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Effects of the North Atlantic Oscillation on precipitation-type frequency and distribution in the eastern United States

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With 11 Figures

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Summary

The North Atlantic Oscillation (NAO) is the primary mode of atmospheric variability over the Atlantic Ocean and plays an important role in climate variability over eastern North America. The frequency of extreme climate events and the associated social and economic impacts is also tied to the strength and phase of the NAO. In this study, seasonal phases of the NAO are compared to changes in the frequency and distribution of winter season (December–March) precipitation-type observations for the years 1961–2001 in the eastern U.S. Statistically significant increases in the frequency of rain observations across the study region are associated with positive NAO phases. Additionally, significant increases in the occurrence of snow are confined to the northern portion of the eastern U.S. during positive NAO phases. Connections between the phase of the NAO and the prevailing synoptic-scale circulation, at least partially, explain the inter-seasonal distribution of precipitation types across the eastern U.S. Using an intra-seasonal or intra-monthly NAO index may reveal a more robust relationship between snowfall observations across the eastern U.S. and surface pressure variability over the North Atlantic.

1. Introduction

Since the early 20th century, researchers have explored relationships between low-frequency fluctuations in atmospheric circulation and global weather patterns (Walker 1924; Walker and Bliss 1932). These distant relationships, called teleconnections, can provide a possible foundation for long-range climatological forecasts (Wallace and Gutzler 1981; Mo and Livezey 1986). Moreover, these low-frequency patterns have been shown to produce extreme climate events (Mo and Livezey 1986), which in turn produce a wide variety of socio-economic impacts (e.g., casualties, injuries, and property and crop damage) (Changnon 1979; Schmidlin 1993). Such extremes may be attributed to anomalous departures in both temperature and precipitation, with impacts across local and continental scales (Namias 1966; Ropelewski and Halpert 1986; Yarnal and Diaz 1986; Kunkel and Angel 1999; Thompson and Wallace 2000; McCabe and Muller 2002).

While many teleconnections have been identified in the Northern Hemisphere, the focus of this study is the North Atlantic Oscillation (NAO). The NAO is the primary mode of atmospheric variability over the Atlantic Ocean and plays a particularly important role in climate variability in eastern North America (Van Loon and Rogers 1978; Wallace and Gutzler 1981; Barnston and Livezey 1987; Hurrell 1995, 1996; Greatbatch 2000). Furthermore, the NAO is a

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manifestation of low-frequency changes in the strength of the surface westerlies across the North Atlantic in response to the large-scale redistribution of atmospheric mass from the Arctic (Icelandic Low) to the subtropical Atlantic (Azores High) (Walker 1924; Walker and Bliss 1932; Hurrell 1995, 1996; Greatbatch 2000). Hurrell and Dickson (2004) found that the NAO accounts for nearly one-third of the variance in sea-level pressure (SLP) over the North Atlantic and one-third of the variance in surface temperatures for the entire Northern Hemisphere from December to March.

Positive NAO phases are typified by anomalously strong centers of high pressure in the subtropical North Atlantic that coexist with deeper-than-normal centers of low pressure in the Arctic and subarctic regions. The result is an increased zonal pressure gradient across the northern Atlantic and increased low-level warm air and moisture advection into the eastern U.S. (Hurrell and Dickson 2004). Specifically, Hurrell (1995) found an increase in moisture convergence along the East Coast of the U.S. when the NAO index was positive. Negative NAO phases are associated with a poleward migration of the subtropical high and subsequent blocking pattern over the North Atlantic (Wallace and Gutzler 1981, Hurrell 1995, Hurrell and Dickson 2004). Consequently, the mean trough axis becomes positioned over the eastern U.S. allowing for more frequent cold-air outbreaks in this area (Hurrell 1996; Thompson and Wallace 2000; Bradbury et al. 2002).

Alternating phases of the NAO and the resultant changes in synoptic-scale circulation patterns have also been shown to influence storm tracks and storm frequency (Rogers and van Loon 1979; Yarnal and Leathers 1988; Hurrell 1995; Hurrell and van Loon 1997; Hartley and Keables 1998; Thompson and Wallace 2000; Bradbury et al. 2003; Hurrell and Dickson 2004). Rogers (1990) illustrated that a positive NAO during the winter is associated with a northeastward displacement of storm activity, while Yin (1994) found that anomalously wet conditions in the Tennessee River Valley may be associated with a positive NAO. Despite these findings, no studies have examined the regional connections between precipitation-type observations and the seasonal phase of the NAO.

Hurrell (1996) and Hurrell and Dickson (2004) have shown that changes in the synoptic circulation patterns associated with the NAO can lead to changes in winter season temperatures and consequently, the type of precipitation (i.e., snow, sleet, freezing rain, and liquid rain) reaching the ground. Previous studies highlight numerous social and economic impacts as a result of increased winter precipitation (Rooney 1967; Changnon 1979; Kocin and Uccellini 1990; Schmidlin 1993). For example, Kocin and Uccellini (1990) documented multiple winter storms over the eastern U.S. that caused numerous deaths and

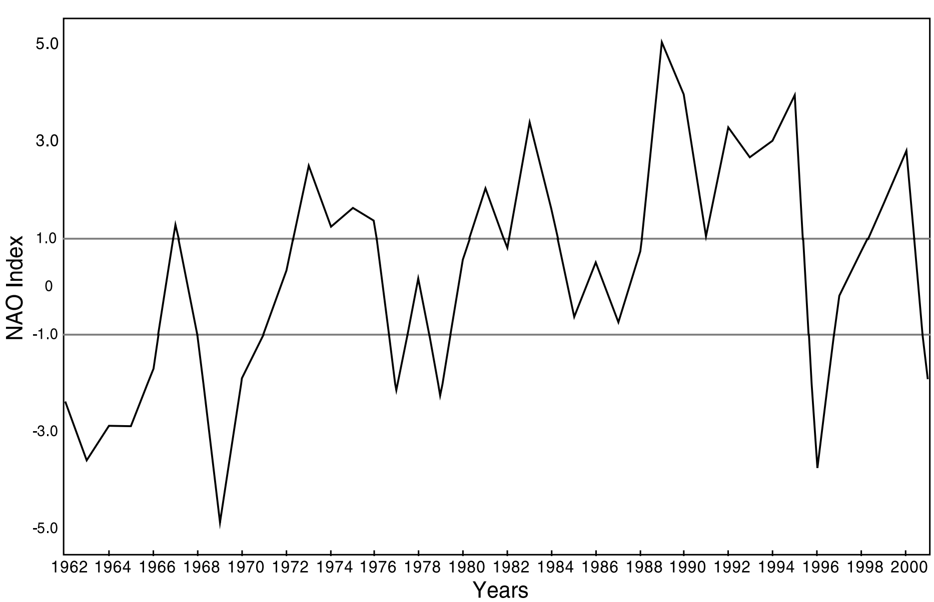

Fig. 1. Seasonal NAO index for the study period (1961–2001). Positive and negative seasons are identified by ≥ 1.0 and ≤ 1.0, respectively

injuries as well as large monetary damage. Other impacts included widespread power outages as well as increased household heating and home repairs, business and school closings, road closures, and increased road maintenance costs.

