Decadal-Scale Trends in Transition Weather Types and Atmospheric Circulation

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OVERVIEW

The application of synoptic-scale weather classification systems to studies of the impact of climate change continues to emerge as a method to investigate regional and global alterations to the Earth's atmosphere. The Spatial Synoptic Classification (SSC, Sheridan 2002) is a semi-automated air mass/weather-type identification system that has been applied in a variety of climatic and biometeorological investigations. The system, originally developed by Kalkstein et al. (1996) and later improved by Sheridan (2002), categorizes daily weather into one of seven discrete types: six air masses and one transition category, the latter of which attempts to identify days with a distinct change from one weather type to another. The SSC remains operational, and categorizes daily weather for hundreds of stations across North America and Europe. For many stations, the record dates from 1949 through 2007. This work will investigate two major questions related to changes in the synoptic-scale climate of the United States through study of the SSC's transition category:

1. What weather does the transition category represent?

Each of the six air mass types of the SSC can be considered a cohesive and distinct unit, whereas the transition category cannot. For example, cool and damp conditions are experienced throughout a Moist Polar air mass. The transition category, however, ambiguously identifies many meteorological patterns associated with changes in the weather. While frontal passages are likely easily captured by the transition category, I plan to investigate what the complete set of days identified as transitions represents. In previous and ongoing research (e.g., Knight et al., 2008), the transition category is often excluded from some analyses because it potentially represents a suite of differing meteorological conditions. Accordingly, I will identify subsets of the transition weather type that may include frontal passages and other synoptic patterns where a significant change in the weather occurs during a day. In doing so, I will learn whether the transition category acts as a “catch-all” for the SSC, labeling days that are not easily classified as one of the six air mass types as a transition.

2. Why is a decreasing trend in transition frequency observed at many stations across the United States?

Kalkstein (1998), Sheridan (2000), and Knight et al. (2008) report a significant decrease in transition frequency at many stations, particularly in the western United States, over the last half century. My goal to place the observed decrease in days identified as transitions in the context of the broader climate picture.

In investigating these two questions, my major contributions will be as follows:

1. A circulation-based assessment of the ability of the SSC to identify transitional weather types,

2. Development of sub-classifications of the transition type for a network of stations, a useable product in future climate study, and

3. Improved understanding of climate change over the continental United States for the past several decades by identifying the climatic variables that are driving the transition decline.

The thesis is comprised of five major sections. In the introduction, I detail the history of the Spatial Synoptic Classification and outline potentially related circulation changes. Part II is intended to serve as a manuscript for submission to *Climate Research* early this summer. Parts III and IV cover portions of the work related to the functionality of the Spatial Synoptic Classification, and Part V offers suggestions for improvements upon my results and closing thoughts on their significance. A full-scale literature review, from which the shorter version in Part I is derived, is included in an appendix.

I. INTRODUCTION

I.1 Study Motivation

In study of relationships between the atmosphere and surface environment, synoptic-scale air mass and weather-type approaches are often considered favorable because of their incorporation of multiple weather elements into distinct classifications. The applications of varying synoptic-scale classification systems include: air quality (Kalkstein and Corrigan, 1986; Davis 1991; Power et al., 2006; Rainham et al., 2005), human health (Dolney and Sheridan, 2006; Morabito et al., 2006), long-term climate change (Kalkstein et al. 1990), agricultural yield (Dilley, 1992), glacial change (Brazel et al., 1992), the urban heat island effect (Brazel et al., 2007; Dixon and Mote, 2003), plant growth (Girardin et al., 2005; Senkbeil and Sheridan, 2007), and snow cover (Leathers et al., 2004; Leathers et al., 2002). The SSC (Sheridan 2002) represents one such system increasingly used in environmental study.

