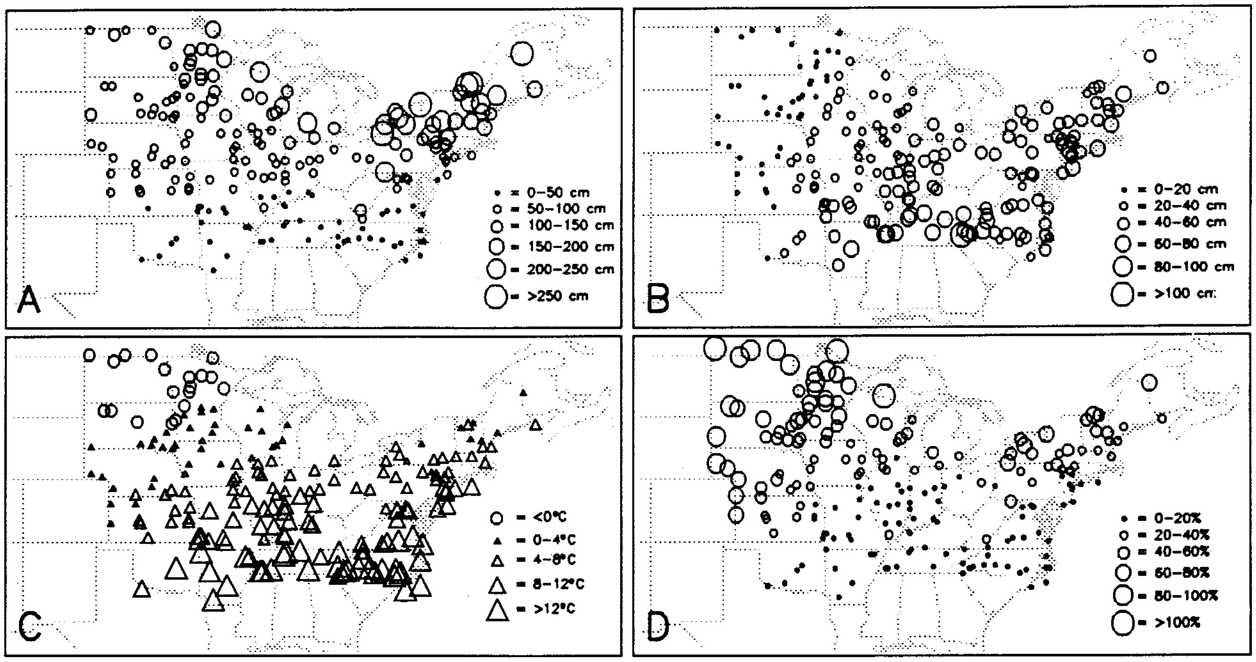

FIG. 2. Mean seasonal (Nov–Apr) station values of (a) snowfall, (b) precipitation, (c) mean maximum temperature on precipitation days, and (d) approximate percent of precipitation represented by snowfall, assuming a 10:1 ratio.

The contrasting patterns of mean snowfall and precipitation relate to the mean maximum temperature on precipitation days (hereafter MTPDs). We examine this variable as opposed to mean temperature on all days as it provides a closer link to precipitation phase. For the fairly dry upper midwest (generally <20 cm of precipitation), seasonal mean MTPDs are near or below freezing (Fig. 2c), implying that precipitation tends to fall as snow. By contrast, while precipitation is abundant over the south and southeast, higher MTPDs result in most precipitation falling as rain. The northeast represents an intermediate case, where high snowfall totals are associated with abundant precipitation, with seasonal mean MTPDs between those of the cold upper midwest and warm south and southeast.

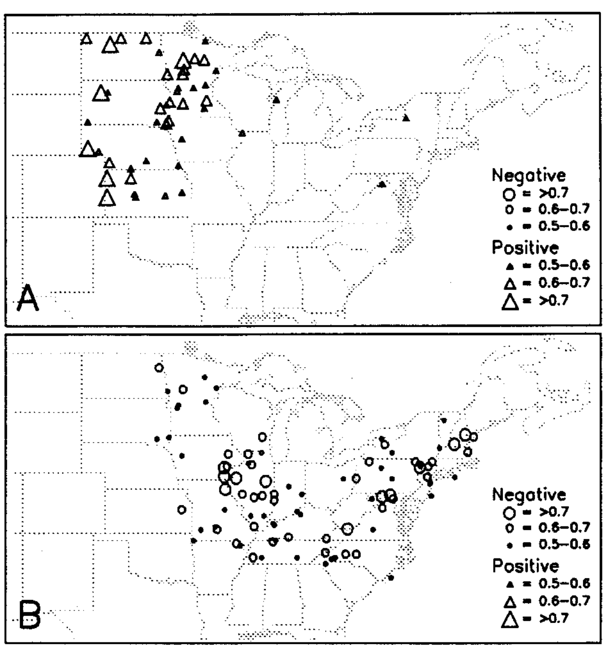

FIG. 3. Spearman rank correlations between (a) seasonal snowfall and precipitation and (b) seasonal snowfall and seasonal mean maximum temperature on precipitation days.

These relationships can be summarized in terms of the approximate fraction of total precipitation represented by snowfall, assuming a 10:1 reduction of snowfall to water equivalent (Fig. 2d). Results for each station are based on those months for which the climatological mean monthly snowfall is nonzero. The number of nonzero monthly means is six for most stations but falls to three for some stations along the southeast coast. Note that especially for extreme southern stations, nonzero climatological means for transitional months (November and April) may be due to snowfall during only a few years of the record. The highest ratios are found over the upper midwest, with the lowest in the southern sector and with intermediate ratios in the northeast. For some stations over the upper midwest, the calculated ratio exceeds 100%. While illustrating the low density of snowfall in this region expected from low MTPDs, one must acknowledge that precipitation is likely underestimated due to the undercatchment problem.

Some initial insight into snowfall variability is provided through correlation analyses. Figure 3 shows the

TABLE 1. Spectrum for the first eight eigenvalues.

	PC 1	PC 2	PC 3	PC 4	PC 5	PC 6	PC 7	PC 8
Nov–Dec								
Eigenvalue	14.98	7.36	5.09	1.07	0.93	0.20	0.15	0.08
Variance*	0.50	0.25	0.17	0.04	0.03	0.01	0.00	0.00
Cumulative variance*	0.50	0.74	0.91	0.95	0.98	0.99	0.99	1.00
Standard error**	2.10	1.03	0.71	0.15	0.13	0.03	0.02	0.01
Jan–Feb								
Eigenvalue	15.94	7.99	4.10	0.92	0.58	0.19	0.09	0.09
Variance*	0.53	0.27	0.14	0.03	0.02	0.01	0.00	0.00
Cumulative variance*	0.53	0.80	0.93	0.96	0.98	0.99	0.99	1.00
Standard error**	2.23	1.12	0.57	0.13	0.08	0.03	0.01	0.01
Mar–Apr								
Eigenvalue	15.88	7.19	4.60	0.92	0.80	0.22	0.15	0.10
Variance*	0.53	0.24	0.15	0.03	0.03	0.01	0.01	0.00
Cumulative variance*	0.53	0.77	0.92	0.95	0.98	0.99	0.99	1.00
Standard error**	2.22	1.01	0.64	0.13	0.11	0.03	0.02	0.01

* Variance described by unrotated eigenvectors.

** Standard error as given by North et al. (1982). If the estimate of an eigenvalue is within the standard error of a neighboring eigenvalue, these PCs form a degenerate multiplet and it is possible that with a different sample of the same field the structure of the resultant PCs will have a different form.

pattern of Spearman rank correlations (Kendall 1955) between seasonal snowfall and precipitation and between seasonal snowfall and mean MTPDs. Spearman rank correlations, performed on the rankings of each variable rather than the raw data, are more appropriate than Pearson correlations when normal distributions cannot be assumed. The seasonal totals of snowfall, precipitation, and mean MTPDs have also been conditioned using only those months for which the climatological mean snowfall is nonzero. Only correlations exceeding 0.50 are plotted, which are significant to at least the 0.01 level (Conover 1980). Results using a higher monthly snowfall threshold of 5.0 cm are very similar.