The purpose of this study is to examine the relationship between the seasonal phase of the NAO (either positive, negative, or neutral) and the frequency and distribution of precipitation-type observations in the eastern U.S. during the winter seasons of 1961–2001. The current study demonstrates that changes in the frequency and distribution of winter precipitation types in the eastern U.S. are influenced in part by changes in the phase of the NAO.

2. Data and methods

To determine the distribution of precipitation types associated with phases of the NAO, this study utilized the National Center for Atmospheric Research's (NCAR) seasonal (December–March) standardized NAO index for the period 1961–2001 (Fig. 1). The study period was chosen to maximize the number of weather stations used for analysis (many stations either did not exist or experienced numerous location changes prior to 1961). However, the 41-year period (40 seasons) represents a sufficient sample for examining influences of low-frequency atmospheric fluctuations, such as the NAO, on regional precipitation-type patterns (Barnston and Livezey 1987). Positive (negative) phases were classified by NAO index values that exceeded $+(-)1.0$. The neutral phase was classified as any season between -1.0 and $+1.0$ (Table 1).

Table 1. List of seasons (December through March) for the period of record, the NAO index value for that season and the phase classification used for the present study. Note the year corresponds to March (i.e., 1962 spans from December 1961 to March 1962)

Year	Index value	Phase
1962	−2.38	negative
1963	−3.60	negative
1964	−2.86	negative
1965	−2.88	negative
1966	−1.69	negative
1967	1.28	positive
1968	−1.04	negative
1969	−4.89	negative
1970	−1.89	negative
1971	−0.96	neutral
1972	0.34	neutral
1973	2.52	positive
1974	1.23	positive
1975	1.63	positive
1976	1.37	positive
1977	−2.14	negative
1978	0.17	neutral
1979	−2.25	negative
1980	0.56	neutral
1981	2.05	positive
1982	0.80	neutral
1983	3.42	positive
1984	1.60	positive
1985	−0.63	neutral
1986	0.50	neutral
1987	−0.75	neutral
1988	0.72	neutral
1989	5.08	positive
1990	3.96	positive
1991	1.03	positive
1992	3.28	positive
1993	2.67	positive
1994	3.03	positive
1995	3.96	positive
1996	−3.78	negative
1997	−0.20	neutral
1998	0.72	neutral
1999	1.70	positive
2000	2.80	positive
2001	−1.89	negative

Precipitation-type data for the eastern U.S. were compiled using a network of National Weather Service first-order stations east of the Mississippi River. Only stations with 75% of the present weather observations for the period of record were used. For this study, 100 first-order stations in the eastern U.S. met this criterion (Fig. 2). Precipitation types included rain, snow, and winter mix. Winter mix was defined as any combination of two or more precipitation types (excluding hail) (e.g., rain/sleet; sleet/snow; freezing rain/rain). Precipitation types for each station were extracted from hourly archived METAR reports. The seasonal frequency of observations for a given precipitation type was compiled by hour for each station and divided by the sum of all hourly reports for all precipitation types. For example, during the 1984–1985 winter season at Allentown, PA. (ABE), 192 hours of snow were reported (i.e., a total of 192 seasonal observations). During this season the total number of rain, snow, and mix precipi-

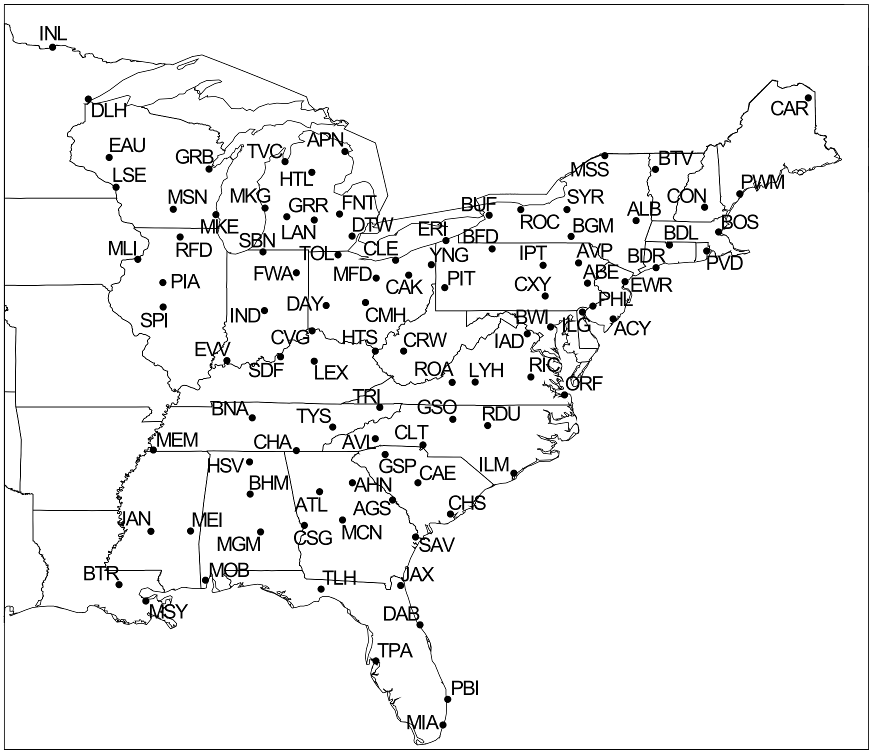

Fig. 2. Network of 100 first-order stations used to determine precipitation-type observations during winter (December–March) for the period 1961–2001

tation reports was 569, giving snow a seasonal percentage of 33.7. In order to facilitate a comparative spatial analysis between the changes in the distribution of each precipitation type across the eastern U.S. and NAO phases, the frequency of each observation was interpolated onto a 2.5-degree grid for each phase and the period of record.

The current study assumed positive spatial autocorrelation of precipitation-type observations between each station. Given this assumption, an inverse distance weighting interpolation method was used for interpreting changes in the spatial distribution of each precipitation type during each NAO phase (Declercq 1996; Yang and Hodler 2000). One hindrance with using any interpolation method is that extreme outliers can become over-smoothed and masked. Thus, by utilizing a distance weighting function, the full range of values for some maps (Figs. 3–8) were not contoured due to a limited number of stations experiencing extreme values (i.e., the data range for precipitation frequency in Fig. 3a falls between 3.6 and 100%; however, the contour range is between 15 and 90%).

Changes in the spatial distribution of each precipitation type between each NAO phase were tested at each first-order station for significance using an independent samples *t*-test with a 95% confidence interval. National Center for Environmental Protection/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis upper-air data (2.5-degree grid) (Kalnay et al. 1996) were utilized to provide insight into the changes in the upper tropospheric height and temperature patterns during each NAO phase. The thermodynamic patterns analyzed included critical temperature fields at 850 and 700 hPa to investigate partial thicknesses critical for winter precipitation-type forecasting (Bocchieri and Maglaras 1983; Keeter and Cline 1991) and integrated thickness (1000–500 hPa) to determine the depth of the thermal layer (Wagner 1957). The 500 hPa geopotential height field was also examined to determine shifts in the storm track and synoptic-scale regions of thermal advection during particular phases of the NAO. Composite grid points for each field were also tested for significant differences (utilizing an independent samples *t*-test with a 95% confidence interval) to provide evidence for changes in the synoptic and thermodynamic patterns associated with the changes in the spatial distribution of each precipitation type.

