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NORTH AMERICAN WEATHER-TYPE FREQUENCY AND TELECONNECTION INDICES

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ABSTRACT

The impact of teleconnections upon the surface climate has largely been examined via a response in monthly mean temperature or total precipitation. In this paper, a different approach is undertaken, by examining the response of synoptic weather-type frequencies to different teleconnection phases.

For over 330 stations in the USA and Canada, the Spatial Synoptic Classification scheme has classified each day in each station's period of record into one of seven weather-type categories, based on thermal, moisture, and other characteristics. The differences in how frequently these different weather types occur in different phases of the North Atlantic Oscillation (NAO) and Pacific–North American (PNA) teleconnection patterns is assessed, for Canadian stations from 1953 to 1993, and for US stations from 1950 to 1999.

For PNA, a significant shift in the transitional frequency is observed, suggesting changes in storm track. Concomitantly, a large shift in Dry Polar and Moist Tropical frequencies is observed across the continent. Across the West, in +PNA wintertime months far fewer Dry Polar days are observed. Across the eastern USA, these polar intrusions are more common, and Moist Tropical is diminished significantly.

The frequency of the transitional situation is also correlated with NAO phase, with differences as large as a factor of two across much of Canada and the northern USA. In northeastern Canada, there is a large replacement of Moist Polar conditions with Dry Polar conditions during +NAO. Farther south, however, across the eastern USA, both polar weather types occur much less often with +NAO. Although previous research has discovered eastern North American connections to the NAO, this research has shown that the connections often extend into the interior West during much of the year. Particularly strong in the spring, Dry Tropical conditions are much more common with +NAO throughout much of the continent, as far west as the Great Basin.

KEY WORDS: teleconnections; synoptic climatology; North America; Pacific–North American; North Atlantic Oscillation

1. INTRODUCTION

A considerable amount of climatological research has suggested that much of the recent climate variability observed can be related to variability within the atmospheric flow (e.g. Burroughs, 1992; Marshall *et al*., 2001). For example, Palecki and Leathers (1993) have shown that 72% of Northern Hemispheric January temperature variability can be accounted for by the variations in six teleconnection indices. Despite these discoveries, the surface climatological response to teleconnection indices has largely been studied in terms of monthly mean temperature and total precipitation. These two variables, though important, cannot convey fully the day-to-day variability of the surface climate with regard to teleconnection indices. For instance, they cannot adequately describe whether cT or mT penetration varies with teleconnection phase.

To supplement this body of research, a synoptic climatological approach has been undertaken with regard to surface climate response. Using the Spatial Synoptic Classification (SSC; Sheridan, 2002) scheme for North America, the weather-type frequency responses of two of the most important teleconnection indices upon

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North America, the Pacific North American (PNA) pattern and North Atlantic Oscillation (NAO) pattern, are examined in this paper.

1.1. PNA pattern

The PNA is a derived index of mid-tropospheric circulation. It features several 'centres of action' over the North Pacific and North America (Wallace and Gutzler, 1981). These four centres are connected, in that a positive geopotential height anomaly near Hawaii tends to be associated with a positive anomaly near Alberta, and negative anomalies in the Aleutian Low and Florida Panhandle. Positive PNA values (+PNA) are associated with positive anomalies over Hawaii and Alberta, and signify a more meridional flow over the North American continent. In winter, this generally means an amplification of the long-wave western North American ridge and eastern North American trough that occur climatologically. Reverse or negative PNA (−PNA), in turn, is associated with a more zonal flow over the continent, with a damping of the ridge–trough system. A PNA pattern has been shown to be the first principal component of Northern Hemispheric circulation in January (Davis and Benkovic, 1994), and a major component during all times of year except summer (Barnston and Livezey, 1987).

Many connections have been made between PNA and North American climate anomalies. A study by Leathers *et al.* (1991) examined correlations between the PNA index and temperature and precipitation for the continental USA between 1947 and 1982. They found a significant positive correlation between temperature and PNA index for all months through much of the western USA, highest in the northwest; similarly strong negative correlations are found in the eastern USA, highest (as high as $r = -0.7$) in the southeast. The relationships are strongest in winter, although still statistically significant in spring and autumn.

Other studies have examined PNA–precipitation relationships. Leathers *et al.* (1991) observe a tendency for +PNA winters to produce a wetter southeast, a drier Ohio River Valley, and a drier US northwest (Skeeter and Parker, 1985). Henderson and Robinson (1994) show that during −PNA years there are generally fewer wintertime precipitation events and more summertime events in the southeastern USA. Spatial precipitation patterns within the southeastern USA also vary; the enhanced ridge–trough system of +PNA years results in a more active jet stream over Florida, increasing precipitation there while decreasing it farther north.

1.2. NAO

The NAO represents a large-scale shift in atmospheric mass, and is generally observed via anomalies of sea-level pressure. The oscillation is between the two characteristic North Atlantic pressure centres: the Azores (Bermuda) High, centred in the North Atlantic, and the Icelandic Low, centred between Greenland and Iceland (Lamb and Peppler, 1987). A positive value of NAO (+NAO) signifies a stronger than average Icelandic Low and Azores High. Conversely, negative NAO values (−NAO) signify weaker than average pressure centres; in extreme cases, this can lead to a reversal of the typical pattern, with a weak high-pressure centre near Iceland (Moses *et al*., 1987).

During +NAO years, a greater pressure gradient results in increased wind velocity over the Atlantic, and *vice versa* (Dickson and Namias, 1976). A stronger Azores High in +NAO winters has been associated with an anomalous southerly flow over eastern North America. In an early study, Dickson and Namias (1976), examining composites of warm and cold winters in the southeastern USA, discovered that warm (cold) winters occur concomitantly with what would become known as +NAO (−NAO). Yin (1994) noted wetter winters in the southeastern USA during +NAO winters. Yarnal and Leathers (1988) noted an increase in temperature and precipitation in Pennsylvania in +NAO years. Rogers (1984) showed a difference in wintertime temperatures between +NAO and −NAO extremes of 2 to 3 °C across much of the eastern USA between 1943 and 1980s earlier in the 20th century, though, the difference is smaller (1 °C). Significant relationships with western North America have not been discovered for the NAO.

1.3. Synoptic methods

The vast majority of the studies regarding effects of the PNA and NAO above focus on a surface response manifested in average temperature or total precipitation anomalies, often on a time scale of a month or longer. Although valid and useful conclusions can be made from such parameters, they do not provide a full understanding of the effects of teleconnections. For example, the same 'average' month can be comprised of a month of all days with near-average temperature or a month filled with 2 weeks of well-above average temperature and 2 weeks of well-below average temperature. Precipitation anomalies can be even more misleading, as point estimates, particularly during the convective season, are poor estimators of a regional precipitation pattern.

Using a synoptic classification scheme to assess climate variability can provide more and different information. Responses can be expressed in terms of changing weather-type or pressure-pattern frequencies, which can be more enlightening in terms of large-scale precipitation anomalies, or for biometeorological or agricultural purposes. Relatively few synoptic studies have devoted much effort to an assessment of this sort. Most of these studies have focused upon anomalies associated with the southern oscillation (e.g. Fraedrich, 1990; Greene, 1996).

In a study on one of the teleconnections studied in this research, Ye and Leathers (1995) examined the relationship between SSC weather-type anomalies and the PNA index at several stations in the southeastern USA. They discovered a large decrease in Moist Tropical (MT) frequency during strong +PNA winters, offset by modest increases in Moist Moderate (MM) and Moist Polar (MP). Also, the Dry Polar (DP) weather type is present more often during +PNA winters. Ye and Leathers (1995) also examined average temperature of weather types in relation to the PNA index, and discovered that all weather types are cooler during +PNA winters when compared with −PNA winters.

The damage to agriculture caused by hard freezes in Florida has prompted research into the relationship between these freezes and teleconnections. Rogers and Rohli (1991) looked at US Great Plains anticyclones with central pressure of at least 104.5 kPa. Over 80% of recorded Florida freezes have occurred in conjunction with these anticyclones. A connection is drawn between the value of the PNA index and freeze occurrences; during high PNA index years, a greater meridionality to atmospheric flow alters the mean anticyclone trajectory to the south, increasing its effect on Florida. Downton and Miller (1993) discovered the NAO index value to be of significant import as well, with greater negative values leading to greater freeze probabilities for Florida.

1.4. SSC

In this study, the weather-type variability associated with the PNA and NAO is studied with the SSC scheme. A brief description of the SSC is presented here; more detail on its development and methodology may be found in Sheridan (2002). The SSC is a hybrid classification scheme, including manual initial identification of air masses, or weather types, followed by automated classification based on these identifications (Frakes and Yarnal, 1997).

Utilizing solely surface weather data (temperature, dew point, sea-level pressure, wind speed and direction, cloud cover), for each given day in a station's period of record, a classification is made into one of the following weather types.

DP air is largely synonymous with the traditional cP air mass classification. It is characterized by cool or cold dry air, and for much of the continent, northerly winds. Skies typically feature little or no cloud cover. This weather type has its source in northern Canada and Alaska, and is advected into the rest of North America by a cold-core anticyclone that emerges from the source region.