Positive correlations between snowfall and precipitation (Fig. 3a) are primarily limited to the upper midwest and extending south into Kansas and Nebraska. This is consistent with earlier results showing that mean MTPDs in this region are low, so that precipitation tends to fall as snow. By contrast, negative correlations between snowfall and MTPDs are found primarily over the midwest, southeast, and northeast (Fig. 3b), but also for some stations over the upper midwest. A further breakdown yields results similar to those in Fig. 3 for each of the 2-month windows November–December, January–February, and March–April to be used in our circulation analyses (section 4a). The most notable difference is for the transitional window March–April, which shows upper-midwest snowfall to be more strongly associated with MTPDs, rather than precipitation. The correlation analyses provide a simple snowfall regionalization, providing a useful framework for contrasting signals associated with different circulation modes: 1) the upper midwest and south into Kansas, where except for March–April, precipitation exerts the dominant control on snowfall; and 2) the midwest, southeast, and northeast, where the phase of precipitation is more variable, with snowfall more dependant on the maximum temperature on precipitation days.

4. Circulation relationships: Methods

a. Principal components analysis

Associations between atmospheric circulation, snowfall, and corresponding patterns of precipitation and MTPDs are assessed through composite analyses, using results from a rotated S-mode PCA of monthly 500-hPa geopotential height. We utilize atmospheric data for the period 1946–94 for 30 grid points over the region 255°–290°E and 35°–50°N, with separate analyses conducted for three temporal windows (November–December, January–February, and March–April). To reduce the effects of seasonality in 500-hPa height within each window, the long-term monthly mean was removed from each grid point. A data matrix was constructed comprising the 30 grid points over the 96 months for each window. A correlation matrix was then computed between each of the grid points and principal components (PCs) generated, which describe coherent patterns of variance over the spatial domain.

To determine the number of PCs to retain for rotation, the spectrum for the first eight PCs (Table 1) was evaluated with respect to the eigenvalue separation test of North et al. (1982). In this test, North et al. (1982) recognize that the PCs are based on a finite number of samples (N) of the instantaneous state of the field. The statistical independence of each PC is determined by computing the standard error of each eigenvalue, given by $(2/N)^{0.5}$. If the estimate of an eigenvalue lies within the standard error of a neighboring eigenvalue, the PC is part of a degenerate multiplet and it is possible with a different sample of the same field that the structure

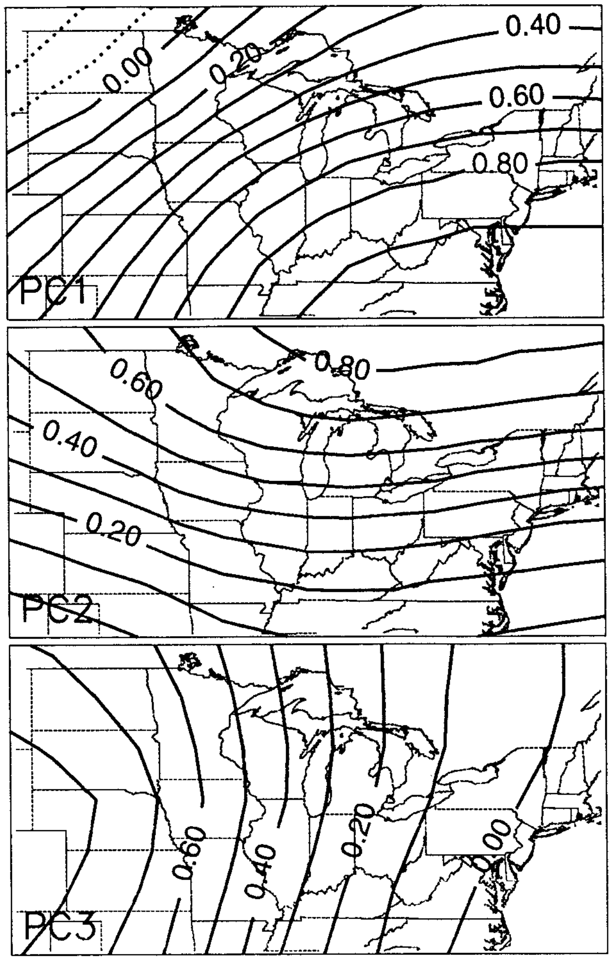

FIG. 4. Spatial loading patterns of the first three 500-hPa PCs for the Jan–Feb window. Results for Nov–Dec and Mar–April are nearly identical.

of the PCs will have a different form. When selecting the number of modes to retain for rotation, it is necessary to ensure that the truncation point does not split a degenerate multiplet (North et al. 1982; O'Lenic and Livezey 1988). In all 2-month windows, the eigenvalues of the first three PCs are both well separated from each other and well separated from PC4 and PC5 (Table 1). PC4 and PC5 are well separated from the higher modes. In this case it is appropriate to rotate either three or five PCs.

As the bulk of the variance in each 2-month window is described by the first three PCs, these PCs are retained and rotated using the varimax algorithm (Richman 1986). Together these three PCs describe 91% (November–December), 93% (January–February), and 92% (March–April) of the total variance in each respective dataset. The spatial loadings for January–February (Fig. 4) show the PCs to be influenced by a dipole between the northwest and southeast of the spatial domain (PC1), high variance over northern New England and southern Canada (PC2), and high variance west of the Mississippi (PC3). The loading patterns in the transitional windows (November–December and March–April) are almost identical. To illustrate these similarities, we compute the pattern correlation between the PC loadings of the three dominant PCs in January–February and the three dominant PCs in November–December and March–April (Table 2). These statistics demonstrate that in each 2-month window, the first three PCs describe variability in similar parts of the spatial domain. The circulation patterns in these PCs (shown later) have subtle differences that can be understood in terms of seasonal changes in climatology. Because of the strong similarities between the PC loading patterns in the three temporal windows, we are confident that our PCs describe stable, physical modes of variability.

TABLE 2. Pattern correlation between the PC loadings for midwinter window (January–February) and the transitional windows (Nov–Dec and Mar–Apr).

	Nov–Dec	*Mar–Apr*
PC1	0.97	0.97
PC2	0.99	0.98
PC3	0.98	0.93

It is useful to place these regional PCs in the context of large-scale teleconnection patterns (e.g., Wallace and Gutzler 1981; Barnston and Livezey 1987). To this end, composite mean 500-hPa height fields were constructed over a large domain (150°–340°E and 20°–80°N) based on extreme positive (>1.0) and negative (<−1.0) component scores for each PC (Fig. 5). From these maps and comparisions with results from Barnston and Livezey (1987), we interpret PC1 as capturing part of the PNA teleconnection, which as described earlier is characterized by centers of high variability over the northwestern Pacific, northwestern North America, and the southeastern United States. PC1 captures at least half of the unrotated variance in the monthly mean 500-hPa height field for each window (Table 1). The composite results for composite PC2 have strong similarities to the Tropical-Northern Hemisphere (TNH) teleconnection pattern, which has centers off the Pacific Northwest coast, near or just north of the Great Lakes [coinciding with the strong loadings of PC2 in this region (Fig. 4)], and near Cuba. The wave train is shifted westward by approximately 20° longitude with respect to the PNA pattern. In turn, we view PC3 as representing part of the east Pacific (EP) pattern, which describes a dipole between centers over Alaska and the southwest United States. The EP pattern appears as a significant mode of variability in the studies of Barnston and Livezey (1987) and Clinet and Martin (1992), the latter using the French ''Hemis'' dataset. Our first three PCs do not capture the North Atlantic Oscillation (NAO) (van Loon and Rogers 1978). This is understood as the Greenland and Atlantic centers of the NAO (reflected at sea level as covaria-