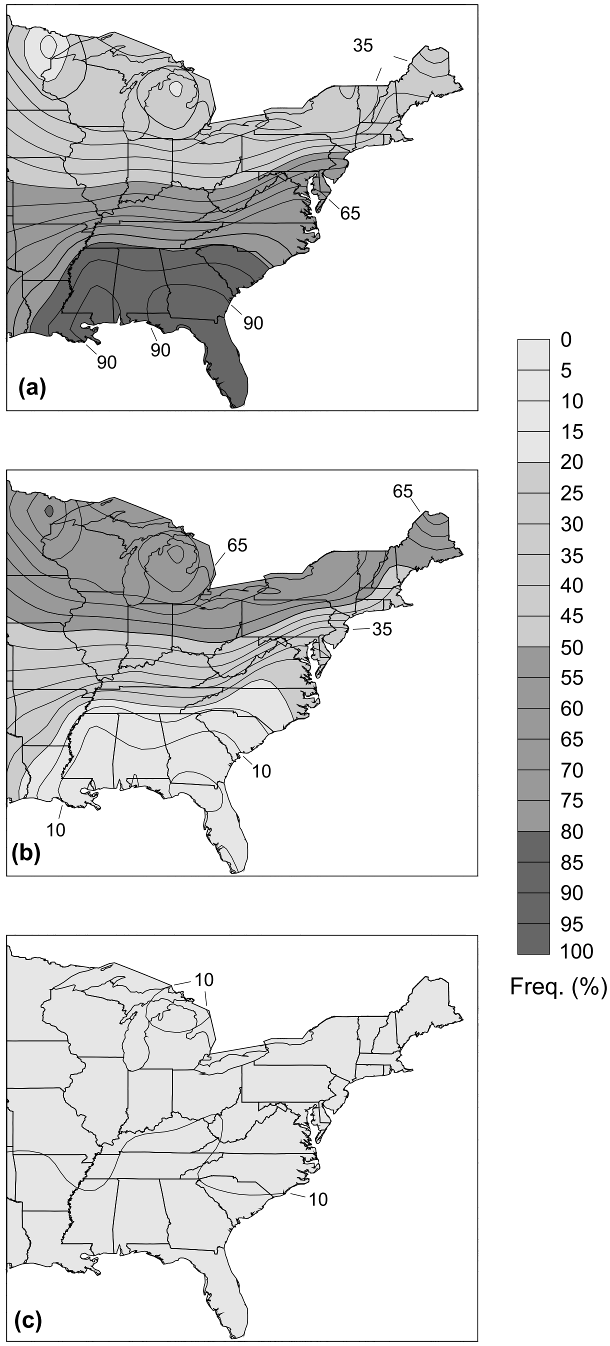

Fig. 3. Precipitation frequencies for the entire period of record for (**a**) rain [data range: 3.6–100%]; (**b**) snow [data range: 0–91.7%]; (**c**) winter mix [data range: 0–13.1%]. Contour interval is 5 percent

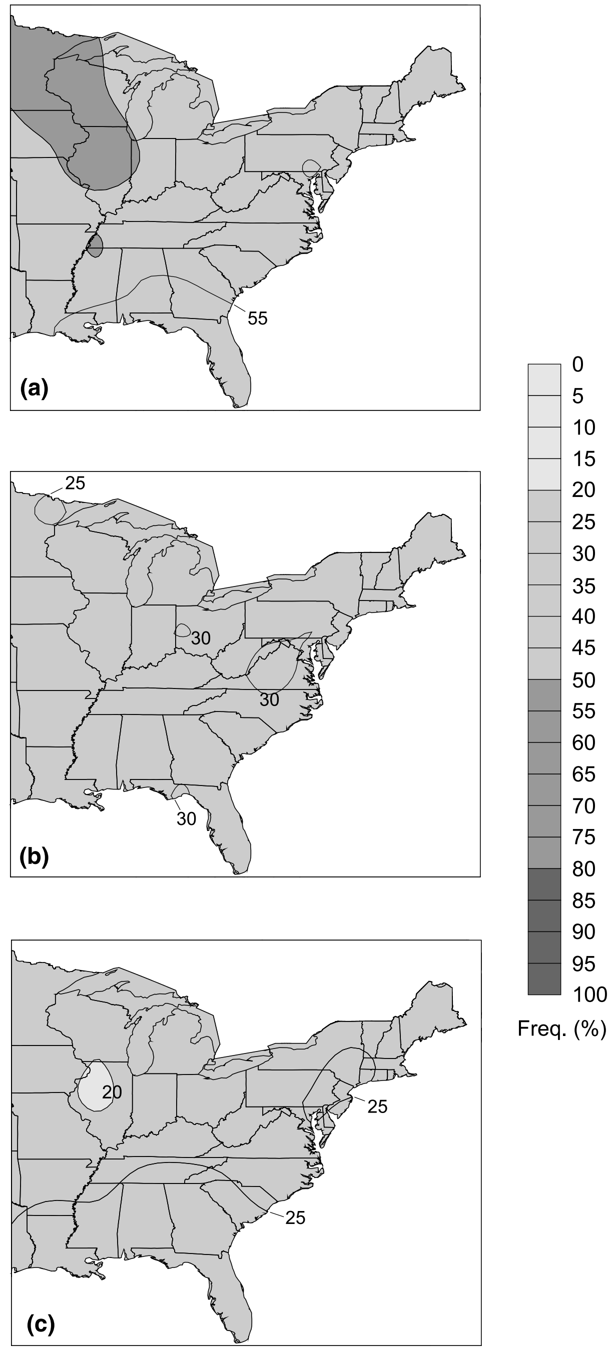

Fig. 4. Precipitation frequencies by phase for rain for the entire period of record for (**a**) positive [data range: 38.7–55.6%]; (**b**) neutral [data range: 21.8–34.2%]; (**c**) negative [data range: 17.8–32.9%]. Contour interval is 5 percent

3. Results

Precipitation types were initially analyzed for the entire period of record to determine where the maximum and minimum winter season frequencies occurred. The frequency of rain observations (out of all present weather observations) ranged from 3.6–100% with a maximum located in Florida and a minimum in the upper Great Lakes region (Fig. 3a). Not surprisingly, the frequency of snow observations revealed an inverse pattern with the Great Lakes region having maximum