Dry Moderate (DM) air is mild and dry. This weather type has no traditional source region. In the eastern and central portions of North America, DM usually appears with zonal flow aloft, which permits air to traverse the Rocky Mountains, and dry and warm adiabatically. It is analogous to the Pacific air mass identified by Schwartz (1991) and others. In other cases, however, it may reflect a significantly modified DP weather type or a mixture of influence of more than one air mass.

Dry Tropical (DT) air is associated with the hottest and driest conditions, and clear skies. It is analogous to the traditional cT designation. Most commonly, it is present or advected from its source region, the deserts of the southwestern USA and northwestern Mexico. It can also be produced by strong downsloping winds, where rapid compressional heating can produce desert-like conditions.

MP air is a large subset of the mP air mass. Weather conditions are cool, cloudy, and humid, often with light precipitation. This can appear via inland advection of air from the North Pacific or North Atlantic. It can also arise when there is frontal overrunning well to the south, or when a cP air mass acquires moisture while traversing a cool water body.

MM air is warmer and more humid than MP air, and also cloudy. This can form either as a modified mP air mass, or independently, south of MP air nearer a warm front. During summer, it can also occur under mT influence on days with high cloud cover.

MT air is analogous to mT; it arrives in North America either via the Gulf of Mexico or tropical Pacific Ocean. This weather type is warm and very humid, cloudy in winter and partly cloudy in summer. Convective precipitation is quite common in this weather type, especially in summer.

These six weather types comprise the SSC catalogue, along with a transitional (TR) situation, which represents a day in which one air mass yields to another, based on large changes in dew point, pressure, and wind. Mean conditions and frequencies of these weather types can be found at http://sheridan.geog.kent.edu/ssc.html.

2. DATA

The PNA and NAO index data have been obtained from the Climate Prediction Center website (http://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.html). These data are based on rotated principal component analysis (RPCA; Barnston and Livezey, 1987) of 70 kPa geopotential heights. For this data set, RPCA is applied to the monthly mean 70 kPa geopotential height anomalies for the period 1964–94. The top ten patterns (rotations) for each calendar month are determined by examining all of the anomaly maps for the month.

Data for these two teleconnections are available from January 1950. The NAO is available all 12 months of the year. The PNA is unidentified in June and July, when it is not one of the ten leading patterns in North American circulation. For both indices, this research employs the standard practice of defining a positive phase month as one with an index value of at least +1.0, a negative month as one with an index value less than or equal to −1.0, and a neutral month for those values between. By the orthogonal nature of RPCA eigenvectors, the PNA and NAO index values are uncorrelated.

SSC weather-type ‘calendars’ are available at 330 stations in North America from 1948 to present in the USA, and from 1953 to 1993 in Canada. For each day, at each station one of the above weather-type classifications is designated.

3. METHODOLOGY

The assessment of differences in weather-type frequency across the different phases of each teleconnection index is performed using a test on two binomial populations (Ott, 1993); in this case, two frequency values. Each calendar month is examined independently; for each month, the mean frequency of each weather type is calculated for each phase of a teleconnection. For example, the January +PNA DM frequency is calculated as the percentage of all days that are classified as DM over all Januarys in the period of record that have a PNA index of 1.0 or higher. A two-sample difference of proportions test compares the means with the calculation of a z-score:

$$z = \frac{\pi_1 - \pi_2}{\hat{\sigma}}$$

where π_1 and π_2 are the two frequencies, and $\hat{\sigma}$ is

$$\hat{\sigma} = \sqrt{\hat{\pi}(1 - \hat{\pi})\left(\frac{1}{n_1} + \frac{1}{n_2}\right)}$$

where n_1 and n_2 represent the total number of days in the months of the particular phase, and $\hat{\pi}$ is

$$\hat{\pi} = \frac{n_1\pi_1 + n_2\pi_2}{n_1 + n_2}$$

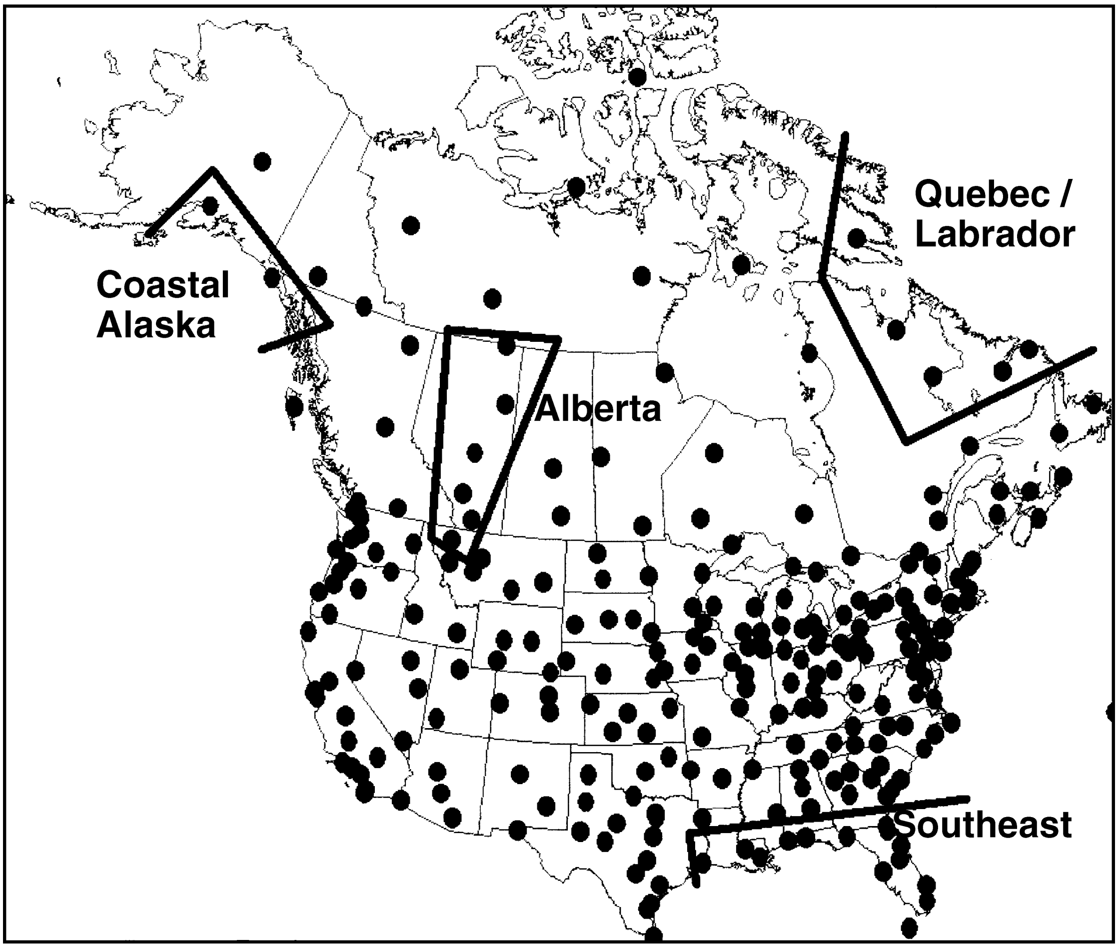

Figure 1. Stations examined in this study. These stations represent all available SSC stations for which at least 30 years of data are available. Boxed areas demarcate the regions mentioned in Figures 4, 5, 6, 9, and 10

This test is not performed if the overall weather-type frequency is under 5%, or if the total number of days of a particular weather type in a phase is fewer than five. Statistically significant differences in this paper are based on the $\alpha = 0.05$ level, unless otherwise noted.

The period examined in this study includes 1950–99 for US stations, and 1953–93 for Canadian stations. Of the 330 available SSC stations, only those with at least 30 years of available data are analysed, a total of 254 stations (Figure 1). Eliminating instances where the weather type is rare, the actual number of stations for which statistical tests are performed for a particular weather-type–month is invariably fewer. The fewest number of stations examined for a particular weather-type–month is 38 for DT in January.

4. THE PNA PATTERN AND WEATHER-TYPE FREQUENCY

The results uncovered in this research strongly support the importance of the upper-level flow pattern that comprises the PNA upon North American surface weather, especially in the winter months. In particular, weather-type frequencies change dramatically across the northwestern quadrant of North America, southern California, and the southeastern USA. In many of these locations, the mean total number of days classified differently between +PNA and −PNA Januarys is greater than ten, one-third of the calendar month (Figure 2).