Days on which the weather transitions from one air mass to the next merit attention because of their potential impact on surface systems (e.g., precipitation associated with frontal passage). More importantly, study of transitions between air masses has the potential to reveal an aspect of climate change not well-examined to date. Recent SSC research has identified increasing frequencies of warm, moist, air masses in the United States over approximately the past five decades (Knight et al., 2008). Such results suggest decadal-scale changes to the United States climate. However, SSC climatologies do not explicitly identify specific, dynamical changes in the overall atmospheric circulation. As such, the development of a more-detailed transition climatology and subsequent analysis has potential to describe and quantify changes in the circulation. Further, as the SSC incorporates a suite of variables, the analysis should reveal more than is possible through study of individual meteorological elements. Therefore, the completion of this work may provide a new perspective on climate change.

I.2 The Spatial Synoptic Classification (SSC)

The original SSC (Kalkstein et al., 1996) represented an improvement over a previous air-mass identification method by the authors, the Temporal Synoptic Index (TSI, Kalkstein et al., 1986; Kalkstein et al., 1987; Kalkstein et al., 1989; Kalkstein et al., 1990). The original TSI used Ward's hierarchical agglomerative clustering method to separate daily meteorological weather data into homogeneous groups, or synoptic types (Kalkstein et al., 1987). The system, however, was unable to identify and evaluate air masses over larger regions, such as the domain of the United States (Sheridan 2002). The SSC was designed to meet an existing need for the creation of a simple, automated continental-scale classification method. Three separate methods were considered for use in the procedure to distinguish between air mass types. Discriminant analysis was found to be most suitable for such a procedure with predetermined groups, preferable to agglomerative clustering, in which group properties are not predetermined, and non-hierarchical clustering, in which the group properties change through an iterative procedure. The nomenclature "air mass" was applied instead of "weather types," which had historically referred to identification systems more related to wind/pressure fields in studies of atmospheric transport. Here, the thermal and moisture properties of the air mass were considered most important. As mentioned previously, many of the early air-mass identification systems focused on the geographic source regions to designate air mass types. The SSC differs from these approaches by instead emphasizing the surface meteorological characteristics at particular locations, rather than source region alone, as the surface characteristics most heavily impact environmental response (e.g., Yarnal 1993).

Critical in the SSC procedure is the identification of "seed days," actual days in a first-order weather station's history that are considered best-representative of the weather a particular air mass should exemplify at a station. Often more than 30 seed days are used to evaluate the mean characteristics of each air mass. Seed day selection criteria also ensured that attributes of air masses between adjacent sites would not vary considerably. Although many components of the SSC are automated, this particular step relies on subjective determination on what weather is most representative of each air mass. By comparing preliminary results with weather maps, the authors concluded that 12 variables provided the best set of meteorological data to use in the seed day procedure: 6-hourly temperature and dew point temperature, mean daily cloud cover and sea-level pressure, and diurnal air temperature and dew point temperature range. The data considered reflect the importance of the thermal and moisture properties of the air masses compared to cloud cover and pressure. After seed days were identified for each of the six air mass types in the SSC, discriminant function analysis matched remaining days in the record to the weather characteristics and air mass that they most closely resembled. A separate discriminant function was employed to identify transition days that considered the diurnal changes to dew point and sea-level pressure. The result of the procedure is an SSC calendar at each station that allows for examination of air mass changes over both time and space.

Kalkstein et al. (1998) used the SSC to evaluate air mass frequency patterns and changes for 100 cities across the United States for the period 1948–1993. For example, the dry moderate type is most common in the Western Plains in summer and winter months, and the dry tropical type most often occurs across the Southwest. The average SSC air mass climatologies for summer (JJA) and winter (DJF) are shown in Figures 1 and 2.