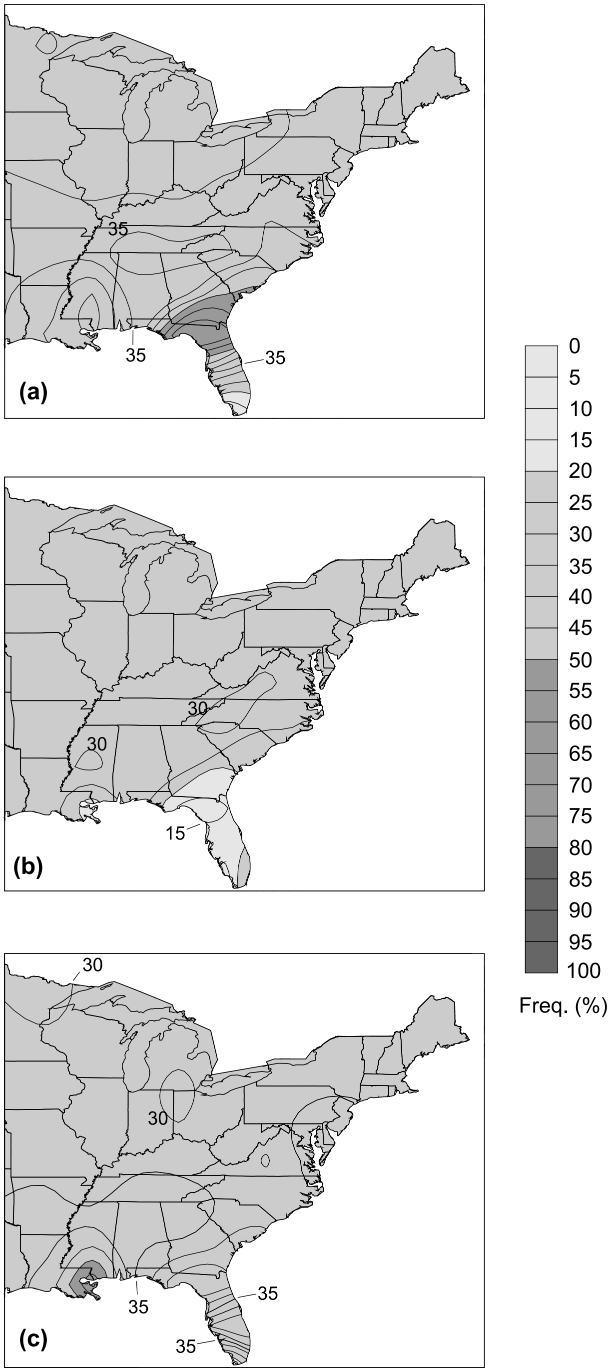

Fig. 5. As in Fig. 4 except for snow for (**a**) positive [data range: 0–75.0%]; (**b**) neutral [data range: 0–100%]; (**c**) negative [data range: 0–100%]

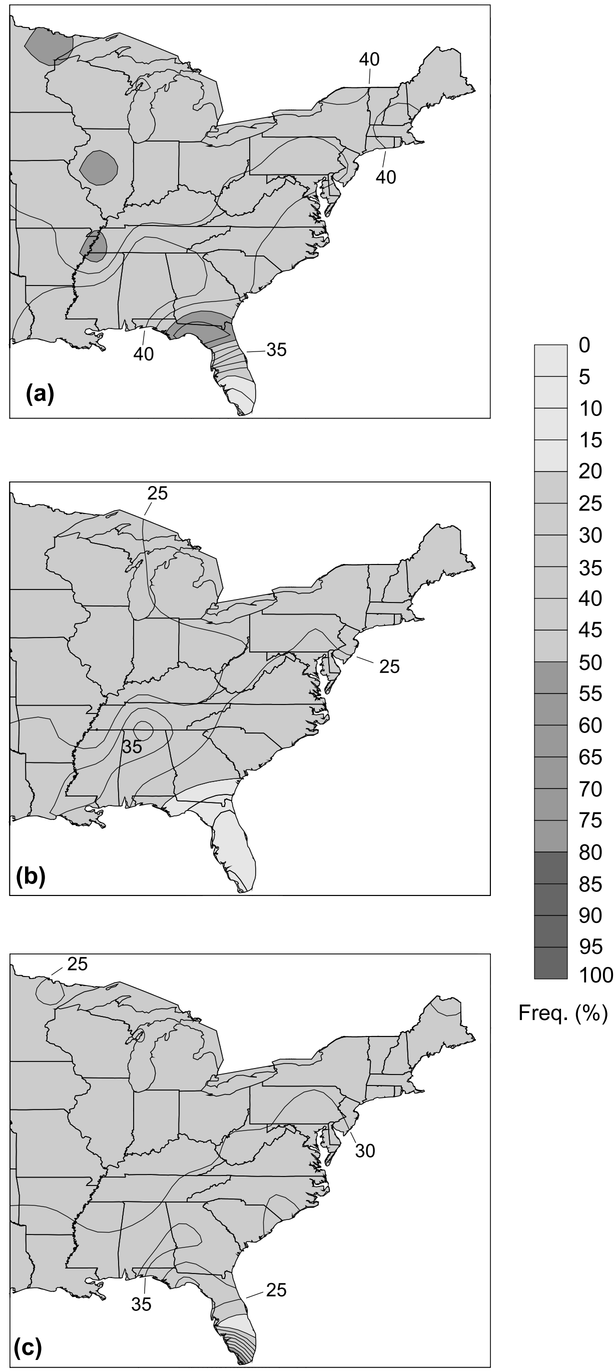

Fig. 6. As in Fig. 4 except for winter mix for (**a**) positive [data range: 0–67.7%]; (**b**) neutral [data range: 0–48.5%]; (**c**) negative [data range: 0–100%]

frequencies (∼92%) and a virtual suppression of snow observations across the Big Bend of Florida (0%) (Fig. 3b). The observational range for winter mix, the least frequent precipitation type, was 0–13% (Fig. 3c). Figures 4–6 show the frequency of observations for rain, snow, and winter mix, respectively, for each NAO phase (e.g., Fig. 4a shows the frequency of rain during positive NAO phases compared to all rain observations for the period of record).

To assure that a low frequency of any precipitation type does not produce misrepresentative results, a minimum threshold value was determined to eliminate stations with precipitation-

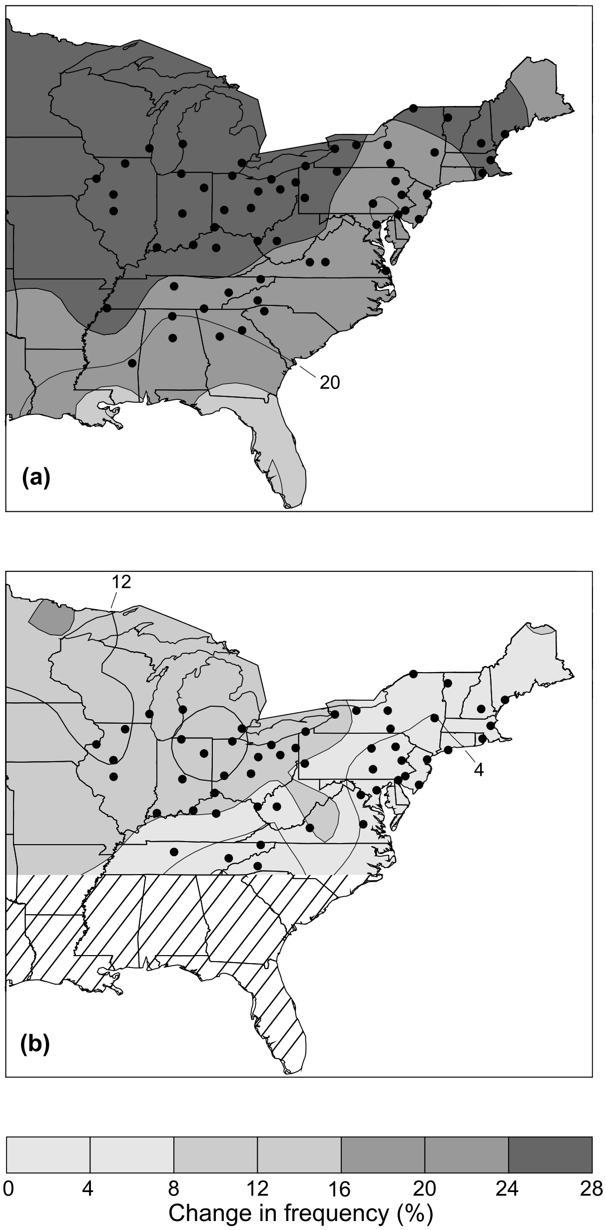

Fig. 7. (**a**) Difference in frequency of occurrence between rain observations in positive minus negative seasons [data range: 5.8–35.5%]. Contour interval is 4 percent. Points identify stations where the change was significantly different; (**b**) same as (**a**) except for snow observations in positive minus negative seasons [data range: −11.3–22.9%]. Hatched area represents where stations were eliminated due to low occurrences of snow observations