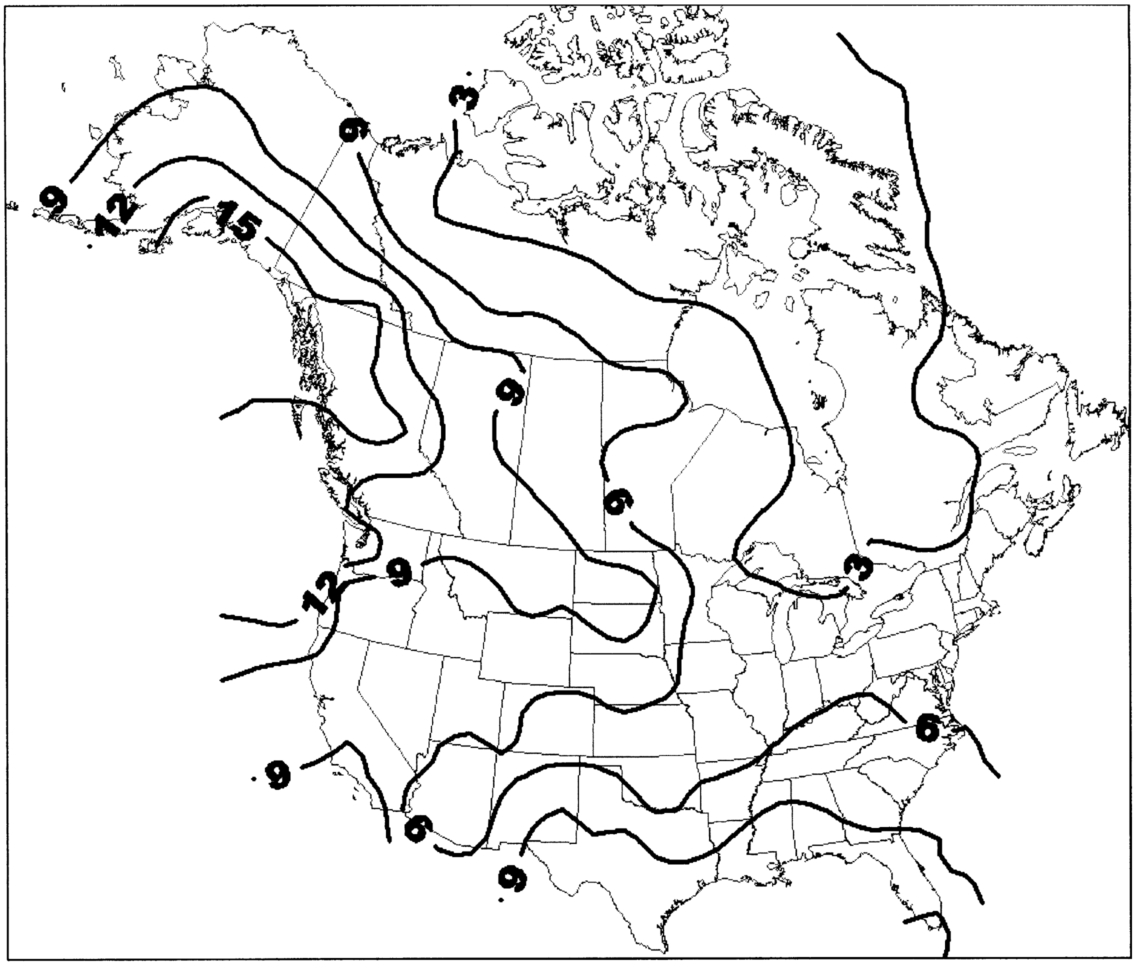

Figure 2. Mean number of days that change weather-type designation between the +PNA and −PNA phase, January

The area of North America least influenced by the PNA pattern appears to be eastern Canada, where fewer than 3 days are classified differently between +PNA and −PNA Januarys.

4.1. Polar weather types (DP, MP)

Of all weather types, the PNA pattern is perhaps best correlated with the frequency of DP. The relationship is strongest in Alaska, western Canada, and the US Northwest, where the correlation is clearly negative (Figure 3). Here, during most months, more than half of the stations examined have statistically significantly fewer DP days with +PNA. At coastal and near-coastal stations, the additional maritime influence is noticeable, as the bulk of the decrease in DP is compensated for by an increase in MP and MM (Figure 4). During January, on average there are 16 DP days in −PNA months along the Alaska and British Columbia coast, but only two in +PNA months. MP and MM together average 10 days and 26 days respectively. The shift is clearly seasonal, with the greatest magnitudes from November through February. As wintertime MP air is around 10 °C warmer and much moister than DP air across much of the far north, this result supports the strong correlation between +PNA and both regional temperature increase (Gan, 1995) and a significant coastal precipitation increase north of 36 °N (Chen *et al*., 1996). During other seasons, PNA phase appears unrelated to polar weather-type frequency along the immediate coast.

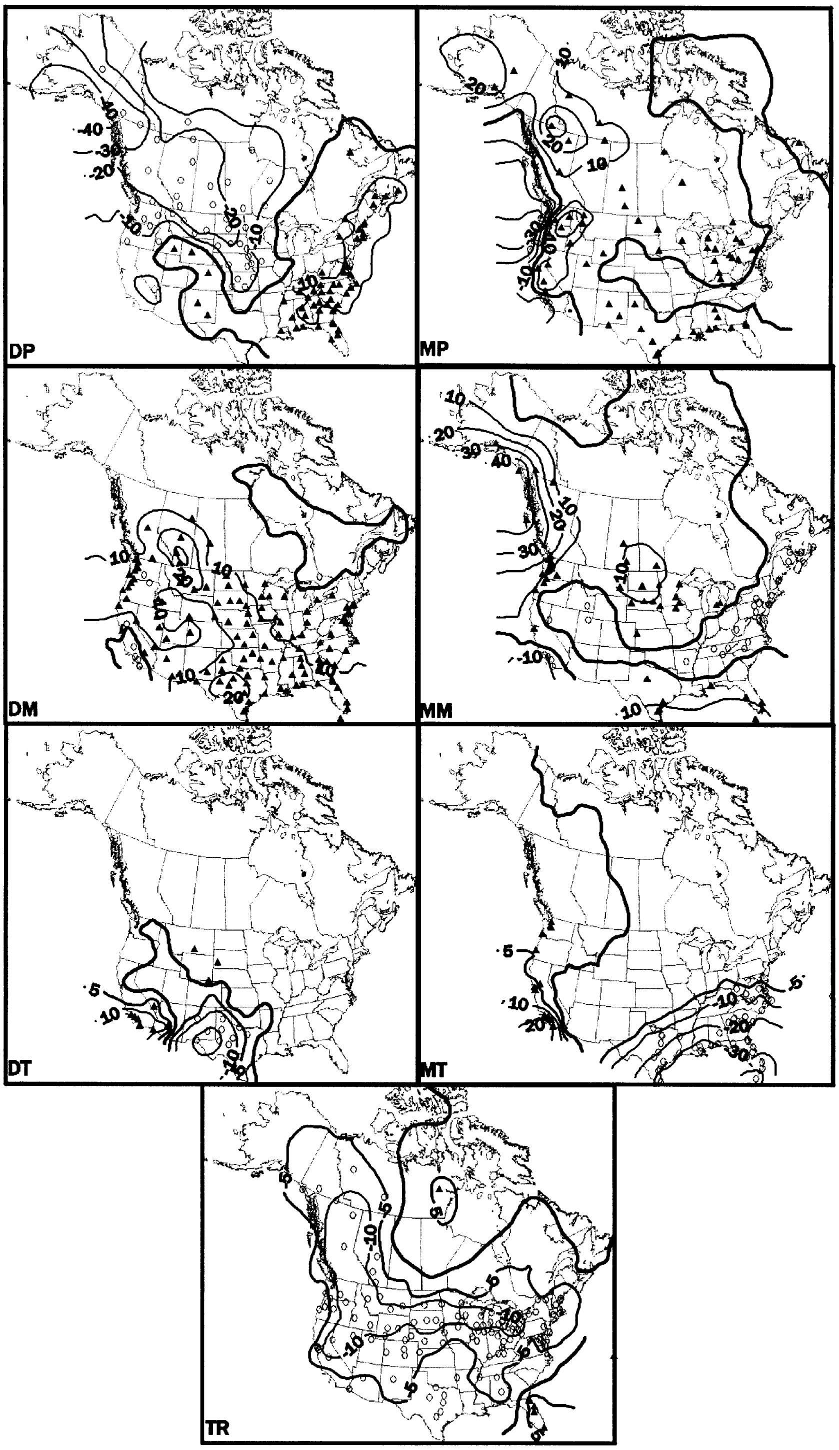

Figure 3. Differences in mean frequency (percentage of days) for each weather type between +PNA and −PNA phases, month of January. Positive contours indicate greater frequency with +PNA. Upward filled triangles indicate locations with statistically significantly greater frequency with +PNA than −PNA; hollow circles indicate a statistically significantly greater frequency with −PNA than +PNA. Isopleths are drawn every 10%, as well as +5 and −5 contours for DT, MT, and TR. The zero contour is thicker