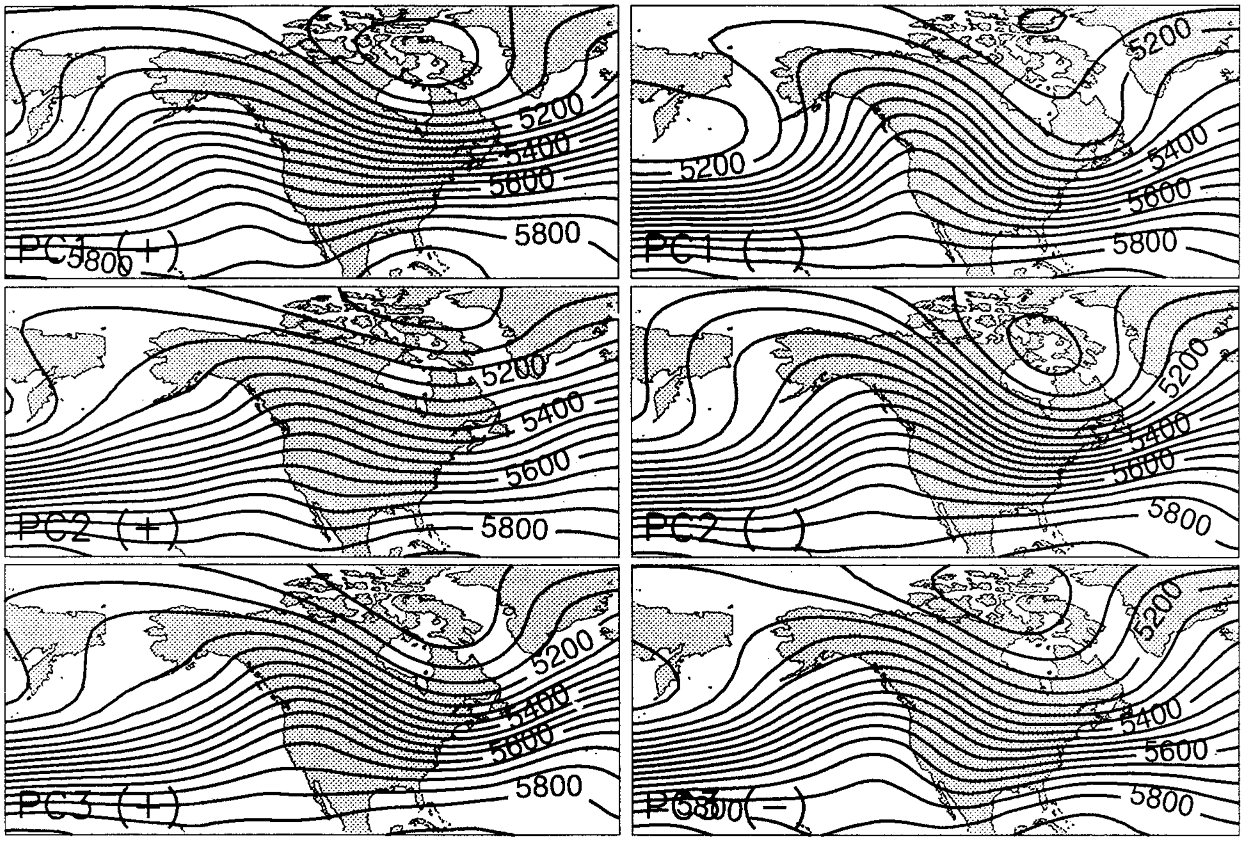

FIG. 5. Composite 500-hPa height fields based on extreme positive and negative component scores for Jan–Feb for the first three PCs.

bility in the strength of the Icelandic low and Azores high) lie largely north and east of our 30-grid window.

b. Regional composites

To capture the mean regional circulation associated with each PC, composite mean 500-hPa height fields were again constructed using component scores of >1.0 and <-1.0 but over a smaller domain centered over the 30-gridpoint spatial window. Each composite potentially contains from 12 to 19 cases (Table 3), with roughly equal representation of cases between the two months representing each temporal window. The component scores were then used to compile corresponding station composite means of snowfall, precipitation, and MTPDs. If the climatological mean snowfall for both months in the temporal window was zero, the station snowfall composites were coded as missing. Composite values for any surface variable were coded as missing if the long-term mean was based on fewer than 30 yr. Occasionally, surface data for a month representing one of the selected component scores were missing; we required that each surface variable composite contain at least 11 cases; otherwise, it was coded as missing. These criteria typically resulted in 5–15 of the 206 stations being discarded, depending on the composite. Positive minus negative station composite differences were then calculated. The differences for snowfall and precipitation were expressed as a percentage of the group mean of the two composites, which provides for more direct comparisons between stations. A positive (negative) difference means that the positive composite value is greater than (less than) the negative composite value.

Although effects of seasonality in the surface variables are present between the two months representing each temporal window, especially for November–December and March–April, no attempt was made to remove this seasonality. While justified as the composite members are roughly equally distributed between the two months, using raw composite differences also results in more easily interpreted results. Forcing an exactly equal number of cases from the two months into each composite, rather than relying simply on the component scores, was found to dilute the circulation signal.

TABLE 3. Number of composite members.

	Nov–Dec		Jan–Feb		Mar–Apr	
	Pos.	Neg.	Pos.	Neg.	Pos.	Neg.
PC1	17	13	12	15	16	15
PC2	14	16	17	19	14	15
PC3	16	15	18	18	12	19

The statistical significance of the station differences was evaluated from *t* tests, using the pooled standard deviations of the positive and negative composite means (Panofsky and Brier 1963). This is arguably not an appropriate test for snowfall as normal distributions cannot be assumed, largely due to the high number of zero snowfall cases, especially in the transitional months (the issue of normality dictating our decision to base Fig. 3 on nonparametric correlations). This effect is lessened through having a mix of cases in the composites from each of the two months. A square root transform was applied to the snow values prior to testing and reducing, but not solving, the problem of nonnormality. A number of experiments were performed to test the differences in composite distributions using nonparametric rank methods (see Lazante 1996). Briefly, it was found that when using 2-month windows, systematic biases tend to be introduced when the number of zero snowfall cases, which are attributed to tied ranks, differs greatly between the months. Normalizing with respect to the monthly means or medians does not resolve this problem. While we acknowledge reservations in applying a *t* test to snowfall, it avoids these problems. The *t* test is of course appropriate for MTPDs and was also found to work well for precipitation, for which zero values are rare. Analyses using 1-month windows were found to provide an insufficient number of cases with extreme component scores.

We organize results in section 5 by first discussing the results for PC1 each 2-month window, followed by results for PC2 and PC3. This is a natural breakdown given the association of the PCs with the PNA, TNH, and EP teleconnections. For each PC we examine first the midwinter composites, which include the months of greatest snowfall, and then contrast these results with the transitional windows. For the composite difference maps of surface variables, we only plot stations for which 1) the *t* tests indicate statistical significance at the 95% confidence interval, and 2) the normalized absolute percent difference in the snowfall and precipitation composites is at least 30% and the absolute composite difference for MTPDs is at least 2.0°C. The second of the above criteria further restricts results to stations with strong signals.

The percentage of stations passing these requirements is indicated along with the corresponding limiting percentages from field significance tests (Livezey and Chen 1983). For these tests we generated 100 time series by randomizing the PC component scores while maintaining the integrity of month to month sequences in each 2-month window. This provides for a more robust field significance test than simply using random numbers as it accounts for month to month persistence (Barnston and Livezey 1987). Using these randomized time series as the atmospheric forcing, we determined the percentages of stations with significant signals for snowfall, precipitation, and MTPDs. If the percentage of stations passing significance based on the true factor scores used for the composites exceeds the percentage for the 95th highest ranking using the randomized scores, field significance is satisfied.

Finally, we note that performing *t* tests on the differences between the station composites implicitly assumes linear circulation relationships, that is, for which the composite means lie on opposite sides of respective climatological (1947–93) means, with the differences on both sides of climatology statistically significant. Additional analyses, using the form of the *t* test based on comparing each station composite mean against the respective climatological mean and standard deviation (rather than the pooled standard deviation of the positive and negative composites) (Panofsky and Brier 1963), reveal that this assumption holds in most, but not all, cases. Furthermore, as this latter form of the *t* test is less restrictive, we tend to find that many stations failing our tests based on the composite differences may show significant differences with respect to the climatological mean for one or both composites. Although our approach tends to identify the stronger and opposing signals, we also draw on results from individual composites evaluated with respect to climatological means.

5. Circulation relationships: Results

a. Principal component 1 (PNA)

Results for the dominant PC1 for January–February are shown in Fig. 6. The patterns for all three surface variables easily pass field significance. The composite 500-hPa height fields for PC1 show a largely zonal flow under the positive mode tending to a weak trough over the west, contrasting with a strong trough under the negative mode with its axis lying roughly along the Appalachians (Fig. 6a). Following earlier discussion, we interpret these composites as illustrating extremes of the eastern North American component of the PNA. The composite difference map for snowfall (Fig. 6b) shows a dipole pattern, with negative station differences over the midwest, southeast, and mid-Atlantic states, and positive differences over Minnesota. By contrast, the precipitation map shows positive differences clustered primarily west of the Appalachians (Fig. 6c); these are of the same sign as the snowfall differences in Minnesota but are of opposite sign elsewhere. Composite differences for MTPDs are also primarily positive. The significant signals are shifted somewhat east of the precipitation signals and are clearly associated with the region of negative snowfall signals. The patterns for all surface variables are well reflected in the individual composites as significant and opposing departures from climatology (not shown) but with a tendency for more stations to exhibit significant snowfall and precipitation signals under the negative composite.