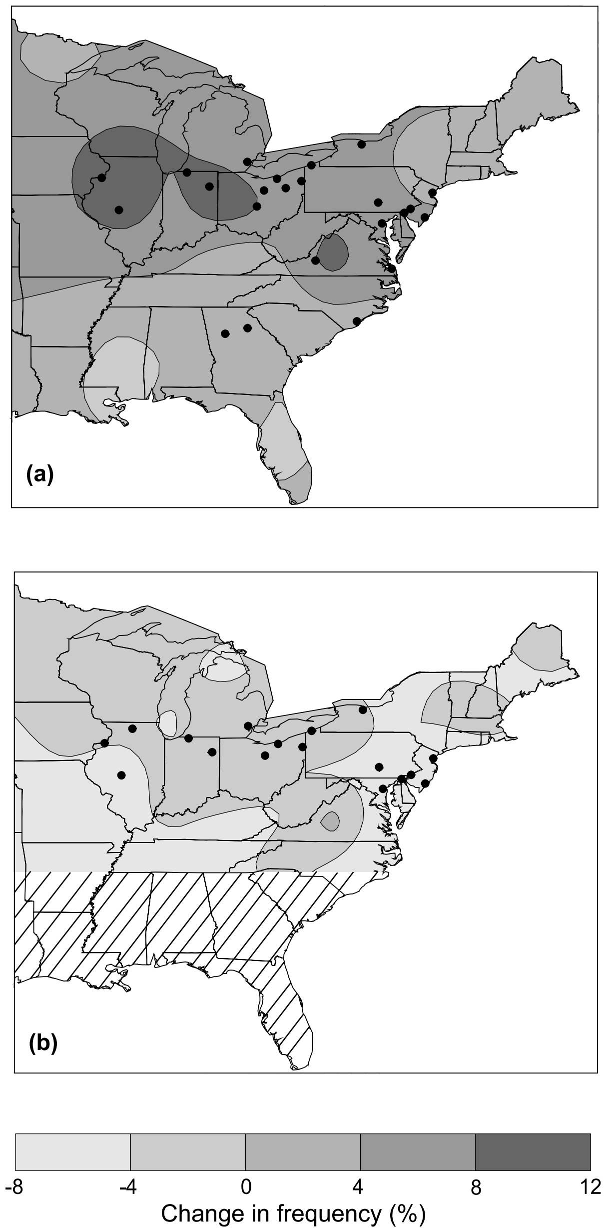

Fig. 8. (**a**) As in Fig. 7a except for neutral minus negative seasons [data range: −4.5–14.6%]; (**b**) as in Fig. 7b except for neutral minus negative seasons [data range: −16.8–7.3%]

type frequencies <10% from further analysis. Ultimately, four stations were removed when examining rain and 31 stations for snow (Table 2). For mixed precipitation, all stations were eliminated even though there were six stations that had a frequency of >10%; these stations were widely scattered throughout the study region and no coherent spatial patterns could be determined regardless of the NAO phase.

3.1 Spatial patterns of significant differences

Table 3 shows results of six independent samples *t*-tests conducted to identify significant differences in the frequency of occurrence of precipitation-

Table 2. First-order stations that did not meet the 10% frequency threshold for each precipitation type for the POR and were eliminated from the study. Note: All stations were eliminated when looking for frequency changes of winter mix precipitation type

Station	Rain	Snow
INL	✓	
DLH	✓	
TVC	✓	
HTL	✓	
MEM		✓
JAN		✓
MEI		✓
BTR		✓
MSY		✓
MOB		✓
HSV		✓
BHM		✓
MGM		✓
CHA		✓
AHN		✓
ATL		✓
MCN		✓
CSG		✓
SAV		✓
AGS		✓
GSP		✓
CAE		✓
CHS		✓
CLT		✓
ILM		✓
GSO		✓
RDU		✓
ORF		✓
TLH		✓
JAX		✓
DAB		✓
TPA		✓
PBI		✓
MIA		✓
EYW		✓

type observations between each NAO phase. Four of the six tests revealed >10 stations with a coherent spatial pattern (i.e., stations within relative proximity to each other). The four tests were: 1) positive versus negative phase rain (Fig. 7a); 2) positive versus negative phase snow (Fig. 7b); 3) neutral versus negative phase rain (Fig. 8a); 4) neutral versus negative phase snow (Fig. 8b). Figures 7 and 8 illustrate the difference in frequency of occurrence between the phases and indicate stations with statistically significant differences at the 95% confidence interval.

The northern tier of the study region experienced an increase of >24% in rainfall observations during the positive phase compared to the negative phase (Fig. 7a). Moreover, a majority of the stations with significant differences exhibited ≥20% increase in rainfall observations. The pattern of rainfall observations between the neutral and negative phases (Fig. 8a) closely resembled Fig. 7a, but with smaller changes in frequency and fewer stations with significant differences.

Similar to changes in the frequency of rainfall observations, the frequency of snowfall observations exhibited increases during the positive phase with the greatest increases in the northern portions of the study region (Fig. 7b). These changes were relatively modest (≥8%) compared to the changes illustrated in Fig. 7a. Examination of the changes in the frequency of snowfall observations between neutral and negative phases (Fig. 8b) showed that the area with the greatest difference followed the same pattern, but with a smaller magnitude and with fewer stations exhibiting significant differences than that shown in Fig. 7b.

In order to determine whether the spatial patterns of significance occurred by random chance or collectively from physical changes in NAO phases, a field significance test was conducted. Correlations between precipitation-type frequencies and NAO phases for each station were compared against the distribution of 1000 simulated correlations from a randomly generated time series using a Monte Carlo technique (Livezey and Chen 1983). All stations shown in Figs. 7 and 8 were significantly correlated with changing phases of the NAO at the 95% confidence interval, except one (ILM; Fig. 8a). These results indicate that alterations in precipitation-type frequency distribution patterns are largely attributed to changes in the phase of the NAO, which may in part be due to changes in synoptic flow and vertical thermal profiles.