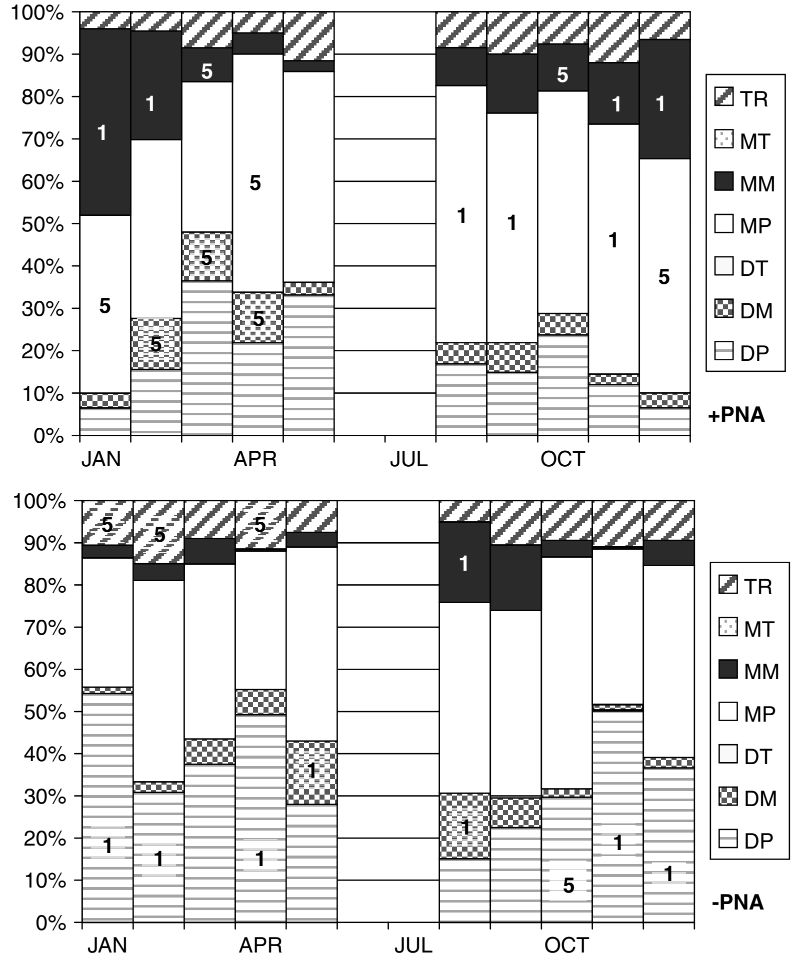

Figure 4. Weather-type frequency histograms by phase of PNA for coastal Alaska (percentage of days in each calendar month). See Figure 1 for stations included. Where there is a statistical difference between the phases, either a '1' or '5' is superimposed upon the phase with the higher frequency. A '1' implies that, for that particular weather-type–month, the difference is significant at $\alpha = 0.01$; a '5' refers to $\alpha = 0.05$

Farther south along the Pacific coast, where DP occurrence becomes much less common, the increased southwesterly flow over the ocean actually serves to diminish MP frequency in +PNA winters; here, rather than bringing in moist air more frequently, warmer moist air replaces cooler moist air. Thus, over Washington, during +PNA months, both MP and DP are replaced by MM; in coastal Oregon and northern California, MP is replaced by MM; and in southern California, MT replaces MP and MM. These differences are found most months of the year, with the highest anomalies during winter. Chen *et al.* (1996) only noted a slight increase in coastal precipitation south of 36 °N during +PNA winter months. Apparently, the increase in precipitation when one moist weather type replaces another is not as significant as when a moist weather type (MP) replaces a dry weather type (DP).

Farther inland, across the Continental Divide, at many locations the differences between PNA phases persist throughout the year. Across Alberta, statistically significant declines in DP with +PNA are observed in all months except February and October (Figure 5). During the winter, the decrease occupies a greater spatial extent, extending southeastward as far as Kansas (Figure 3); in other months, the difference is largely contained within Canada. At these inland locations, the DP decrease with +PNA is mostly balanced by an increase in DM, from adiabatically warmed westerlies.

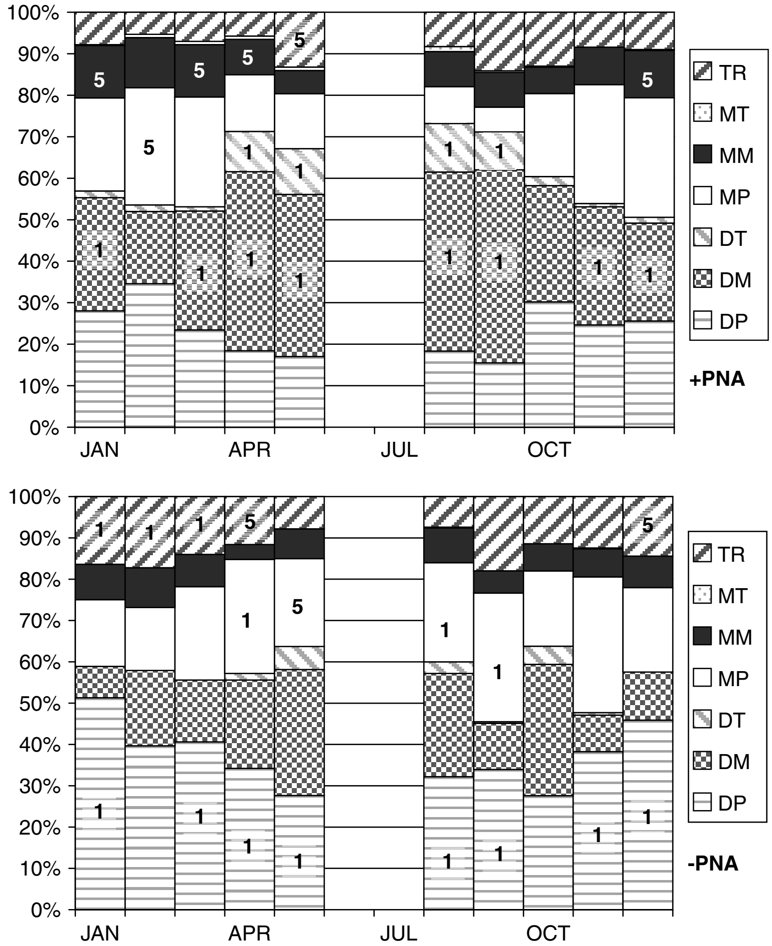

Figure 5. Same as Figure 4, except for Alberta

The increase in northerly flow with +PNA across eastern North America increases both DP and MP frequency from October to February across much of the eastern third of the USA and the Atlantic Provinces. Although absolute differences are not large (between 5 and 15%), given the relative scarcity of these weather types in parts of the southeastern USA, these changes are important (Figure 5). At Athens, GA, for example, DP days are almost twice as common in +PNA winter months as −PNA months. For points farther south, over the Florida peninsula, DP occurrences are almost non-existent unless the PNA phase is positive. These results clearly support the work of Rogers and Rohli (1991), who have related cold-weather-related crop damage in Florida to incidence of +PNA.

4.2. Moderate weather types (DM, MM)

In contrast to the polar weather types described above, the trend in the DM weather type is virtually the same for most of the year continent-wide: more with +PNA (Figure 3). This same trend appears to arise for different reasons, however. Across the western half of North America, stretching southeastward (paralleling the mean upper-level flow with +PNA) from the Yukon to Nebraska, a very sharp increase in DM is found, arising from the increase in adiabatically warmed westerlies. The peak frequency difference is in the lee of the Canadian Rockies, where during +PNA months up to an additional 33% of days are DM, compared with −PNA months (Figure 5). Although the pattern persists for most of the year, no pattern is observed in the months of February and October.

A second area of positive correlation between the PNA index and DM frequency is observed across much of the southeastern and south central USA. In some months, including January (Figure 3), the positive anomaly extends northward to encompass nearly the entire eastern USA. Although the tendency is the same, instead of DM replacing one of the polar weather types, for the most part DM replaces the tropical weather types, particularly MT. With the trough across the eastern half of North America, anomalous northwesterly flow suppresses the influence of the Bermuda High; hence, drier, mild air works into the southeast with much greater frequency. For most inland US stations east of the 100th meridian, a similar increase is observed most months of the year; for locations with proximity to the Gulf of Mexico, however, this pattern disappears during the warm season.

Nearly all significant PNA-related MM frequency anomalies occur west of the Rocky Mountains during the cold season. Along the northern coastlines, from Alaska to Oregon, significantly greater frequencies of MM from 10 to 45% of days with +PNA relative to −PNA are observed. Depending on location, MM displaces DP, MP, or both. This pattern persists from November to March (Figure 4). Farther south along the coast, especially over southern California during early winter, significantly less MM is observed with +PNA (Figure 3). At these locations, the MT weather type increases in occurrence in connection with this decrease. It appears likely that the same mechanism is operating: farther north, the warmer maritime flow is moving days from MP to MM; the same flow farther south moves days from MM to MT.

The observations of increased MM with +PNA across the southeastern and north central USA in January (Figure 3) do not appear significantly during adjacent months.

4.3. Tropical weather types (DT, MT)

Owing to their confinement across the southern USA during much of the wintertime, the tropical weather types display the least spatially extensive relationships with PNA. During the winter, the DT weather type has a dichotomous pattern radiating out from near its source region in the Sonoran Desert: with +PNA, DT frequency increases to the west and decreases to the east. DT more readily moves west in +PNA winter months, as the ridge supports the formation of a high-pressure system over the Great Basin, increasing Santa Ana wind frequency. From November to January, much of southern California receives three times as many DT days in +PNA months compared with −PNA months. The decrease in the westerlies over the south central USA diminishes the influence of the DT weather type at points east of the desert; hence, across New Mexico and Texas, DT largely disappears in +PNA winter months.