These results reflect the climatological relationships presented in Fig. 3. The positive snowfall signals in Minnesota are in accord with the general control on

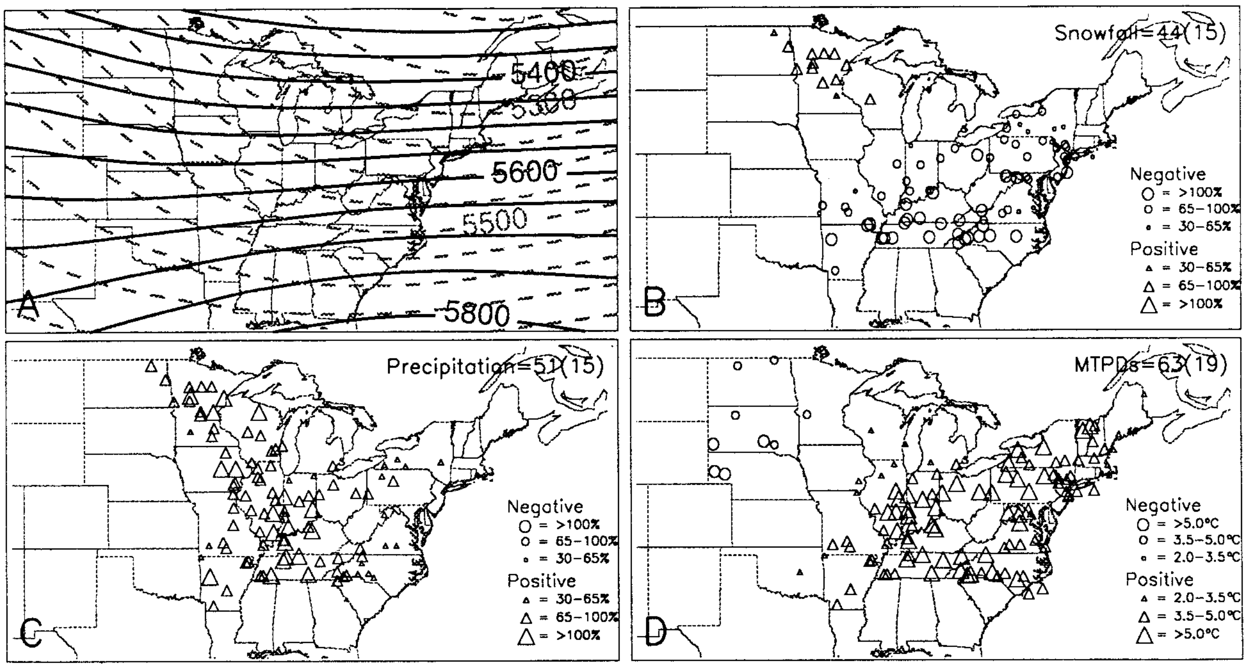

FIG. 6. PC1 signals for Jan–Feb, expressed as (a) positive (solid lines) and negative (dashed lines) 500-hPa composites, (b) positive minus negative composite differences in snowfall, (c) positive minus negative composite differences in precipitation, and (d) positive minus negative composite differences in mean maximum temperature on precipitation days. The percent of stations showing significant signals is also indicated along with the limiting values from field significance tests (the latter in parentheses).

snowfall in this region by precipitation. However, note in Fig. 6d that there are also a few stations in this area with negative differences in MTPDs. The extensive area of negative snowfall signals, in lying clearly under the region of higher MTPDs, illustrates the more important role of precipitation phase for this sector. Note that for many of the stations in this area, decreases in snowfall occur despite significant increases in precipitation, illustrating further the temperature control. The positive MTPD differences reflect the warmer conditions associated with the zonal flow in the positive 500-hPa composite as contrasted with the colder conditions under the strong trough in the negative (positive PNA) composite. The precipitation composite differences are qualitatively understood from suppression of precipitation west of the trough line in the negative composite. However, as mentioned, the positive composite precipitation signals are also significantly above climatological means. This is broadly consistent with the weak western trough, which would tend to favor the development of Colorado lows that subsequently migrate eastward. The patterns for both precipitation and MTPDs are similar to the PNA signals shown by Leathers et al. (1991) for January and February.

The November–December circulation maps are similar to those for midwinter. The primary contrast, apart from the higher 500-hPa heights in both composites, is that the weak western trough in the positive composite is slightly more pronounced, with the eastern U.S. trough in the negative composite shifted slightly west (Fig. 7a). Significant station snowfall signals (Fig. 7b) are less numerous (28% vs 44%) but show the same general spatial structure, differing primarily in the southward shift of the region of positive differences. This latter change is associated with a westward shift in positive precipitation signals (Fig. 7c). This change in precipitation signals is consistent with the westward shift of the strong negative composite trough. Despite the shift in precipitation signals, the pattern of MTPDs is similar to January–February except for the lack of negative signals over the upper midwest (Fig. 7d). Inspection of the positive and negative composites individually does reveal statistically significant opposing signals with respect to climatology, but with more widespread negative composite signals for both snowfall and temperature (contrasting with January–February). This is understood as compared to the midwinter case, the trough in the negative composite is shifted west, resulting in lower temperatures over a larger area (also accounting for the lack of an upper-midwest temperature signal for the composite differences in Fig. 7d). In turn, the widespread temperature forcing is manifested in more significant snowfall signals.

The circulation composites for the March–April window (Fig. 8a) are most similar to those for November–December, but illustrating the tendency for the PNA to be less strongly expressed during the winter/spring transition shows weaker flow in both cases (as inferred from the spacing of the height contours). Snowfall signals (Fig. 8b), although passing field significance, are rela-

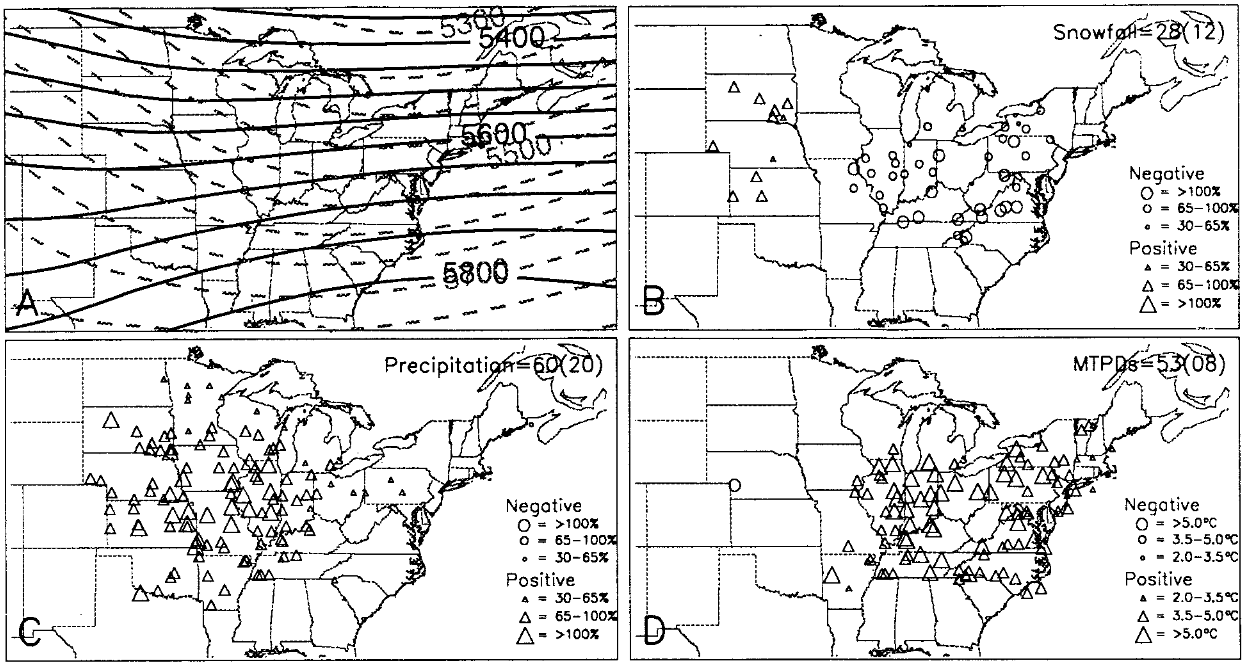

FIG. 7. Same as Fig. 6 but for Nov–Dec.

tively few and primarily clustered along the spine of the southern Appalachians (see Fig. 1). By contrast, the precipitation and MTPD signals are still robust (Figs. 8c,d), displaying the same general pattern seen in the other two windows. This is a situation where information is masked by using composite differences, as the positive and negative composites examined individually show more widespread temperature and snowfall signals, again with a greater number in the negative composites. The southern Appalachains represent a region where the negative composite (which is the positive PNA) snowfall increases are particularly marked.