3.2 Synoptic circulation patterns and vertical temperature analysis

Changes in the precipitation-type frequency and distribution between NAO phases are dependent on the synoptic and thermal profiles associated with each phase. Thus, various fields were analyzed to determine the atmospheric changes as-

Table 3. Results of the six independent samples *t*-tests conducted on precipitation-type frequencies between each NAO phases. *A* ✓ Indicates stations where a significant difference ($p < 0.05$) was found and ∗ indicates stations not tested due to elimination from the study. The tests conducted were: *1*) positive versus negative rain, *2*) positive versus negative snow, *3*) neutral versus negative rain, *4*) neutral versus negative snow, *5*) positive versus neutral rain, *6*) positive versus neutral snow

Station	1	2	3	4	5	6	Station	1	2	3	4	5	6
ABE	✓	✓					IAD		✓				
ACY	✓	✓	✓	✓			ILG	✓	✓	✓	✓		
AHN	✓	∗	✓	∗		∗	ILM		∗	✓	∗		∗
ALB	✓	✓					IND	✓	✓				
ATL	✓	∗	✓	∗		∗	IPT		✓				
AVL	✓	✓			✓	✓	JAN		∗		∗	✓	∗
AVP	✓	✓					LEX	✓	✓				
BDR		✓					LYH	✓					
BFD	✓						MEI	✓	∗		∗	✓	∗
BGM	✓	✓					MEM	✓	∗		∗		∗
BHM	✓	∗		∗		∗	MFD	✓	✓	✓	✓		
BNA	✓	✓					MKE	✓	✓				
BOS	✓	✓					MKG	✓	✓				
BTV	✓	✓			✓	✓	MLI	✓	✓	✓	✓		
BUF	✓	✓					MSS	✓	✓				
BWI	✓	✓	✓	✓			ORF	✓	∗	✓	∗		∗
CAK	✓	✓	✓				PHL	✓	✓	✓	✓		
CHA	✓	∗		∗	✓	∗	PIA	✓	✓				
CLE	✓	✓	✓	✓			PIT	✓	✓				
CMH	✓	✓	✓				PVD	✓	✓				
CON	✓	✓					PWM	✓	✓				✓
CRW	✓	✓			✓	✓	RFD	✓	✓		✓		
CVG	✓	✓					RIC		✓				
CXY	✓	✓	✓	✓			ROA	✓	✓	✓			
DAY	✓	✓					ROC	✓	✓	✓	✓		
DTW	✓	✓	✓	✓			SBN	✓	✓	✓	✓		
ERI	✓	✓	✓	✓			SDF	✓	✓				
EVV	✓	✓					SPI	✓	✓	✓	✓		
EWR	✓	✓	✓	✓			SYR	✓	✓				
FWA	✓	✓	✓	✓			TOL	✓	✓				
GSP	✓	∗		∗		∗	TRI	✓	✓				
HSV	✓	∗		∗	✓	∗	TYS	✓	✓			✓	✓
HTS	✓	✓				✓	YNG	✓	✓	✓	✓		

sociated with each phase of the NAO. Mean temperature differences at the 850 and 700 hPa levels were between 1 and 1.5 °C higher across much of the eastern U.S. when the NAO was in a positive phase (Fig. 9a and c, respectively). In correspondence with these thermal patterns, differences in the 1000–500 hPa thickness values were between 20 and 30 gpm higher when the NAO was in a positive phase (Fig. 9e). The position of the composite 0 °C isotherm at the 850 and 700 hPa levels shifted poleward by approximately 1° latitude, indicating an expansion of a mid- to low-tropospheric layer of relatively warmer air when the NAO was positive (Fig. 9b and d, respectively). When integrated through the lower half of the troposphere (1000–500 hPa), the composite 5400 gpm isopach during positive NAO phases shifted poleward similar to the 0 °C isotherm at 850 and 700 hPa (Fig. 9f). This relatively warmer layer covered much of the southern half of the study area, extending from the Gulf Coast to the Mid-Atlantic and Ohio River Valley.

When tested for significant differences between positive NAO and negative NAO phases, all grid points in the NCEP/NCAR Reanalysis dataset indicated significantly higher temperatures and thicknesses at these critical levels during positive NAO phases. These patterns provide evidence of an anomalous high pressure center in the subtropical North Atlantic during positive NAO phases (Fig. 10), which has been shown to lead to stronger than normal south-southeasterly

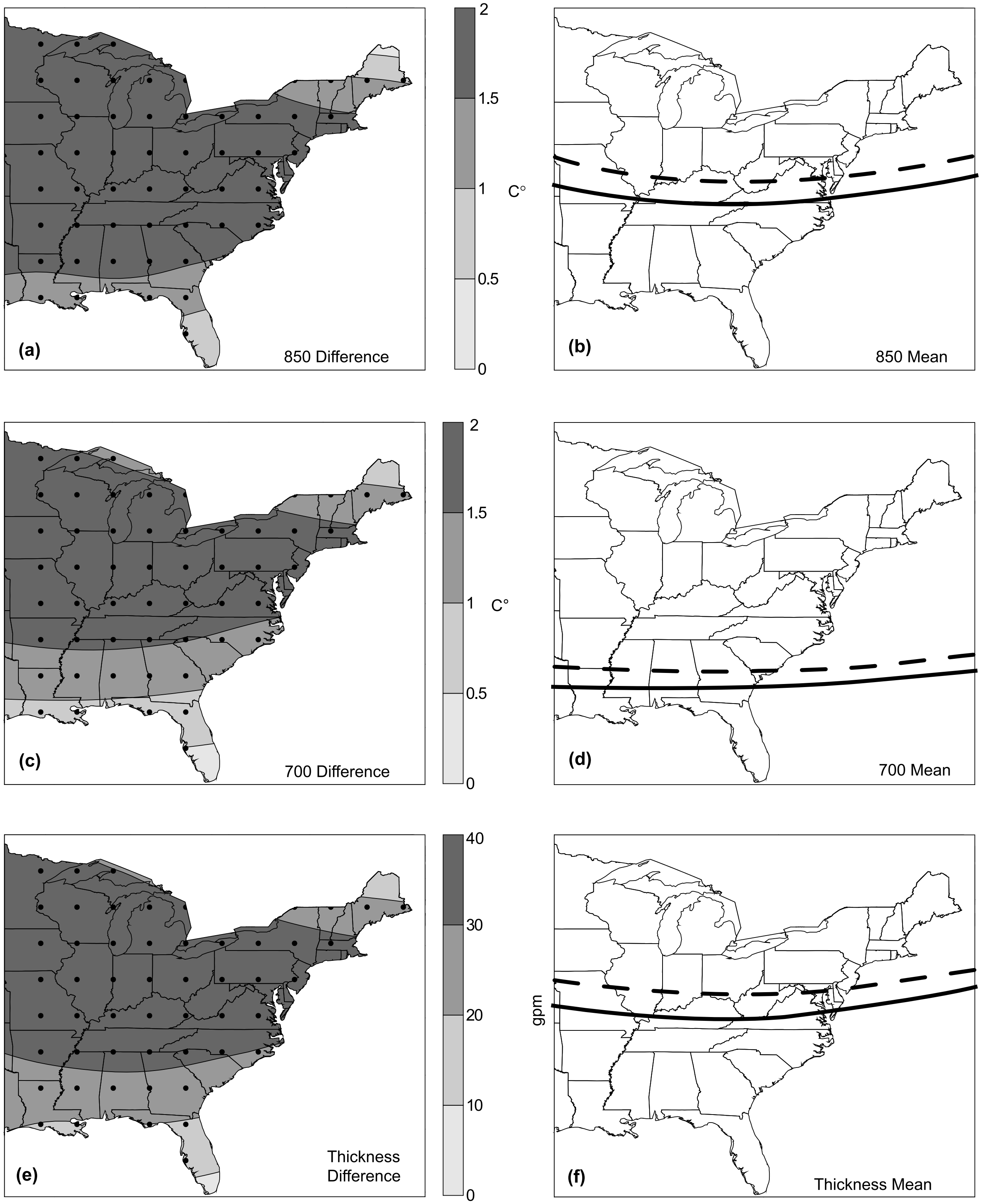

Fig. 9. (**a**) Difference (positive minus negative phases) in °C in 850 hPa temperature field (shading), points indicate the NCEP grid points with a significant difference ($p < 0.05$) between the phases; (**b**) mean location of 850 hPa 0 °C isotherm during positive (dashed line) and negative (solid line) phases; (**c**) same as (**a**) except for 700 hPa temperature; (**d**) same as (**b**) except 700 hPa temperature; (**e**) same as (**a**) except for 1000–500 hPa thickness difference in gpm; (**f**) same as (**b**) except for mean location of the 5400 gpm isopach for 1000–500 thickness