Along with DP, MT has one of the strongest correlations with PNA phase, most notably a negative correlation across the southeastern USA. Nearly all stations in the vicinity of the Gulf of Mexico have statistically significant differences during the winter. The anomalous trough associated with +PNA is related to up to 12 fewer MT days in an average January than during a −PNA January (Figure 6). Once winter becomes spring, however, there is still a significant negative correlation, yet the location of the peak difference is shifted. By May, it appears that MT air is certain to penetrate the extreme southeastern USA, regardless of phase; however, PNA phase strongly determines how far inland it penetrates. During spring, peak differences of up to 10 to 15% appear in the Ohio River Valley, where they persist throughout the warm season before migrating southward again in the autumn.

The only other region of significant MT penetration, southern California, shows a positive correlation between MT and PNA phase. Here, as mentioned above, the anomalous southwesterly flow is apparent, as MT frequency increases by up to a factor of five during the winter months. Interestingly, both the eastern and western patterns are broken continent-wide by October, during which there is virtually no discernible trend across the continent.

4.4. Transition (TR)

The +PNA pattern is associated with far fewer TR days during the winter across nearly all of North America, especially across the Rockies and northern tier of the USA (Figure 3). The broad western upper-level ridge contributes to extremely low TR frequencies, often less than 5% in much of the West, suggesting that virtually no sharp changes in weather conditions occur. The primary area with a reversed anomaly is in

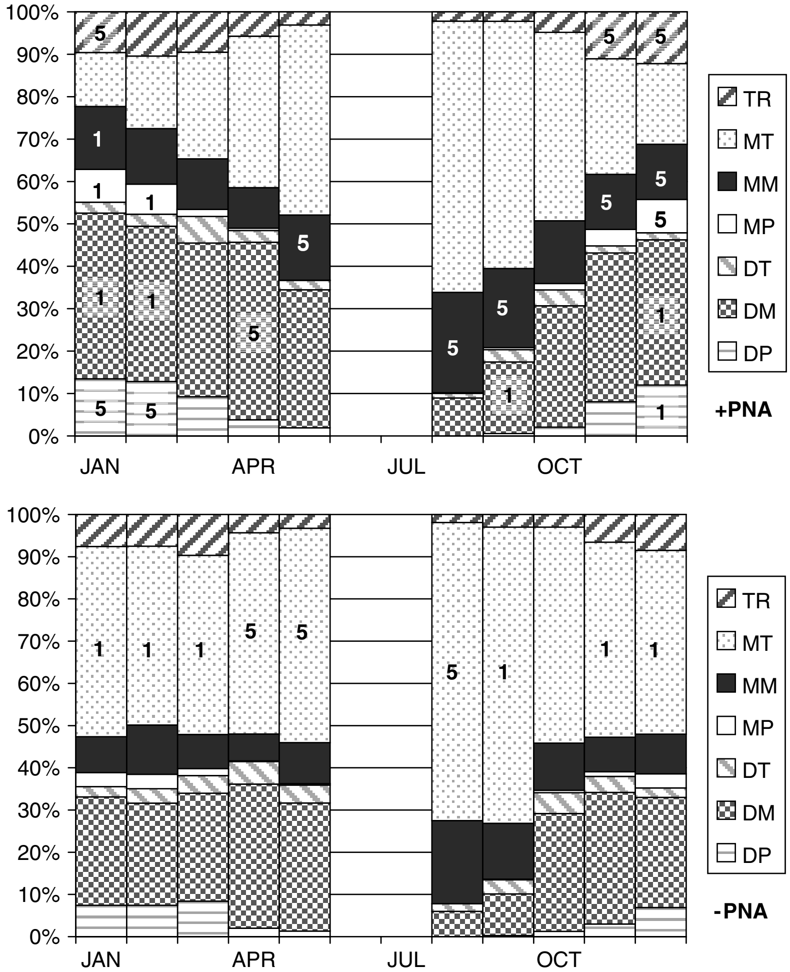

Figure 6. Same as Figure 4, except for the southeast

southern Florida, where the jet stream, and hence cyclonic activity, is much closer than usual during +PNA winter months.

The differences described above persist from December to March with only small changes. During all other seasons, however, the difference between phases is much less; any decreased TR frequencies associated with +PNA are contained within western Canada and the northern US Great Plains.

5. THE NAO AND WEATHER-TYPE FREQUENCY

Over the continent as a whole, although NAO is associated with many significant changes across North America, the number of days that change weather-type classification between phases is not as great as with PNA (Figure 7). Reflecting its definition, peak differences are found along the eastern fringe of the continent, where, on average, at least 6 days are classified differently between +NAO and −NAO. A double maximum occurs, encasing a local minimum over the Atlantic Provinces, likely the transition zone between influence of the Icelandic Low to the Bermuda High. Only over northeastern Canada, however, does the shift exceed 10 days/month between phases.

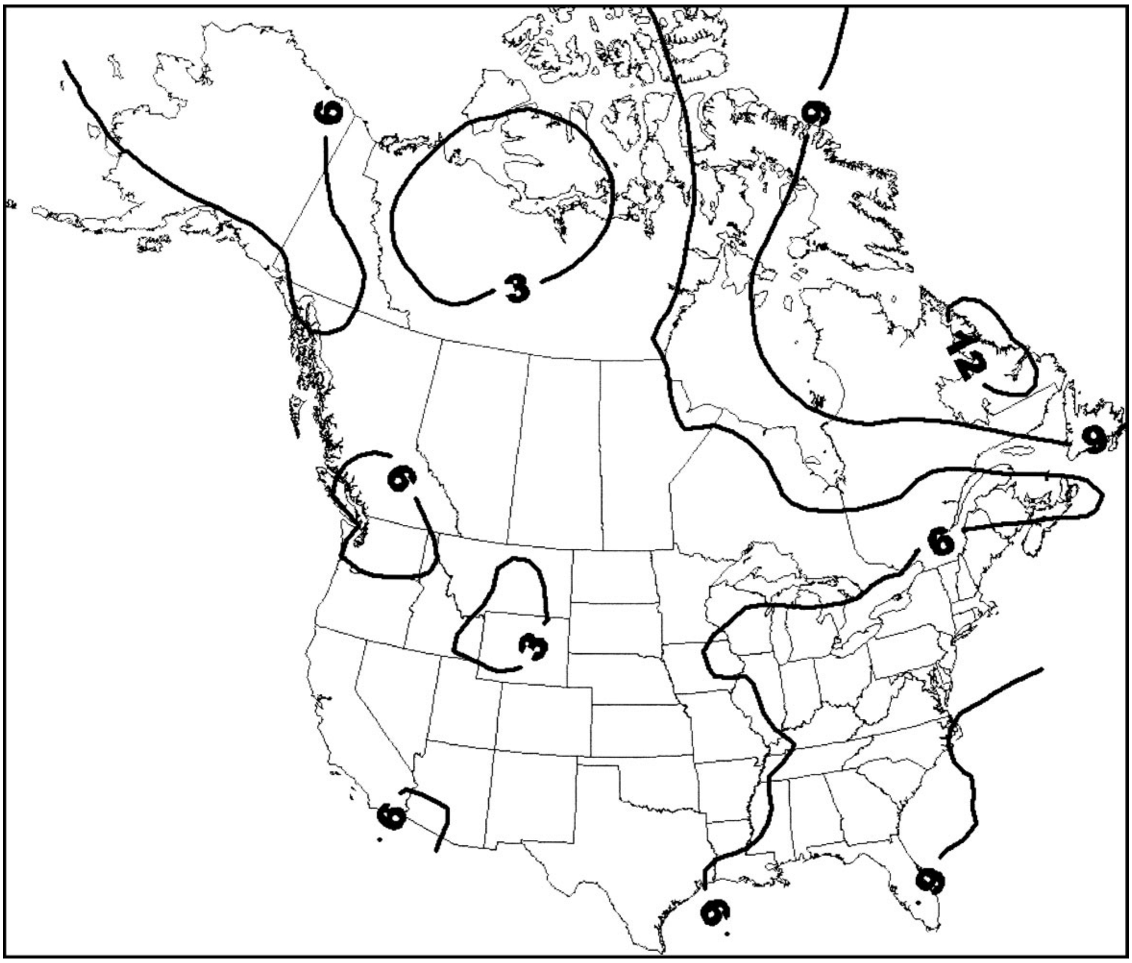

Figure 7. Same as Figure 2, except for differences between +NAO and −NAO

5.1. Polar weather types (DP, MP)

As with PNA, it is the frequency of the polar weather types that varies most with NAO phase (Figure 8). This variability is most noticeable across eastern Canada. Here, where polar weather types dominate year-round, NAO phase is related to a significant shift from DP to MP. Across several stations in northern Quebec, Baffin Island, and Labrador, the increased northerly flow around the western flank of the Icelandic Low dramatically increases DP frequency in +NAO months by over 30% of days. A typical +NAO month in winter contains 24 DP days and only three MP days; for −NAO, the influence is much more similar (14 versus 11). Overall, the shift is strongest in the cold season (Figure 9); at some locations, however, the largest anomalies occur in the transitional season. Although it is intuitive that, in +NAO months, anomalous northerly winds bring in colder, drier air, the transitional peak suggests that NAO phase may also impact upon the freezing of open water, hastening the process during +NAO autumns.