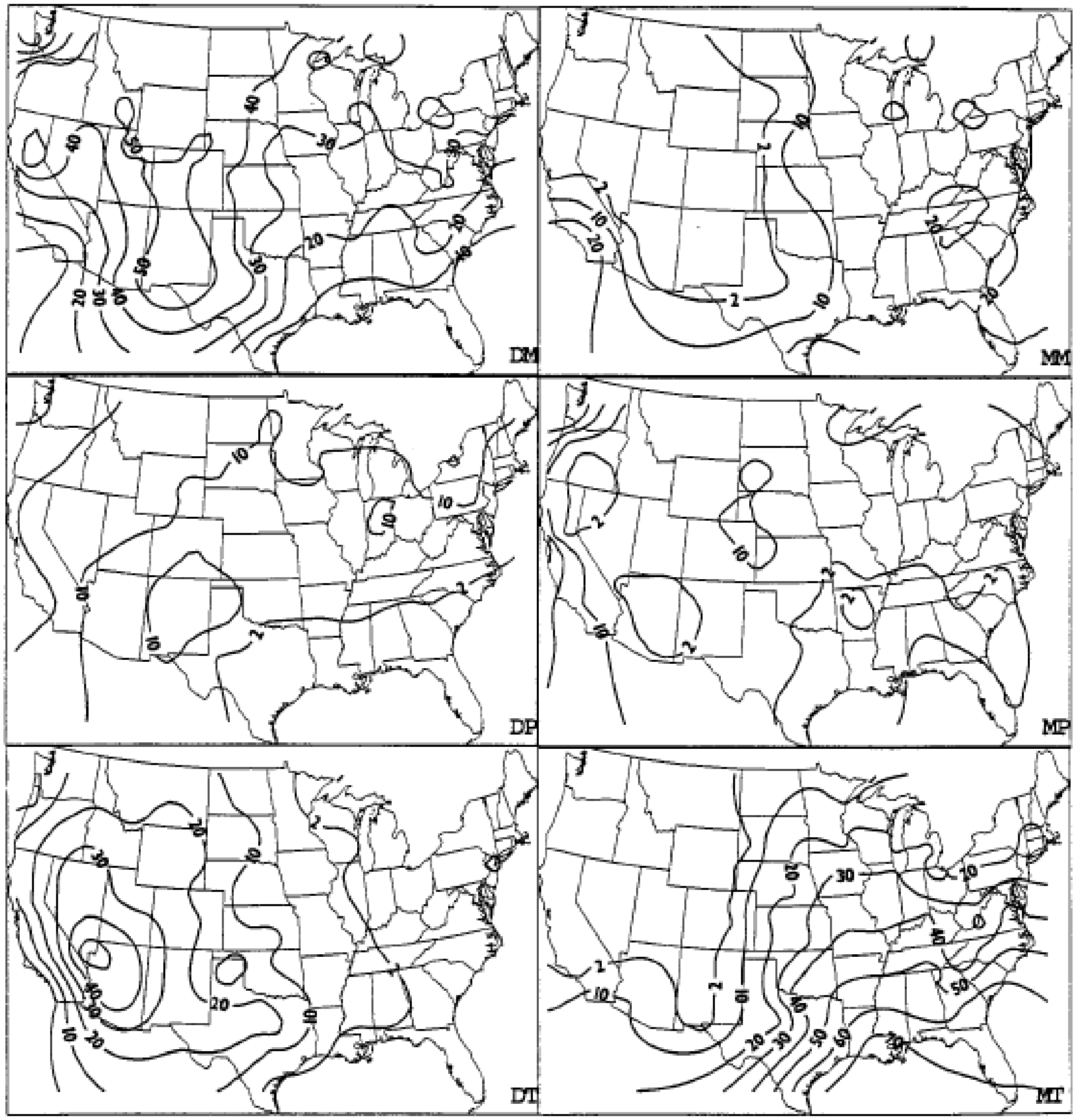

Figure 1. Mean SSC air mass frequencies for summer, from Kalkstein et al., 1998. Please refer to page 11 for explanation of air mass abbreviations.