The tendency for a greater number of stations with significant snowfall signals in the negative composites

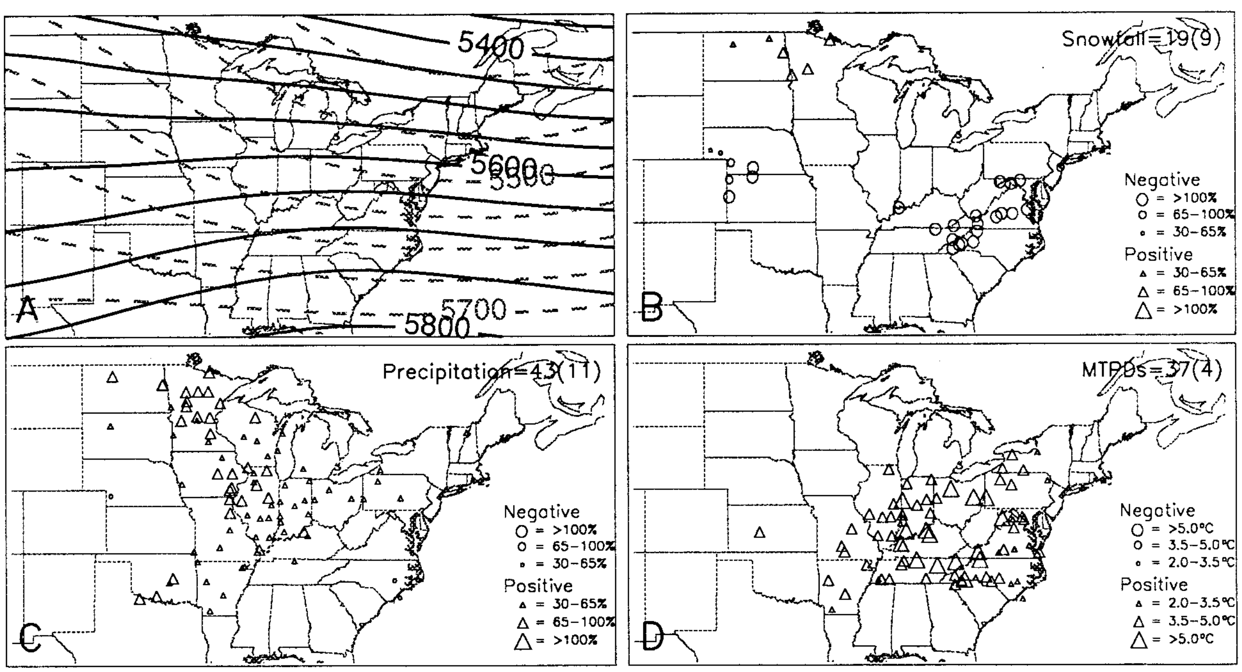

FIG. 8. Same as Fig. 6 but for Mar–Apr.

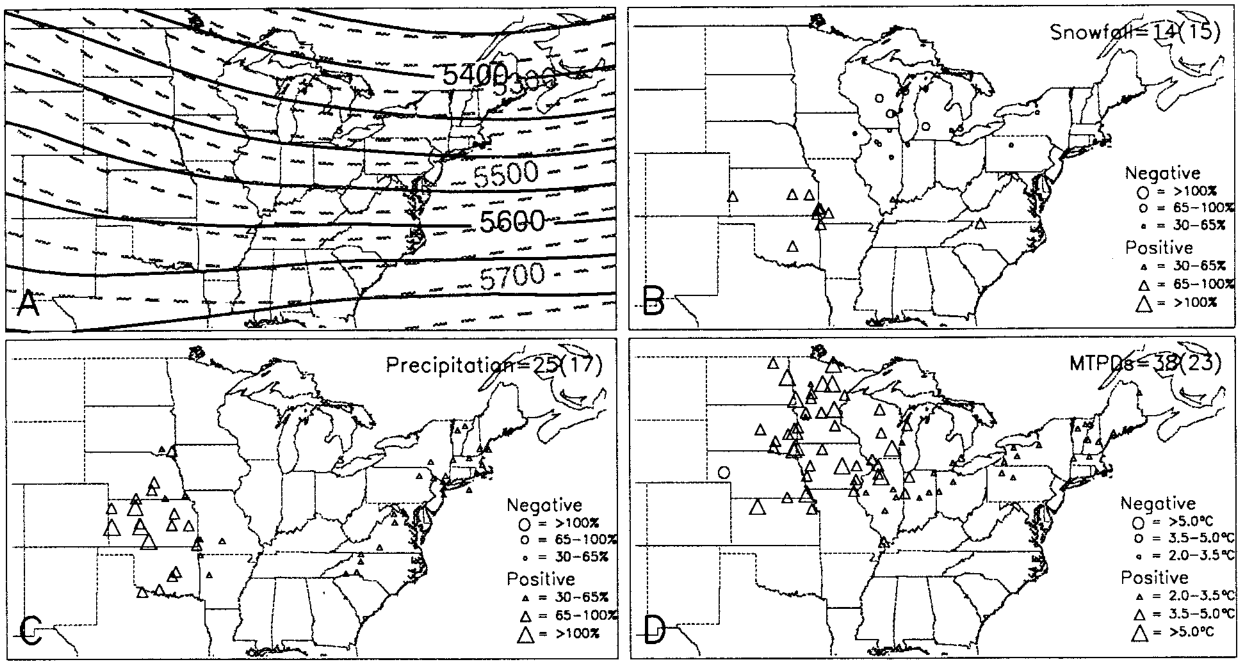

FIG. 9. PC2 signals for Jan–Feb, expressed as (a) positive (solid lines) and negative (dashed lines) 500-hPa composites, (b) positive minus negative composite differences in snowfall, (c) positive minus negative composite differences in precipitation, and (d) positive minus negative composite differences in mean maximum temperature on precipitation days. The percent of stations showing significant signals is also indicated along with the limiting values from field significance tests (the latter in parentheses).

(found in all three temporal windows) may also be understood in part from the general snowfall–temperature relationships described in section 3. As MTPDs in the southeastern United States are generally above freezing (Fig. 2c), conditions are delicately poised with regard to precipitation phase. Negative temperature anomalies may lead to increased snowfall. However, as under mean conditions, precipitation tends to fall as rain (Fig. 2d), and positive temperature anomalies may not be reflected in corresponding snowfall anomalies. Put differently, positive temperature anomalies have little effect on precipitation phase.

b. Principal component 2 (TNH)

PC2 is interpreted as capturing part of the TNH teleconnection pattern. This pattern has centers that are shifted westward with respect to the PNA pattern so as to be out of phase with it (Barnston and Livezey 1987). Both circulation composites for January–February show a broad trough across the eastern United States, slightly deeper for the negative composite, with a subsidiary weak southwestern trough in the positive mode (Fig. 9a). The most obvious difference is the stronger flow in the negative composite. As the two composites lack a pronounced contrast between primarily zonal versus meridional flow as seen for PC1, we would not be surprised to see correspondingly weaker responses in the surface variables. Based on the composite differences, snowfall signatures for extremes of the TNH are poorly expressed with the percentage of significant stations failing field significance (Fig. 9b). Precipitation signals (Fig. 9c) are only half as numerous compared to the PNA. The pocket of positive differences centered over Kansas appears to be associated with the weak southwestern trough in the positive circulation composite. Weak precipitation signals are also found along the East Coast. Positive MTPD signals (Fig. 9d) are found for 38% of stations, but again the percentages are lower than for the PNA (63%) and primarily clustered over the upper midwest, where the difference in tropospheric heights in the circulation composites is most pronounced (not shown).