During the brief warm season, there is no relationship between DP frequency and NAO phase in northeastern Canada. This result corroborates the diminished strength of the Icelandic Low in the summer, and the resultant dominance of the NAO index by the strength of the Bermuda High alone.

Farther south along the Atlantic Coast, locations are much more significantly affected by the strength of the Bermuda High than the Icelandic Low. Here, both MP and DP are affected similarly: with the stronger southerly flow around the stronger high of +NAO, both fewer DP and fewer MP days are observed. The absolute phase differences are less than those in Canada, with maximum differences of around 15 to 20% of

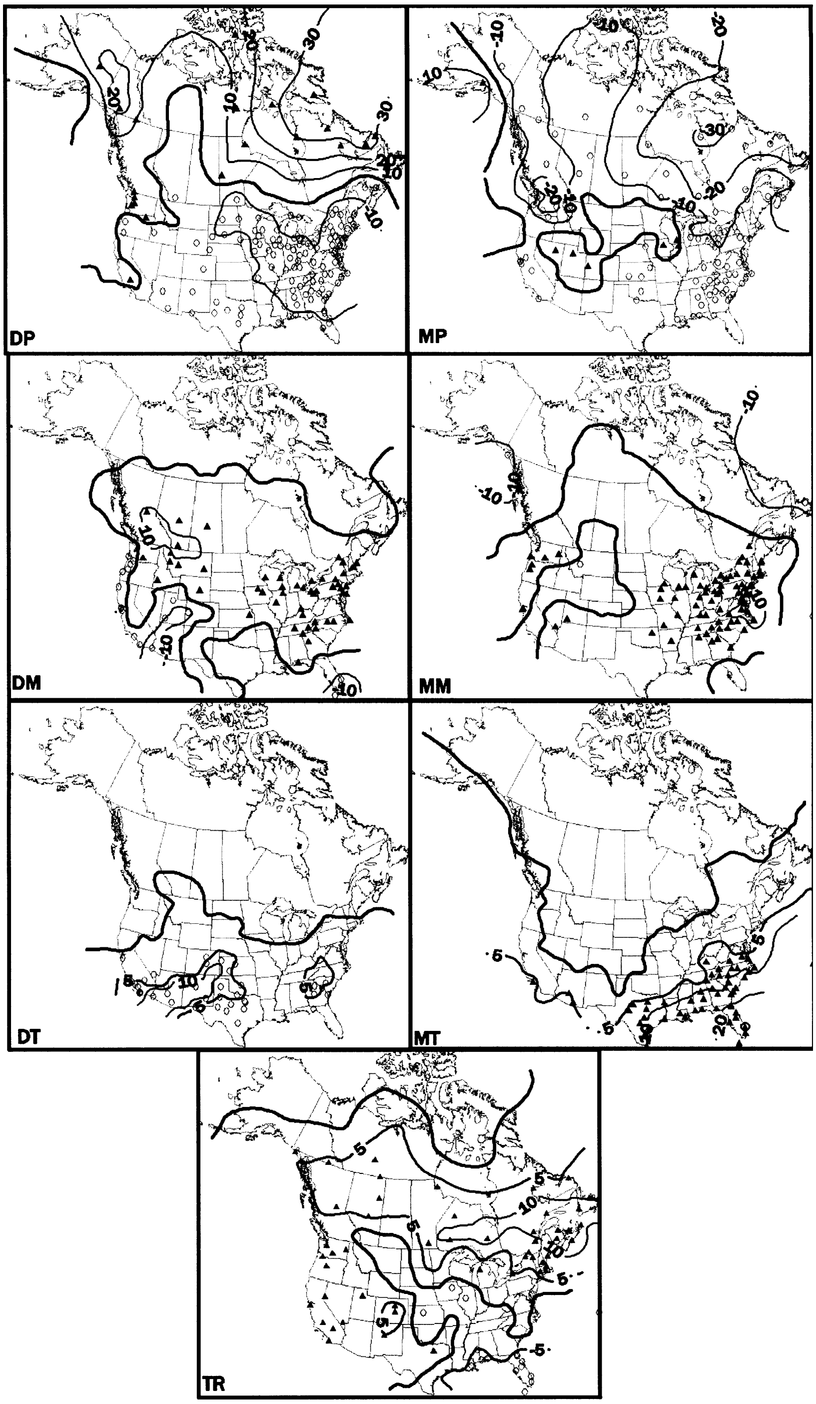

Figure 8. Same as Figure 3, except for differences between +NAO and −NAO

days. The pattern holds consistently over the southeastern USA from December through March (Figure 10), and shifts north during the remainder of the year; by April, the northern tier of the USA is the primary area, and by July the statistically significant differences are found almost exclusively in extreme southeastern Canada. These locations correspond roughly with the southward limit of penetration of DP and MP during different

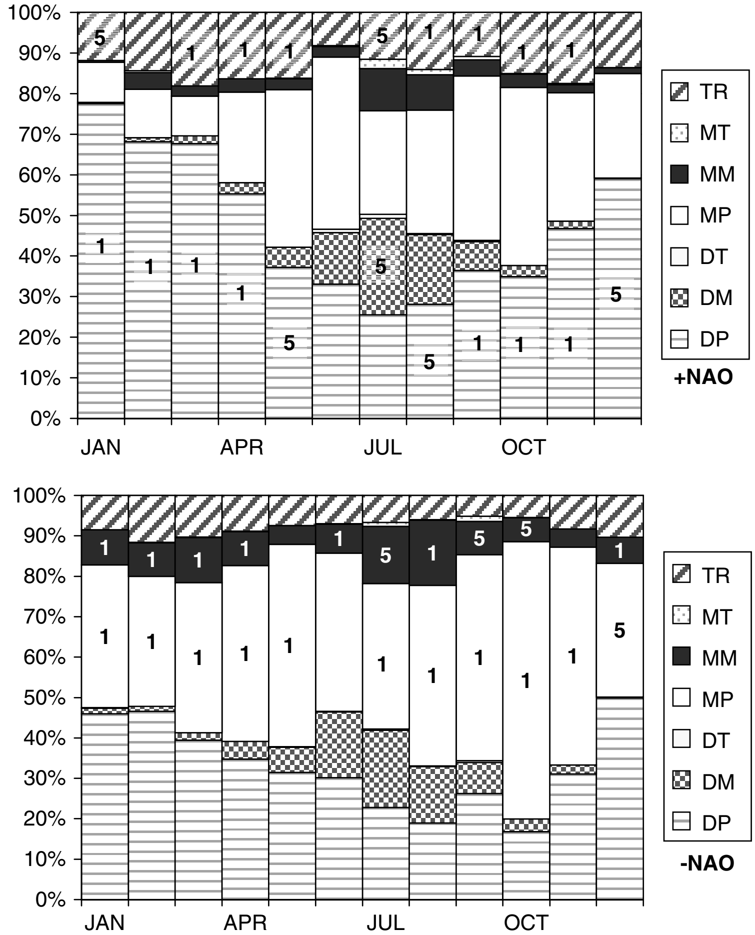

Figure 9. Weather-type frequency histograms by phase of NAO for Quebec and Labrador (percentage of days in each calendar month). Key is the same as in Figure 4

times of the year, and, at all of these locations, +NAO largely prohibits polar weather-type occurrence. These results corroborate the positive relationship between NAO and temperature across the eastern USA discovered by Moses *et al*. (1987).

5.2. Moderate weather types (DM, MM)

The moderate weather types, largely due to their in-between character, show some of the weakest relationships with NAO. During the wintertime, DM frequency is significantly positively correlated with NAO phase across much of the eastern USA, but differences between phases are generally under 10%. This pattern peaks in January. By April the region has no particular pattern, and by July the wintertime trend is reversed, with less DM during the +NAO phase. It appears that, during the winter, the increased pressure gradient between the two pressure centres that comprise the NAO increases the westerly flow upstream across North America during the positive phase. Hence, not only is there anomalous southerly flow (around the Bermuda High) across the eastern USA but westerly flow as well. As summer approaches, however, with the increasing proximity of the Bermuda High, the southerly anomaly becomes paramount with +NAO. Thus, more moist air is brought into the region as MM and MT, decreasing the DM frequency.