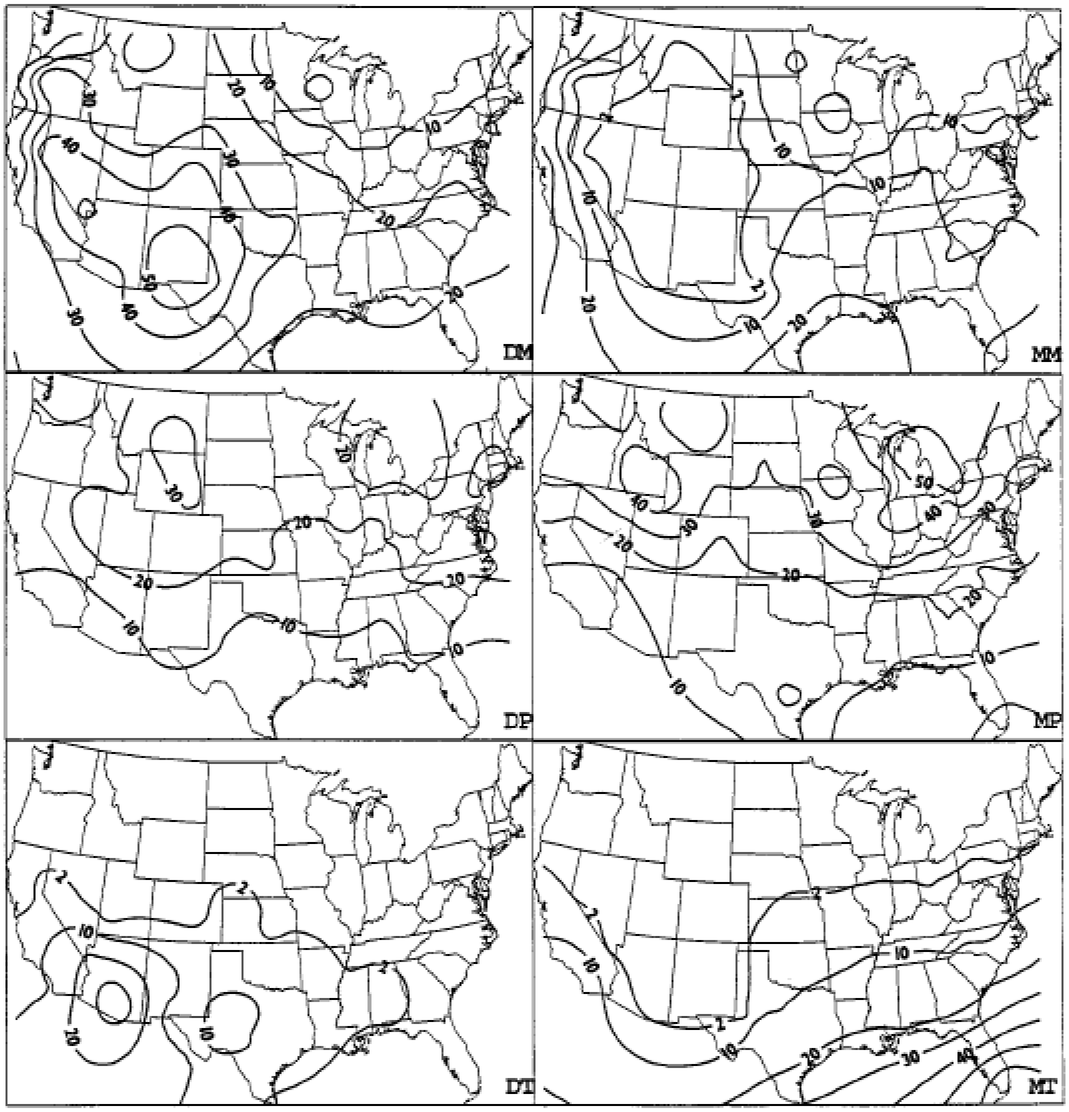

Figure 2. Mean winter SSC air mass frequencies from Kalkstein et al. 1998.