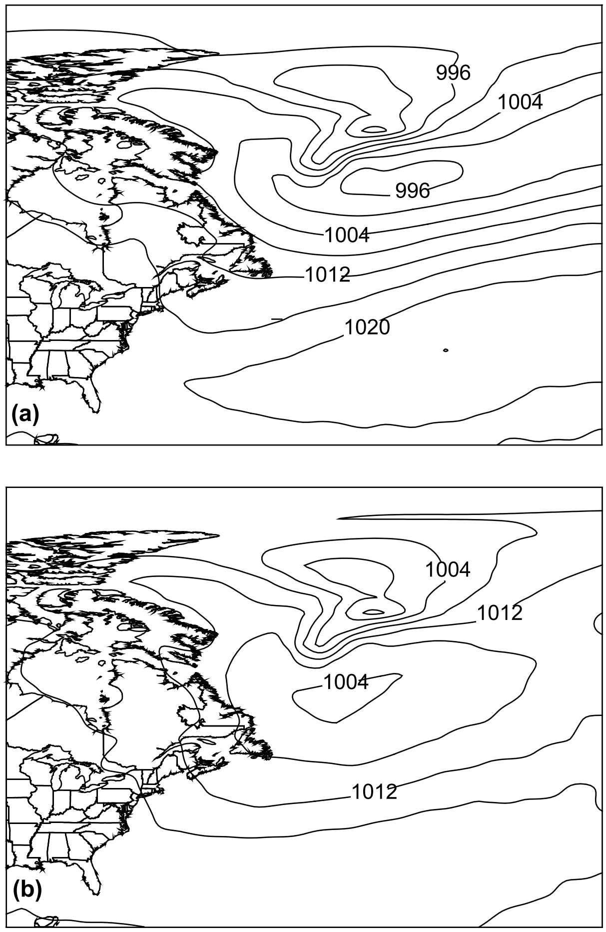

Fig. 10. (**a**) Mean sea-level pressure field for positive phase; (**b**) same as (**a**) except for negative phase

flow of warm moist air into the southeastern U.S. (Hurrell and Dickson 2004).

Positive NAO phases were also associated with positive 500 hPa height anomalies between 20 gpm along the Gulf Coast and 30 gpm across the northern two-thirds of the study region (Fig. 11). These differences were statistically significant at the 95% confidence interval for all grid points. Mid-tropospheric height rises across the eastern U.S. correspond to warming and an increased mean layer depth, thus supporting the location and migration of both elevated and integrated warm layers through the mid-troposphere.

Changes in the storm track are also tied to latitudinal shifts in the strength of the upper-level circulation patterns. During positive NAO phases the eastern U.S. is primarily situated beneath an upper-level zonal height configuration, which is closely tied to a poleward shift of the storm track. As a result the frequency of cold air intrusions into the southeastern U.S. decreases (Hurrell and Dickson 2004). The significant increase in rainfall observations during positive NAO seasons, shown in Fig. 7, may be ascribed largely by these synoptic circulation patterns and the resultant vertical and horizontal thermal distributions.

The increase in the frequency of snowfall observations during positive NAO phases runs opposite to the general circulation and thermal advection patterns that typify a positive NAO. One might expect a significant increase in snowfall observations during negative NAO phases resulting from a weakened SLP gradient over the North Atlantic and subsequent weakening of subtropical thermal and moisture transport into the eastern U.S. (Hurrell and Dickson 2004). One possibility relates to the time scale over which the NAO indices were calculated. By using a standardized seasonal index computed over a four month period, transient features in the synoptic-scale circulation may not be adequately resolved. Indeed, much of the temperature variability over a given winter season may be tied to synoptic-scale weather systems that persist for a week or less (Konrad 1998).

Similarly, the lack of observations of mixed precipitation may be related to the spatial and temporal scales over which it forms. In the eastern U.S. mixed precipitation is often observed in narrow and short-lived transition zones between mainly frozen (snow) and liquid precipitation (Stewart 1992). Local and regional topography are also important precipitation forcing mechanisms that can lead to the production of various precipitation types. As a result it is not uncommon to see the coexistence of mixed precipitation in regions of varying topographic landscapes (e.g., the southern Appalachians; Richwein 1980). Nevertheless, it is likely that NAO indices computed over intra-seasonal (or perhaps intra-monthly) scales may help explain the variance observed in precipitation types over the eastern U.S., particularly in regards to snowfall.

Ultimately, portions of the eastern U.S. experienced widespread significant increases in the frequency of both, rain and snow observations during positive NAO seasons. This may be partially explained by the changes in the synoptic scale patterns, which are closely associated with increases in zonal flow, storm frequency, and ver-