Inspection of the individual composites expressed as differences from climatological means also shows weaker signals compared to the PNA but with somewhat stronger patterns than shown in Fig. 9. Figure 10 shows for each variable the stations for which the positive composite minus climatology difference is significant. Similar to our other plots, we express the differences as percentages of climatological values. The precipitation and temperature signals reflect those in Fig. 9. A roughly zonal pattern emerges for snowfall (Fig. 10a), with negative departures for the upper midwest and Great Lakes region and some positive departures to the south, primarily clustered over eastern Kansas and Missouri. The northern signals appear to be primarily associated with higher MTPDs (Fig. 10c). Although positive snowfall signals are seen to the south, they are associated with positive differences in both temperature

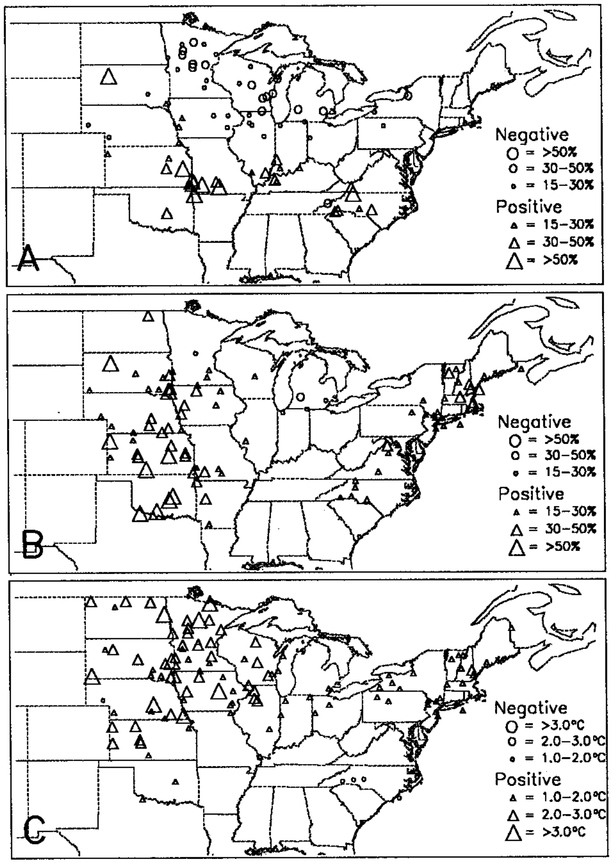

FIG. 10. Significant PC2 station signals (positive composite minus climatology) for Jan–Feb for (a) snowfall, (b) precipitation, and (c) maximum temperature on precipitation days.

and precipitation. The precipitation change, hence, arguably dominates the snowfall signal in this area. The negative composite (not shown) has generally opposing signals. Clearly, the interpretation of these signals is less straightforward than for the PNA.

Both circulation composites for November–December show somewhat deeper troughs (Fig. 11a), but the snowfall signals again fail field significance (Fig. 11b). The precipitation signature is similar to the midwinter case but with the positive signals for the western stations more widespread (Fig. 11c). Few MTPD signals emerge (Fig. 11d), with the pattern again qualitatively similar to January–February. Again, however, more extensive signals, similar to those for January–February, emerge when the positive and negative composites are examined separately.

Similar to the other two windows, the negative circulation composite for March–April shows a shallow trough. However, the positive composite depicts a weak and primarily zonal flow, tending to northerly over the northwest part of the domain (Fig. 12a). The TNH precipitation and MTPD signatures are weak, but there is a comparatively well-developed pattern of negative snowfall differences from Missouri extending northeast into New England with another cluster of negative signals over the upper midwest, representing 29% of all stations. In explanation, we note that despite the null results from the *t* tests on the MTPD composite differences, widespread negative MTPDs signals are found in the negative composite; comparatively few signals, generally of opposing sign, are found for the positive composite. Tropical/Northern Hemisphere snowfall sig-

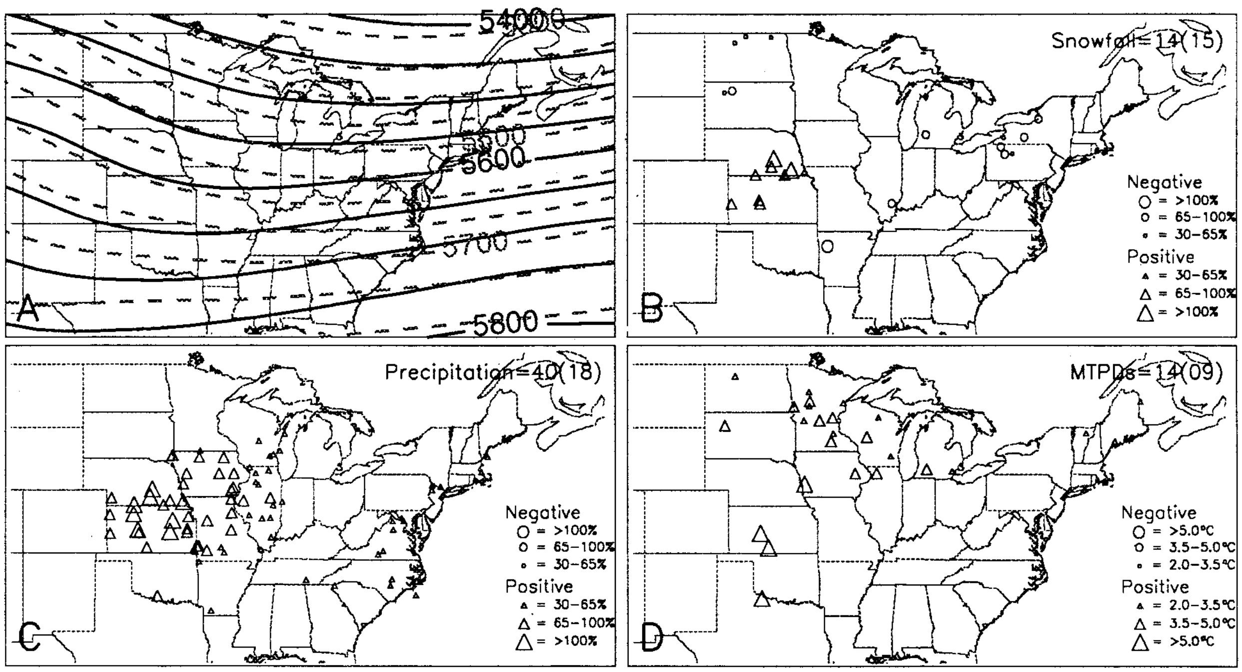

FIG. 11. Same as Fig. 9 but for Nov–Dec.

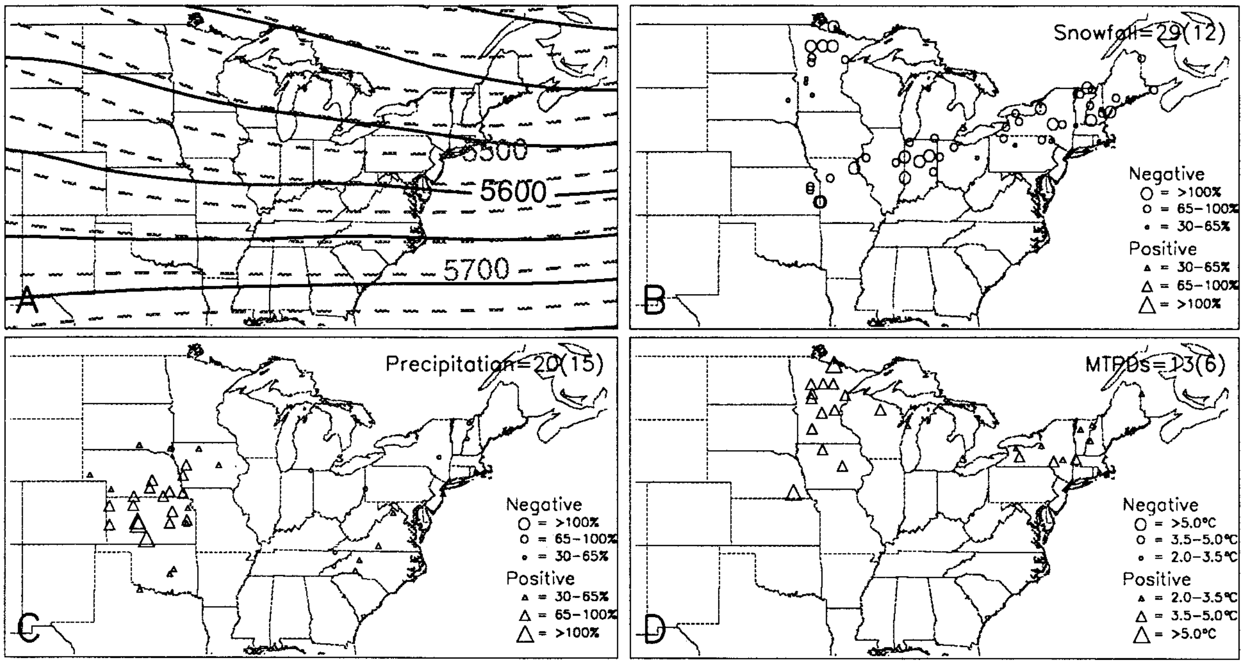

FIG. 12. Same as Fig. 9 but for Mar–Apr.

nals based on the composite differences are only well expressed in this transitional window when conditions are marginal for snowfall. It appears that the slightly colder conditions under the negative mode are just sufficient to change the phase of precipitation for enough events to yield a coherent signal. In part, the difficulties in interpreting PC2 may stem from our use of monthly, rather than daily, data.

c. Principal component 3 (EP)

PC3, which we interpret as a component of the EP teleconnection pattern, shows a more highly contrasting circulation regime than for PC2. As such, we would expect stronger signals in the surface variables. The January–February loading pattern for PC3 (Fig. 4) argues for variability in geopotential heights primarily over the western part of the domain. However, the composite analyses for this window (Fig. 13a) show extremes of PC3 as more clearly interpreted in terms of a western ridge–eastern trough (positive composite) and a weak midwestern trough–eastern ridge (negative composite). The positive mode of PC3 is similar to the negative PC1 (positive PNA) composite, but with the trough shifted east.