One of the weaknesses of the original SSC (henceforth, SSC1) was the inability to classify air masses throughout the year, as seed days had to be identified individually for each season. Sheridan (2002) reworked many of the procedures of the original method into the SSC2, the system to be used in this research. Like its predecessor, the SSC2 was designed as a system incorporating both manual and automated methods. In addition to accommodating year-round classification, the SSC2 improves the spatial continuity of weather types and frequencies and increases the number and domain of stations with SSC calendars (Sheridan, 2002). In 2002, the SSC2 had data available for 327 stations across the United States and Canada, with an average of 44.6 years of data available at each station. To date, nearly 400 stations have become available, including several in Europe (SSC homepage). For the remainder of the text, the acronym "SSC" refers to Scott Sheridan's SSC2.

The seven types identified in the present-day SSC are Dry Polar, Dry Moderate, Dry Tropical, Moist Polar, Moist Moderate, Moist Tropical, and Transition. Descriptions of the seven types appear below, from Sheridan (2002) and Kalkstein et al. (1998):

> Dry Polar (DP) air masses often bring clear, dry conditions, and in winter months are typically associated with the lowest temperatures. Analogous to continental polar (cP) air, DP commonly originates from Canada or Alaska and moves into the United States with the advancement of an anticyclone.
>
> Dry Moderate (DM) air masses generally follow a more zonal trajectory across the continent than DP, although DM classification may result from the modification of DP over the continent. This air mass is observed with clear skies and seasonal temperatures.
>
> Dry Tropical (DT) days occur very infrequently across much of the U.S., most predominantly occurring in the western states, the typical source region of such air. DT days are nearly always the warmest in the summer months. This classification may also result from compressional warming.

Moist Polar (MP) air masses are associated with low temperatures, cloudy skies, and often light precipitation related to the advancement of an air mass from polar maritime regions. MP designation may also result from the presence of an overrunning boundary to the south or modification of DP air.

Moist Moderate (MM) conditions are often found directly south of an MP air mass, and are characterized by light winds, cloudy skies. MM is commonly observed in the immediate vicinity of overrunning frontal boundaries.

Moist Tropical (MT) air masses bring hot, moist weather to an area, and are often observed across the southeastern states during the summer months related to the general circulation of the subtropical anticyclone. MT air is also found in the warm sector of a typical cyclone. Across much of the country in the summer this weather type is associated with convective storms.

The transition type is identified on days that experience a significant shift in the weather, such as when one air mass is giving way to another, during a frontal passage, etc. Further details on transition identification may be found below.

Similarly to the SSC1, the redeveloped SSC uses seed days to identify the mean characteristics of weather types for specific locations. In the original system, seed days could be selected for the winter and summer months only because of the rapidly changing meteorological characteristics of each weather type during the transitional seasons, spring and fall. The seed-day selection procedure in the new SSC utilizes sliding seed days. First, seed days are selected for four two-week windows throughout the year, one two-week period falling during the hottest time of the year, another during the coolest, and two during midpoints between the warmest and coolest periods. Once the characteristics for each air mass for each two-week window are determined for the same 12 variables (at 04, 10, 16, and 22 EST) as in the SSC1, a polynomial is fit to the sum of the actual meteorological data throughout the year and the linearly-fit departures for each air mass. Thus, for each air mass and for each day of the year there is an expected value for each of the 12 variables. Figure 3 shows a graphical example of how this calculation is performed.