Significant relationships between MM frequency and NAO phase are almost entirely contained within the eastern half of North America, where a +NAO month leads to an increased occurrence of MM. During winter,

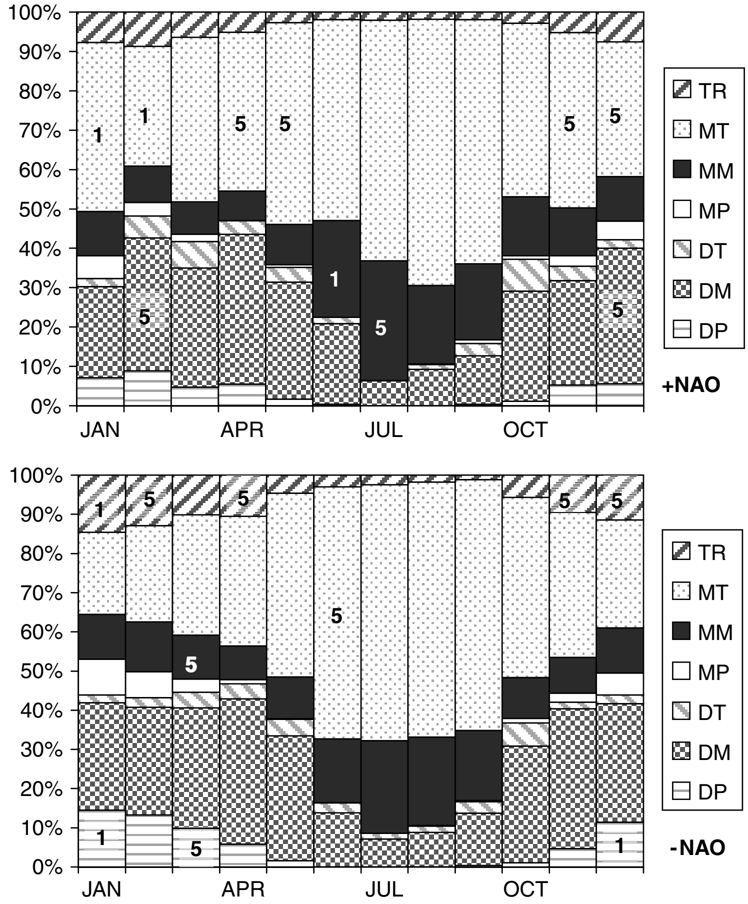

Figure 10. Same as Figure 9, except for the southeast

a large region extending from central Georgia north to the US–Canadian border and west to the Mississippi River has MM on approximately 10% more days during +NAO months compared with −NAO months. Especially farther north, this difference represents a two- to three-fold increase in terms of actual frequency. MM frequency also decreases across portions of northeastern Canada in the wintertime (Figure 9). Although MM is not common across this region, year-round MM air will almost never occur this far north unless the Icelandic Low is weak (−NAO).

5.3. Tropical weather types (DT, MT)

Despite being limited in spatial extent, the tropical weather types contain several significant correlations with NAO. Virtually everywhere that the MT weather type penetrates experiences an increase in frequency during +NAO phase. During the winter, the Gulf Coast is most significantly affected, with MT occurrence during +PNA months up to 25% of days greater than during −NAO months (Figure 8). Outside of winter, these differences diminish (Figure 10); during the warm season, the peak region of MT increase with +NAO is found across the northeastern and north central USA.

DT frequency largely increases with +NAO over much of its potential range as well. During the winter, this is generally contained within the source region and to its immediate east (Figure 8). In spring, however, this region expands to include much of the northern and central USA (Figure 11). This springtime anomaly further suggests that the +NAO increase in westerlies across Europe is also observed over North America, resulting in a greater potential for DT penetration eastward.

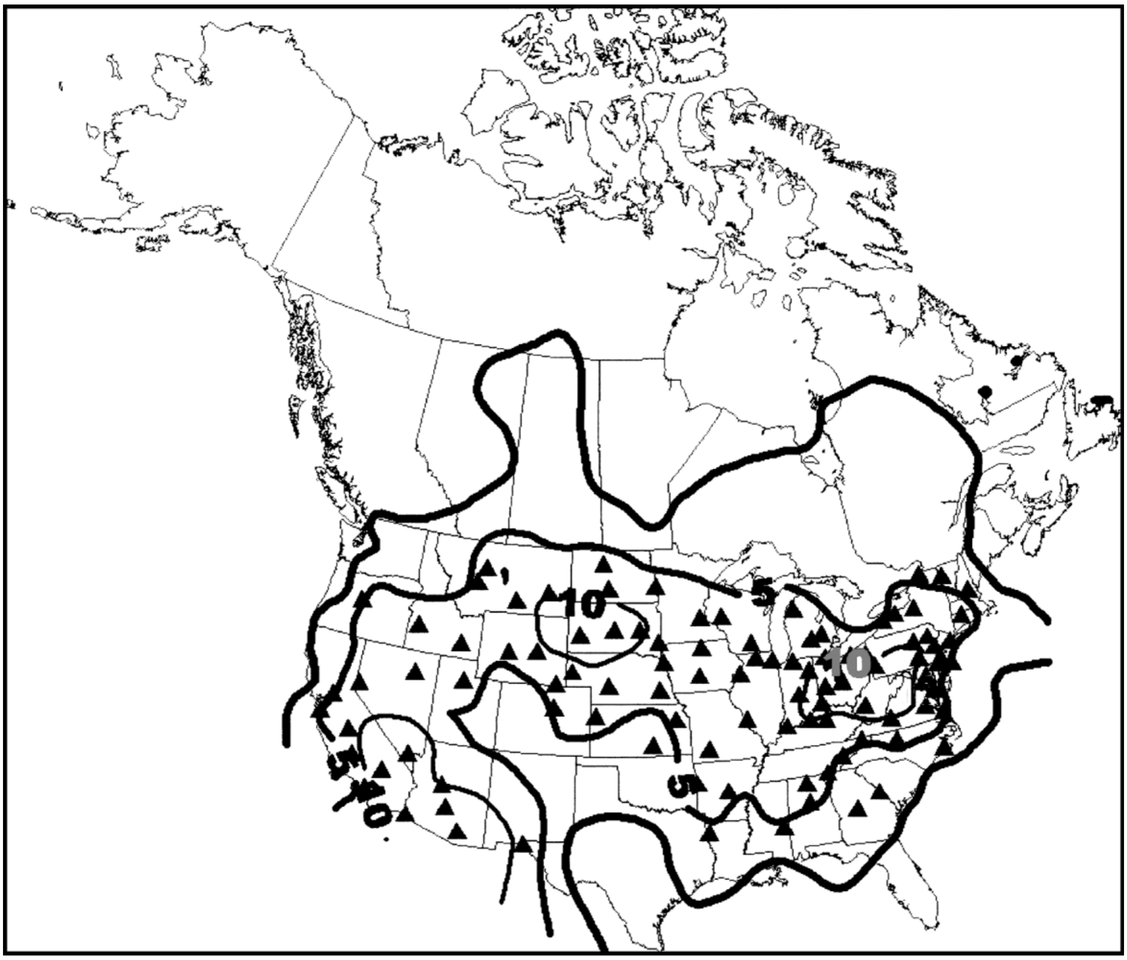

Figure 11. Same as Figure 8, except for the month of April and DT weather type only

During summer, the pattern is much more muted. As mentioned above, during the summer the +NAO is best correlated with a strong Bermuda High, and thus an increase in southerlies. Across much of the south central and southwestern states, these additional southerlies apparently imply greater advection of moisture, depressing the DT frequency and increasing MT. Dallas–Fort Worth, TX, for example, observes 14 DT days in a typical −NAO July, and only four in an average +NAO July.

5.4. Transition (TR)

The largest TR frequency response occurs in northeastern North America, where, year round, +NAO brings a greater number of transitional situations. The peak region is centred almost every month around Labrador and northern Quebec (Figure 9), where most non-summer months show differences exceeding 10% of days, a near doubling of the TR frequency. During winter, an increase in the westerlies could be responsible for this increase. During summer, where the pattern is still observed, though with a lesser magnitude, it suggests that a stronger Bermuda High could steer a greater number of systems to the north than during +NAO. In some months, notably January (Figure 8) and April, this difference stretches across the entire continent, centred between 45 and 50 °N. During other months, however, all significant differences are found in the eastern half of Canada and the adjacent areas of the northeastern USA.

The southeastern USA experiences fewer transitional situations with +NAO (Figure 10), suggesting the stronger subtropical high steers storms away from the region.

6. SUMMARY

In this paper, a clear relationship between frequencies of different weather types and both the PNA and NAO teleconnection patterns has been established. For both of these indices, some expected signatures were uncovered, along with some previously undiscovered results.

The PNA pattern is observed to affect nearly the entire North American continent, save northeastern Canada. The most extensive influence is along the northern Pacific coast, where as many as 16 days in a typical January are classified differently by the SSC depending upon PNA phase. A large shift in transition frequencies is observed, with fewer transitions over the interior west of North America and more over the extreme southeastern USA, with +PNA. At some western stations, winter TR frequencies fall as low as 0.5 days/month during +PNA. Concomitant with these shifts are changes in the penetration of different weather types. A large shift in DP and MT frequencies is observed across the continent. Across the West, in +PNA wintertime months far fewer DP days are observed, as much more Pacific air is advected inland. Across the eastern USA, these polar intrusions are more common, and MT is diminished significantly in the +PNA phase. The direction of penetration of DT is also correlated with PNA phase: in −PNA winters, DT more commonly penetrates eastward into Texas, whereas in +PNA winters, westward penetration into California is much more common. The relationships uncovered in this work largely substantiate previous work on temperature anomalies (e.g. Leathers *et al*., 1991) and precipitation pattern anomalies (e.g. Henderson and Robinson, 1994).

Aside from the changes in TR frequency, a change in the variability of weather types is also noticeable, especially in the southeastern USA. Many locations near the seasonal limits of DP penetration in the eastern USA only observe DP air during +PNA phase. At Key West, FL, during −PNA months the zonal flow inhibits much mid-latitude cyclonic activity from reaching the area; as a result, on average, 23 MT days are observed, with only five DM and two MM days. During +PNA months, however, the continental influence becomes more noticeable, as DM is the most common weather type, with 12 days on average, accompanied by eight MM but only seven MT days. Once again, using the synoptic methodology, changes are noticed on nearly half of the days within a given month. Once away from the Gulf Coast, however, although similar patterns are observed, the number of different days decreases rapidly, to six per month from Oklahoma to Virginia.