Note the widespread pattern of negative station snowfall differences (51%) over the midwest and extending into Kansas and Nebraska (Fig. 13b) and the negative precipitation differences (Fig. 13c), which are largely collocated with the snowfall signals (51%). Inspection of the individual composites confirms that the precipitation pattern can be interpreted in terms of below climatological values for the positive composite when the stations with the strongest signals lie primarily west of the trough axis and above climatological values for the negative composite when they lie largely under or east of the weak midwestern trough. The snowfall signals for each individual composite are also largely opposing with respect to climatology. Similar surface signals are observed for the November–December composites (Fig. 14) and are interpreted similarly except that reductions in snowfall are less widespread (34%) and shifted somewhat north, with more widespread reductions in precipitation that also extend north (77%). March–April shows weak snowfall and precipitation signals (Fig. 15). However, the individual composites expressed as departures from climatology reveal significant signals for March–April with patterns closest to those for November–December, with snowfall and precipitation below climatology for the positive composite and above climatology for the negative composite.

The snowfall signals associated with the EP pattern are clearly more directly associated with precipitation rather than temperature changes; indeed, MTPD signals for all windows fail field significance. As noted, the negative snowfall signals for November–December as well as the weaker signals for March–April not apparent in Fig. 14 are primarily limited to the upper midwest and the Kansas–Nebraska region. In general, the association between precipitation and snowfall is in accord with the results in Fig. 3. Although we also see the expected regional correspondence between snowfall and precipitation for January–February, the strong snowfall signals to the east do not reflect the expected temper-

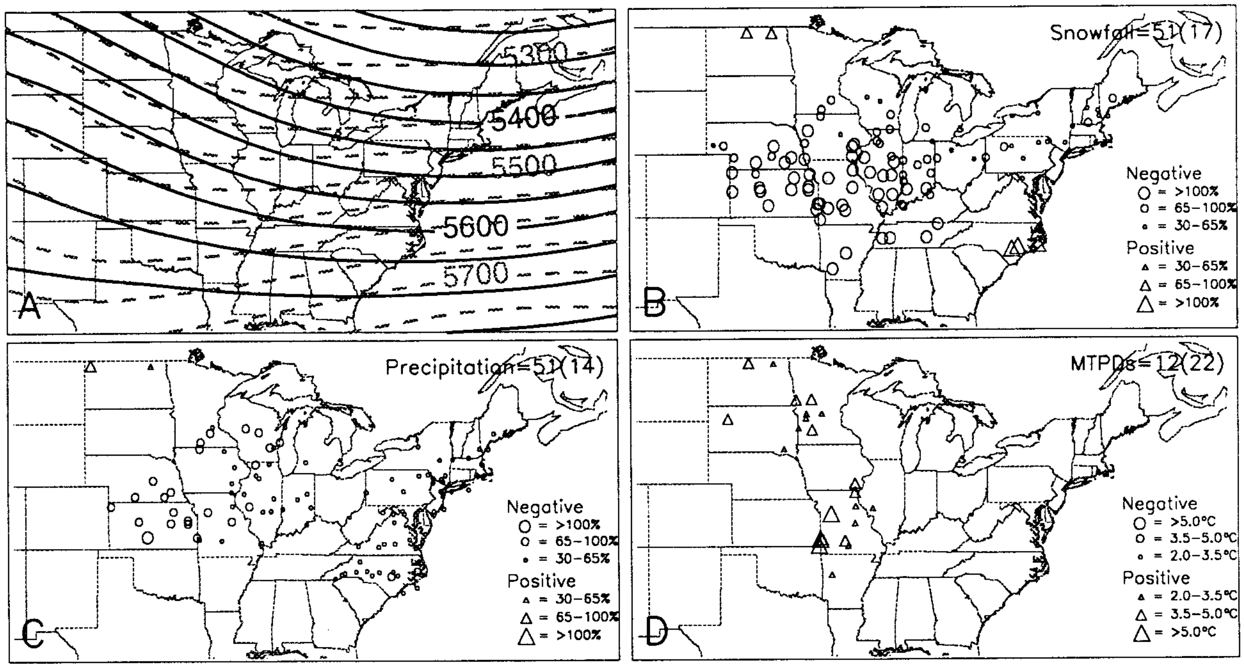

FIG. 13. PC3 signals for Jan–Feb, expressed as (a) positive (solid lines) and negative (dashed lines) 500-hPa composites, (b) positive minus negative composite differences in snowfall, (c) positive minus negative composite differences in precipitation, and (d) positive minus negative composite differences in mean maximum temperature on precipitation days. The percent of stations showing significant signals is also indicated along with the limiting values from field significance tests (the latter in parentheses).

ature association. Nevertheless, we do find some tendency in all three temporal windows for MTPDs in the positive (negative) EP composites in this area to be significantly higher (lower) than climatology. While these snowfall decreases (increases) under the positive (negative) mode appear most directly related to precipitation, temperature appears to play a complementary, reinforcing role.

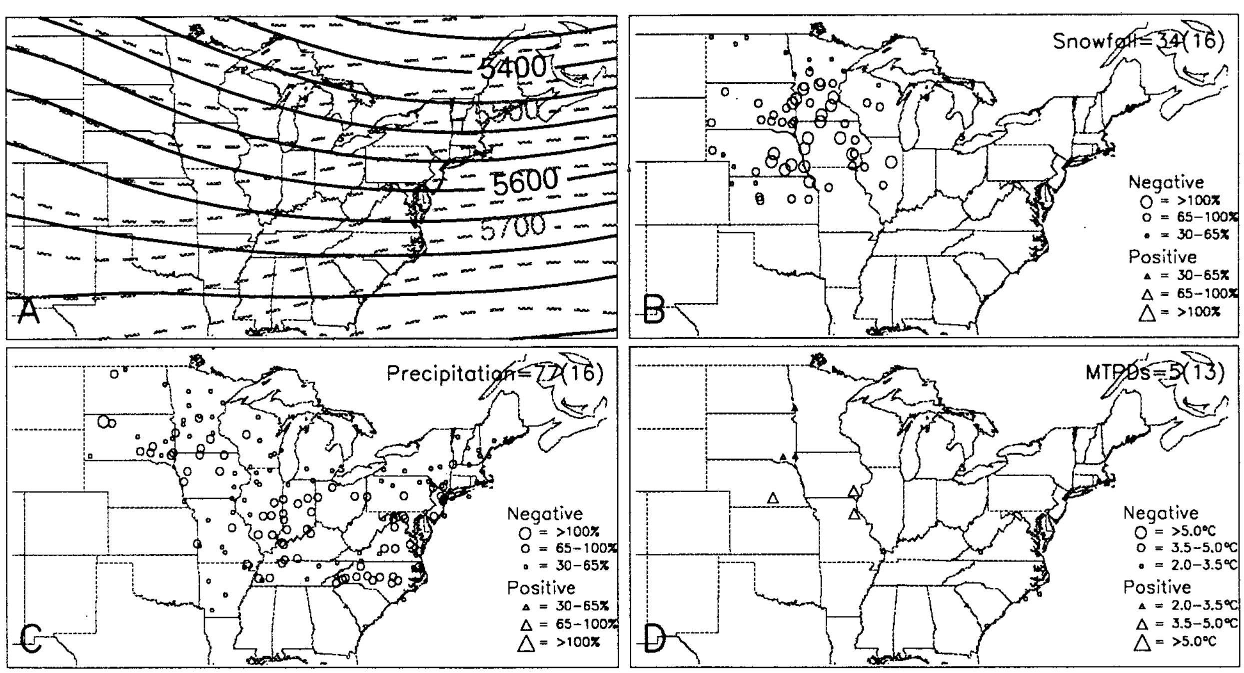

FIG. 14. Same as Fig. 12 but for Nov–Dec.