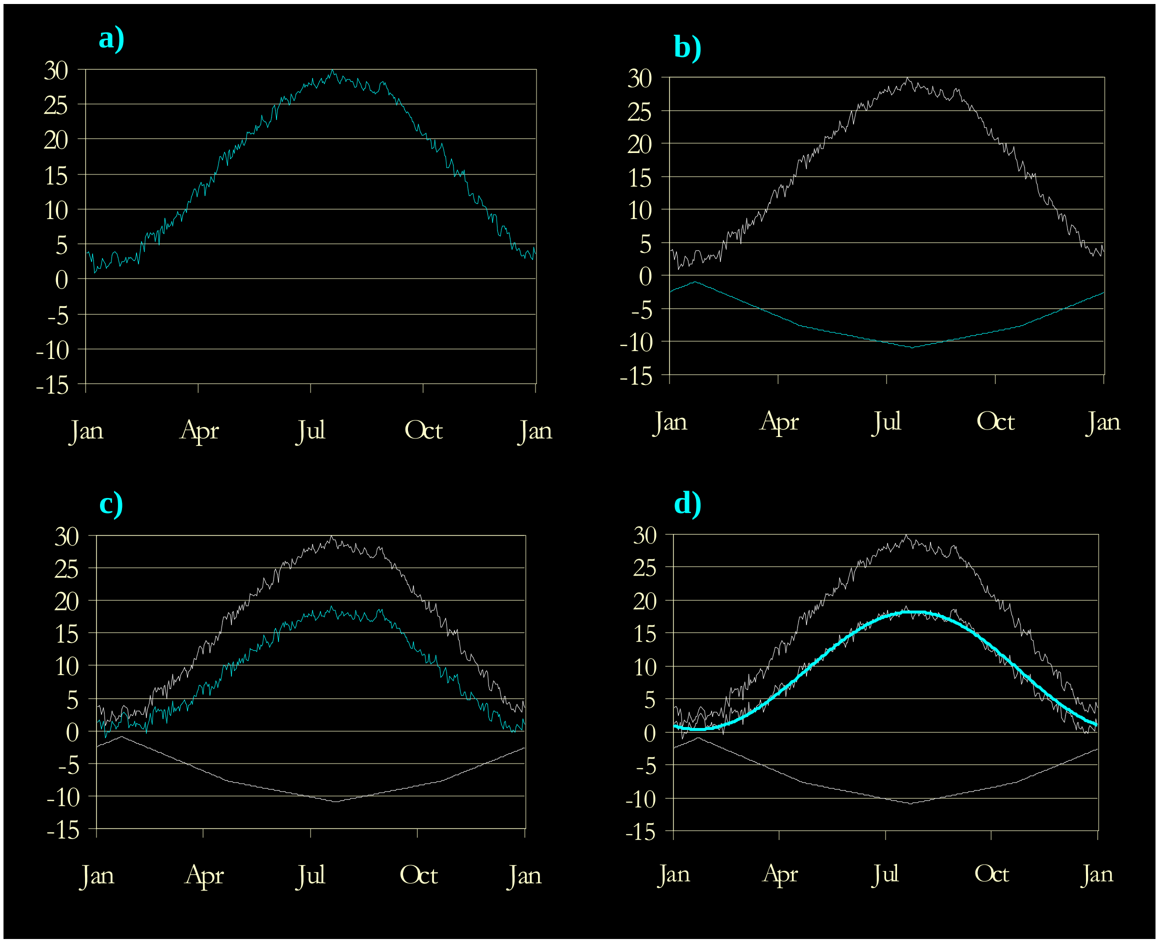

Figure 3. Example of the sliding seed day procedure for Wilmington, DE, MP air mass, 4pm temperature. a) Average 4pm temperature for all days at Wilmington. b) Same as before, with average 4pm temperature departure on MP days added as new light blue curve. Four points of the light blue curve (Jan, Apr, July, Oct) represent seed day values from 2-week windows. The curve represents a linear fit through those points. c) The summation of the two curves from (b) (middle curve). d) A polynomial is fit through the summed data (smoothed light blue curve) to give the expected afternoon temperature for MP days throughout the year at Wilmington. From Sheridan (2000).