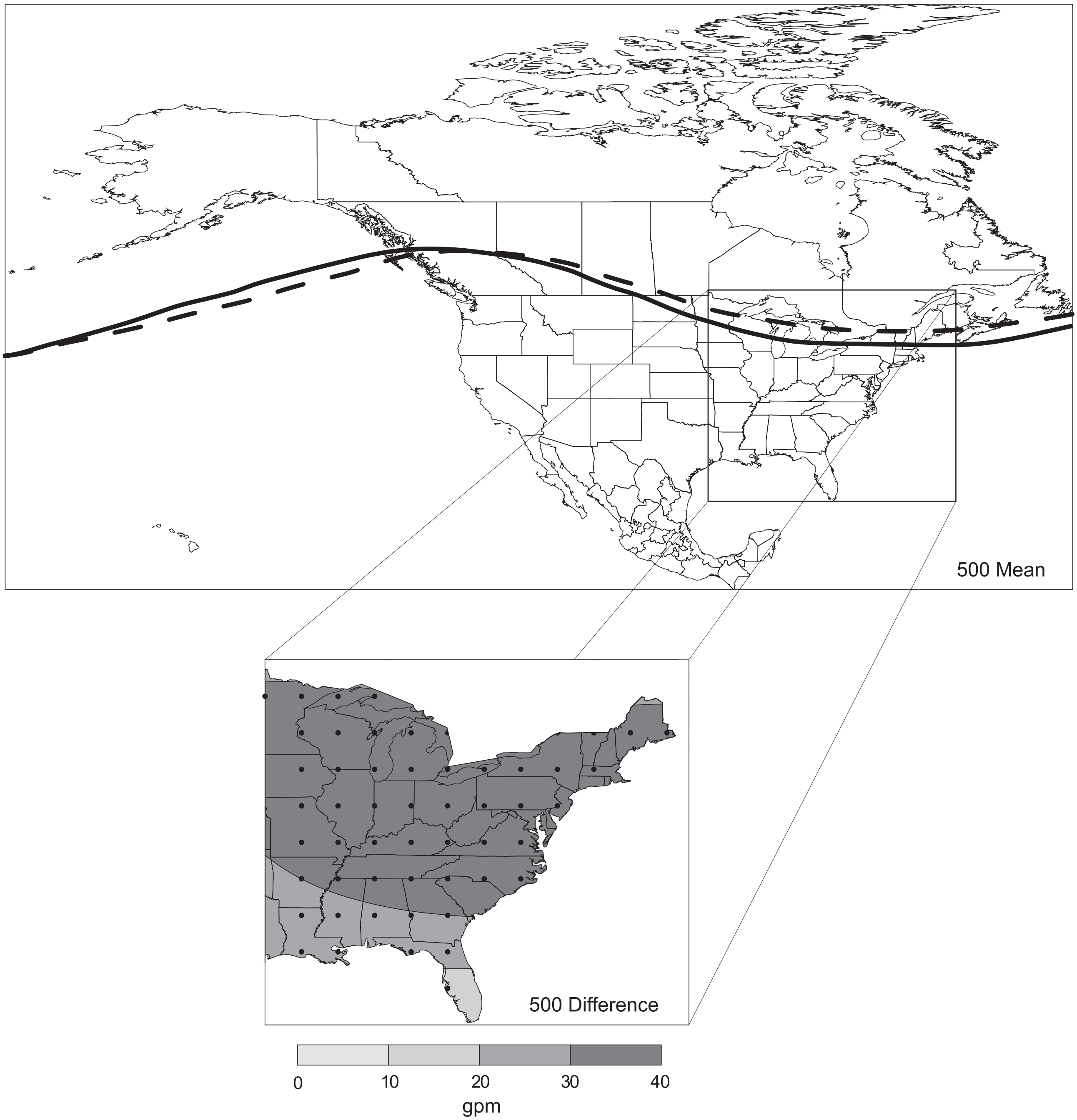

Fig. 11. Large map shows the composite 5400 gpm isoheight for positive (dashed line) and negative (solid line) phases. Inset map shows the height differences (positive minus negative phases) and points represent NCEP grid points with significant difference ($p < 0.05$) between the phases

tical temperature structures across the central and northern portions of the study region. The number and distribution of stations with significant increases in rain are higher and more widespread, respectively, suggesting that changes in the frequency and distribution of rainfall during alternating phases of the NAO are mostly linked to significantly increased temperatures within the atmospheric column across the region. The smaller differences in snow frequency and less widespread stations exhibiting significant differences may be reflective of these relatively warmer columns. However, significantly warmer columns do not necessitate the elimination of increased snow frequencies since the analysis was performed on a seasonal basis. This suggests that changes in the frequency and distribution of snow are more closely tied to changes in overall storm frequency and the timing of those events.

4. Conclusions

The NAO has been shown to have a pronounced effect on temperature and precipitation regimes across the eastern U.S. during the winter season (December–March). The current study highlights an apparent connection between the mean seasonal phase of the NAO and the distribution and frequency of precipitation-type observations. Specifically, the northern tier of the eastern U.S. experienced a statistically significant increase in the occurrence of rainfall observations during positive NAO phases. One explanation is the increase in strength of the subtropical high pressure cell (i.e., Bermuda High), which helps induce relatively stronger southerly flow of warm moist air into the eastern U.S. (Hurrell and Dickson 2004). These thermal and moisture advection patterns, along with increases in the integrated and partial layer thicknesses in the mid- to low troposphere, provide evidence to support an increase in rainfall observations during positive NAO phases. However, significant increases in the occurrence of snowfall were also observed during positive NAO phases. This result may be partially explained by increased storm frequency and the timing of these events as they relate to the poleward shift in the storm track.

Other factors aside from the NAO may contribute to changes in thermal profiles and the resultant seasonal precipitation-type patterns across the eastern U.S. Surface conditions such as snow cover have been shown to be highly correlated ($R^2 = 0.78$) with anomalies in mean monthly temperature (Karl et al. 1993). Namais (1985) suggested that snow cover, or the lack thereof, helps to modify overlying and downstream air temperatures. Therefore, a prevailing storm track superimposed upon an air mass modified by extensive snow cover may increase the probability of frozen precipitation. Another factor includes anomalies in sea surface temperatures (SSTs) and their influence on lower tropospheric thermal profiles. Trenberth and Shea (2005) found that surface temperatures are directly correlated to SSTs. Additionally, Ramos da Silva et al. (2006), using a regional atmospheric model, found positive Atlantic SST anomalies to be positively correlated with temperatures in the lower troposphere (850–700 hPa). The added heat and moisture from warmer SSTs may be advected across parts of the eastern U.S. under favorable large-scale circulation patterns, which may in turn help derive the thermal profile for the production of liquid or frozen precipitation.

During negative NAO phases a combination of a weakened subtropical high, an amplified trough over the eastern U.S., and a blocking pattern over the North Atlantic allows for more cold air intrusions into the southeastern region of the study area (Hurrell 1996; Thompson and Wallace 2000; Bradbury et al. 2002). Moreover, the thermal characteristics of the atmosphere examined in the present study strengthen the case for more frequent negative-phase cold-air intrusions, thus increasing the occurrence in the southern portion of the study area (not shown). Initial analyses showed some areas within the southern portion of the study region experienced increased snow reports during negative NAO phases. Due to the relatively small number of observations compared to the remainder of the study region these stations were removed.

Other studies (e.g., Konrad 1998) have shown that regional temperature anomalies over the eastern U.S. are strongly connected with intra-monthly (20–25 days) fluctuations in other teleconnection indices such as the Pacific/North American pattern. It is unknown whether the seasonal NAO index used in the present study correlates most strongly with the regional patterns of precipitation types relative to shorter time scales. At first glance, the patterns of rainfall frequency appear more strongly correlated to the seasonal NAO index than the patterns of snowfall. Dole (1989) determined that Northern Hemispheric teleconnection patterns often exhibit abrupt transitions between phases that occur on intra-monthly time scales. Therefore, it is possible that the higher frequency of snowfall observations during seasonal positive NAO phases is due to the intra-seasonal timing of storm track displacement.

While the current study highlights significant changes in the regional patterns of the frequency of rain and snow, these results do not necessarily reflect changes in precipitation intensity and amount. A comprehensive understanding of the influence of the NAO on winter precipitation in the eastern U.S. would benefit from the combined results of the present work with an analysis of changes in precipitation amount. Changes in the intensity and amount of each precipitation type may vary as a result of both storm frequency and intensity. At this time, any relationship between the intensity of each precipitation type, storm activity, and the NAO is conjecture. In addition to concerns of intra-season variability in precipitation, the authors plan to address the issue of covariance in precipitation amount and intensity as they relate to changes in NAO phases in a forthcoming study. This information can then be used to improve long-range seasonal forecasts for the facilitation of better awareness, preparation, and possibly reduce the hazardous economic and societal effects in the regions that are greatly influenced by such teleconnections as the NAO.

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