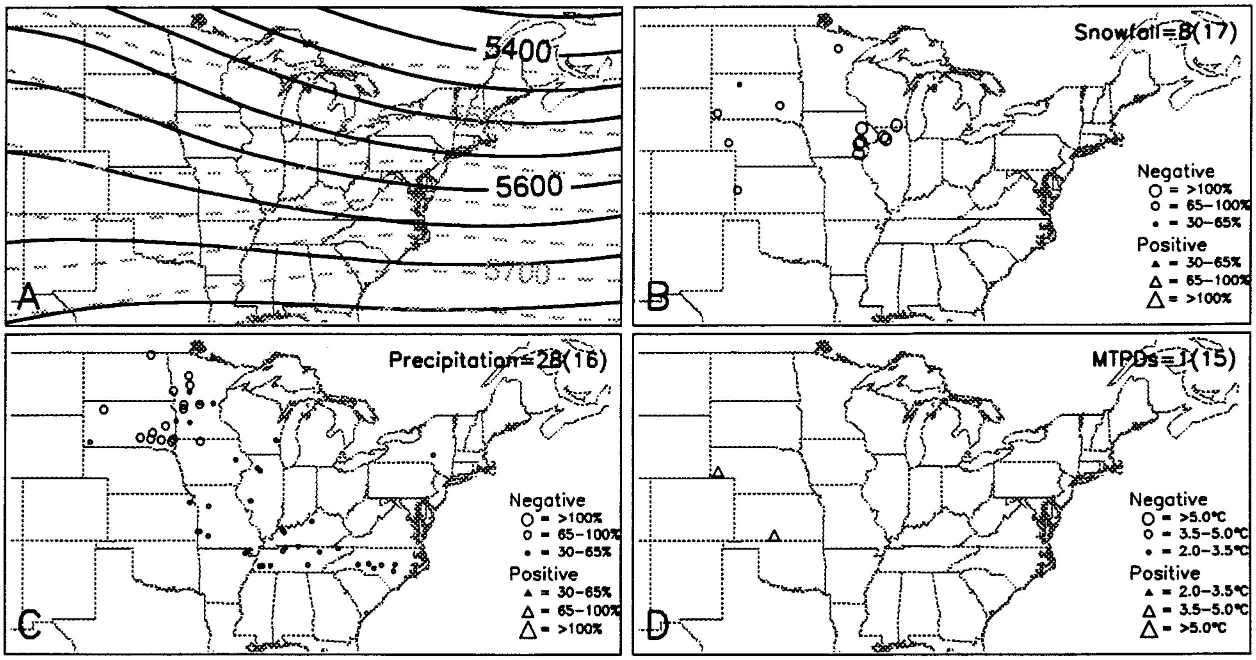

FIG. 15. Same as Fig. 12 but for Mar–Apr.

6. Summary and conclusions

Monthly data from the Historical Daily Climatic Data Set are used to examine characteristics of snowfall over the eastern half of the United States. Composite analyses, based on a rotated PCA of monthly mean 500-hPa geopotential height patterns, are used to diagnose relationships between snowfall and circulation for the 2-month periods November–December, January–February, and March–April. The three PCs retained for each window capture components of the PNA, TNH, and EP teleconnection patterns. For all three windows, PC1 (the PNA) captures at least 50% of the unrotated variance in 500-hPa height.

Spearman rank correlation analyses reveal two climatological snowfall regimes: 1) the relatively dry and cold upper midwest and Kansas–Nebraska region, where snowfall is strongly a function of total precipitation, and 2) the warmer and moister midwest, southern, and northeast sectors, where snowfall is more a function of the mean maximum temperature on precipitation days. These general relationships are best expressed in relation to snowfall variability associated with extremes of the PNA. PNA snowfall signals are most strongly developed during January–February, with significant positive minus negative composite differences found over the midwest, southeast, and mid-Atlantic states; southeastern U.S. snowfall increases (decreases) under the positive (negative) mode of the PNA, when this region lies under a 500-hPa trough (zonal flow or weak ridge). This signal is not due to changes in precipitation (precipitation for many stations is reduced under the positive mode), but to associated lower (higher) maximum temperatures on precipitation days. Stronger signals are found in positive PNA extremes under colder conditions, which will have a larger impact on precipitation phase. A corresponding negative (positive) snowfall signal is found under the positive (negative) PNA mode over the upper midwest, which relates to precipitation changes. Similar signals are found for November–December. PNA snowfall signals for March–April are weaker and best expressed over the high-elevation southern Appalachians.

With respect to significant positive minus negative composite differences, extreme modes of the TNH have weak influences on snowfall for both January–February and March–April. However, like the PNA for March–April, somewhat more coherent patterns are found when the individual positive and negative composites are compared to climatological means. January–February shows a roughly zonal snowfall signal, with the positive composites indicating below-normal snowfall over the upper midwest and Great Lakes and above-normal snowfall to the south, with generally opposing negative composite signals. Stronger relationships are found for March–April, for which positive minus negative composite differences are negative over the upper-midwest and midwestern states and extending into New England. This signal best reflects negative temperature departures under the negative composite. By contrast, the EP pattern, which in its extreme positive and negative modes describes an eastern trough–western ridge and a weak midwestern trough–eastern ridge, respectively, is associated with widespread snowfall signals for both January–February and November–December, with weaker signals in March–April. For the midwinter case the positive (negative) mode of the EP pattern is associated with negative (positive) snowfall differences over the midwest and extending westward into Kansas and Nebraska. The patterns for November–December and March–April are qualitatively similar. In contrast to the PNA, the observed snowfall signals are most directly associated with precipitation changes.

Snowfall is arguably an important variable to monitor for climate change, especially for ''marginal snowfall'' regions such as the southeast where the precipitation phase tends to be highly variable. However, the results presented here illustrate the potential difficulty in separating the effects of any background change in temperature or precipitation due to increasing concentrations of greenhouse gases or from natural variability related simply to circulation. In this context, we find no evidence in these data of robust, spatially coherent trends in seasonal total snowfall (November–April) over the period 1947–93, although trends are significant for some individual stations. However, given the sensitivity of trend analyses to the period of record chosen and treatment of the data, we do not consider our results to be at odds with other studies (e.g., Leathers et al. 1993; Leathers and Ellis 1996) that have found trends. The latter study demonstrates large increases in snowfall for the lake effect regions of western New York and northwestern Pennsylvania, using a fairly high density station network for the snowfall seasons 1930–31 through 1989–90.

Given our results, it is also not surprising that regression analysis of monthly factor scores also indicates no trends in the strength of any of the three primary PCs used, the exceptions being March for PC2 and PC3 and November for PC1. Interestingly, there have been significant positive trends from January–April for the period 1947–93 in the ''three point'' PNA index of Yarnal and Diaz (1986), which we reconstructed from the monthly 500-hPa fields. This index is intended to more fully describe the PNA wave train on the basis of centers of high variance over the North Pacific Ocean, the Cordillera of northwestern North America, and the southeastern United States. No trends, however, are found in the eastern component of this index, which is essentially captured by our PC1. What this serves to point out is that understanding climate anomalies associated with modes of large-scale, low-frequency atmospheric variability requires focused analyses of regional circulation signals, as the relationships between regional and large-scale modes may not be straightforward. Further studies have been initiated by our group to examine variability in western U.S. snowpack water resources.

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APPENDIX

Quality Control of the HDCD

Snowfall reports are deleted when 1) snowfall is greater than zero and minimum temperature is greater than 4°C; 2) snowfall is greater than or equal to the state (the 24-h record); 3) snowfall exceeds 1 cm but precipitation is zero; 4) snowfall is between 2.5 and 8.0 cm and more than 50 times the precipitation total; 5) snowfall is between 8.0 and 15 cm, more than 40 times the precipitation total, when the daily maximum temperature is greater than −4°C; 6) snowfall exceeds 15 cm and is more than 20 times the precipitation total, with the daily maximum temperature greater than −4°C; and 7) snowfall exceeds 15 cm, is more than 30 times the precipitation total, and the daily maximum temperature is less than −4°C. Precipitation reports are excluded if precipitation is 1) greater than 130 mm; 2) greater than the prescribed maximum (100-yr) daily precipitation event for the state; 3) at least 1 mm, with zero snowfall and a maximum temperature is less than −1°C; and 4) greater than twice the snowfall with a maximum temperature is less than −1°C. Minimum temperature reports are excluded if 1) today's minimum temperature is less than the state minimum or greater than the state maximum, 2) today's minimum temperature is greater than yesterday's maximum temperature, and 3) today's minimum temperature is more than 60°F lower than today's maximum temperature. Maximum temperature reports are excluded if 1) today's maximum temperature is greater than the prescribed state maximum or less than the prescribed state minimum, 2) today's maximum temperature is less than or equal to today's minimum temperature, and 3) today's maximum temperature is less than yesterday's minimum temperature.

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