Outside of the cold season, the effects of PNA phase are smaller both in terms of scale and magnitude, with few stations showing changes of more than 6 days/month. The only exception is in the lee of the Canadian Rockies, where, throughout much of the year, changes of over 10 days/month are observed. In Edmonton, Alberta, for example, in a +PNA August there are 13 DM days and only nine polar (DP and MP) days. A −PNA August brings, on average, 22 polar days, but only four DM days, clearly demonstrating a marked shift in dominance from westerlies to northerlies.

For the NAO, different connections have been observed. Two peak areas of influence are observed: northeastern Canada, under the influence of the Icelandic Low, and the eastern USA, under the influence of the Bermuda High. During +NAO months, the increased baroclinicity is associated with a much higher TR frequency, sometimes by a factor of two, across much of Canada and the extreme northern tier of the USA, right in between the principal areas of weather-type change described above.

In northeastern Canada, with +NAO conditions there is a large replacement of MP with the DP weather type, in all seasons except the summer. Farther south, across the eastern USA, both polar weather types occur much less often with +NAO, replaced by the moderate and tropical weather types. Although previous research has discovered eastern North American connections to the NAO, this research has shown that the connections often extend into the interior West during much of the year. Particularly strong in the spring, the polar weather types are replaced by DM and DT in much of the interior US West.

Across the southern USA, as with +PNA, the −NAO phase is also generally associated with much more variable weather, not merely negative temperature anomalies. At New Orleans, LA, for example, 11 MT days occur in an average +NAO January. In −NAO Januarys, the mean number of MT days is only three, with the difference compensated for by increases in DM, MM, MP, and TR.

Frequency changes in other seasons are generally less pronounced, despite their statistical significance. The increase in DT in +NAO spring months is particularly interesting, as, although it affects much of the continent, it does not translate to any larger pattern shift. At Newark, NJ, for example, there are, on average, four DT days in an +NAO April and only one in an −NAO April. This is balanced by a decrease in DP days from seven to four, with no other weather-type changes of greater than 1 day.

One final interesting anomaly noticed at many stations with both PNA and NAO is the 'October disconnection', whereby October anomalies are, in many cases, the inverse of those of adjacent months. Although they generally are not statistically significant, they do not follow the pattern of adjacent months. Whereas several studies (e.g. Leathers *et al*., 1991) have shown weaker connections in October than other months, none has shown the inverse relationship frequency observed in this research. It is difficult to explain a causal mechanism for this particular observation.

It should also be noted that this research examined the weather-type response to El Niño–southern oscillation (ENSO) as well, although the results are not presented. As a +PNA pattern is often observed as a response to a warm event (Leathers, 1994), the results with ENSO are therefore quite similar in direction to those discovered with PNA. However, there is considerable variability in how ENSO manifests itself in the circulation over North America (e.g. Keables, 1992), principally due to the variability in the spatial pattern of Pacific sea-surface temperature anomalies (Schoner and Nicholson, 1989). This circulation variability, in general, results in weather-type phase-related (warm event versus cold event) differences that are approximately half of those discovered with PNA.

Future work is planned on focusing upon the determination of how much of the trends observed in SSC weather types (Kalkstein *et al*., 1998) can be attributed to the variability of the teleconnections examined here, compared with other changes, including snow-cover variability, instrumentation changes, urbanization, or anthropogenic causes. As the RPCA method of deriving index values assures that NAO and PNA are uncorrelated, an examination of the combined effects of the two indices could prove useful as well. Values of PNA and NAO may be evaluated on a smaller time scale, perhaps on a daily basis, to attempt to clarify further the importance of upper-level circulation upon surface weather types, and any variability therein.

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REFERENCES

Barnston AG, Livezey RE. 1987. Classification, seasonality, and persistence of low-frequency atmospheric circulation patterns. *Monthly Weather Review* **115**: 1083–1126.

Burroughs WJ. 1992. *Weather Cycles: Real or Imaginary?* Cambridge University Press: Cambridge.

Chen T-C, Chen J-M, Wilke CK. 1996. Interdecadal variation in U.S. Pacific Coast precipitation over the past four decades. *Bulletin of the American Meteorological Society* **77**: 1197–1205.

Davis RE, Benkovic SR. 1994. Spatial and temporal variations of the January circumpolar vortex over the Northern Hemisphere. *International Journal of Climatology* **14**: 415–428.

Dickson RR, Namias J. 1976. North American influences on the circulation and climate of the North Atlantic sector. *Monthly Weather Review* **104**: 1255–1265.

Downton MW, Miller KA. 1993. The freeze risk to Florida citrus. Part II: temperature variability and circulation patterns. *Journal of Climate* **6**: 364–372.

Fraedrich K. 1990. European Grosswetter during the warm and cold extremes of the El Niño/southern oscillation. *International Journal of Climatology* **10**: 21–31.

Frakes B, Yarnal B. 1997. A procedure for blending manual and correlation-based synoptic classifications. *International Journal of Climatology* **17**: 1381–1396.

Gan TY. 1995. Trends in air temperature and precipitation for Canada and northeastern USA. *International Journal of Climatology* **15**: 1115–1134.

Greene JS. 1996. A synoptic climatological analysis of summertime precipitation intensity in the eastern United States. *Physical Geography* **17**: 401–418.

Henderson KG, Robinson PJ. 1994. Relationships between the Pacific/North American teleconnection patterns and precipitation events in the south-eastern USA. *International Journal of Climatology* **14**: 307–323.

Kalkstein LS, Sheridan SC, Greybeal DY. 1998. A determination of character and frequency changes in air masses using a spatial synoptic classification. *International Journal of Climatology* **18**: 1223–1236.
Keables MJ. 1992. Spatial variability of midtropospheric circulation patterns and associated surface climate in the United States during ENSO winters. *Physical Geography* **13**: 331–348.
Lamb PJ, Peppler RA. 1987. North Atlantic Oscillation: concept and an application. *Bulletin of the American Meteorological Society* **68**: 1218–1225.
Leathers DJ. 1994. Global meteorological teleconnections associated with El Niño/Southern oscillation events. In *The Oceans: Physical–Chemical Dynamics and Human Impact*, Majumdar SK, Miller EW, Forbes GS, Schmalz RF, Panah AA (eds). Pennsylvania Academy of Science: Philadelphia; 157–170.
Leathers DJ, Yarnal B, Palecki MA. 1991. The Pacific/North American teleconnection pattern and United States climate. Part I: regional temperature and precipitation associations. *Journal of Climate* **4**: 517–527.
Marshall J, Kushnir Y, Battisti D, Chang P, Czaja A, Dickson R, Hurrell J, McCartney M, Saravanan R, Visbeck M. 2001. North Atlantic climate variability: phenomena, impacts, and mechanisms. *International Journal of Climatology* **21**: 1863–1898.
Moses T, Kiladis GN, Diaz HF, Barry RG. 1987. Characteristics and frequency of reversals in mean sea level pressures in the North Atlantic sector and their relationship to long term temperature trends. *Journal of Climatology* **7**: 13–30.
Ott RL. 1993. *An Introduction to Statistical Methods and Data Analysis*, 4th edition. Duxbury Press: Belmont, CA.
Palecki MA, Leathers DJ. 1993. Northern Hemisphere extratropical circulation anomalies and recent January land surface temperature trends. *Geophysical Research Letters* **20**: 819–822.
Rogers JC. 1984. The association between the North Atlantic Oscillation and the southern oscillation in the Northern Hemisphere. *Monthly Weather Review* **112**: 1999–2015.
Rogers JC, Rohli RV. 1991. Florida citrus freezes and polar anticyclones in the Great Plains. *Journal of Climate* **4**: 1103–1113.
Schonher T, Nicholson SE. 1989. The relationship between California rainfall and ENSO events. *Journal of Climate* **2**: 1258–1269.
Schwartz MD. 1991. An integrated approach to air mass classification in the North Central United States. *Professional Geographer* **43**: 77–91.
Sheridan SC. 2002. The redevelopment of a weather-type classification scheme for North America. *International Journal of Climatology* **21**: 51–68.
Skeeter BR, Parker AJ. 1985. Synoptic control of regional temperature trends in the conterminous United States between 1949 and 1981. *Physical Geography* **6**: 69–84.
Wallace JM, Gutzler DS. 1981. Teleconnections in the geopotential height field during the Northern Hemisphere winter. *Monthly Weather Review* **109**: 784–812.
Yarnal B, Leathers DJ. 1988. Relationships between interdecadal and interannual climatic variations and their effect on Pennsylvania climate. *Annals of the Association of American Geographers* **78**: 624–641.
Ye H, Leathers DJ. 1995. The association between the Pacific/North American teleconnection patterns and air masses in the southeastern United States. *Middle States Geographer* **28**: 18–24.
Yin Z-Y. 1994. Moisture conditions in the south-eastern USA and teleconnection patterns. *International Journal of Climatology* **14**: 947–967.