The procedure used to identify transition seed days differs slightly. Instead of considering the 12 meteorological variables as above, the transition procedure considers three: the diurnal dew point temperature range, diurnal sea-level pressure range, and largest diurnal wind shift (all of observations at 04, 10, 16, and 22 EST). High values for each of these variables should be associated with a major change in the overall weather. If all three of these parameters exceed 1.3 standard deviations above the mean, the day is eligible to become a transition seed day. This threshold of 1.3 standard deviations was selected to ensure that transition frequencies were similar to those of the SSC1, in which the transition frequency was deemed acceptable (Sheridan, 2002).

After the seed days were established for the original station (Wilmington, DE), a seed day transfer procedure was applied with the goal of decreasing differences in the SSC climatologies between adjacent stations. The seed day transfer procedure placed an emphasis on using days on which the same air mass was observed at adjacent stations, which increased the overall cohesiveness of the SSC coverage. More details on this part of the procedure may be found in Sheridan (2002).

The discriminant analysis employed in the SSC1 was not an appropriate classification method for the revamped SSC, as the new method's sliding seed day procedure resulted in different characteristics for each type on every day of the year. The evaluation method selected was a simple z-scoring procedure. A z-score was calculated for each variable of each air mass on a daily basis as the difference between the actual and theoretical values squared divided by the variance. These scores are summed across all twelve variables, and the air mass with the lowest sum is selected as that day's SSC classification. After this primary classification, a secondary method checks whether or not the day should be identified as transition. The procedure is repeated as above, except here only the three transition variables are evaluated. If the new transition z-score sum for the transition type is lower than the transition z-score sum for the air mass type designated from the primary classification, the day is re-classified as transition. If it is greater, the day retains its original classification. This procedure is repeated for every day throughout the record, to generate an SSC calendar for each station. The calendars can be used to create various air mass climatologies (Figures 4–5).

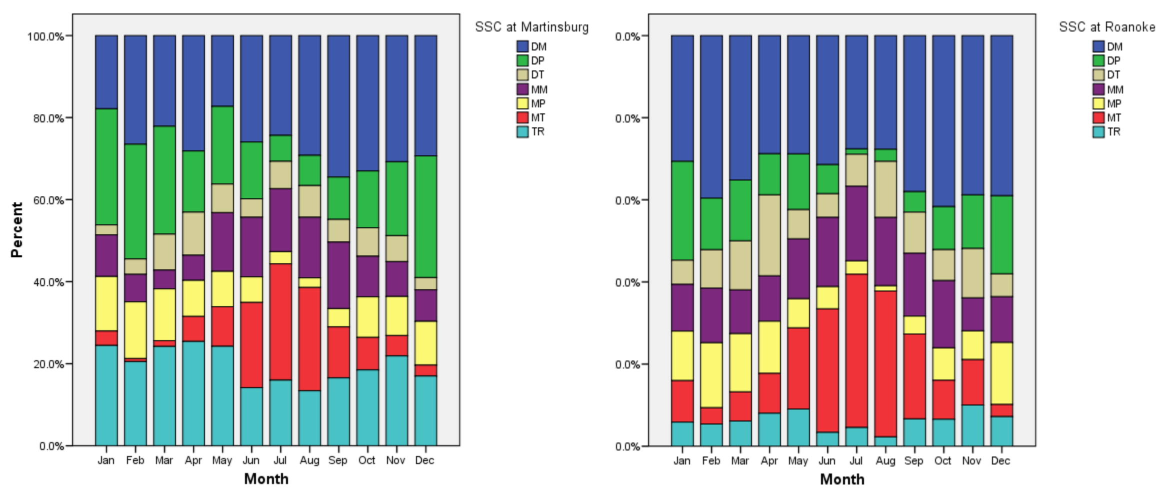

Figure 4. Average monthly SSC frequencies at a) Martinsburg, WV, and b) Roanoke, VA 1997–2006. Adapted from Hondula et al. 2009.

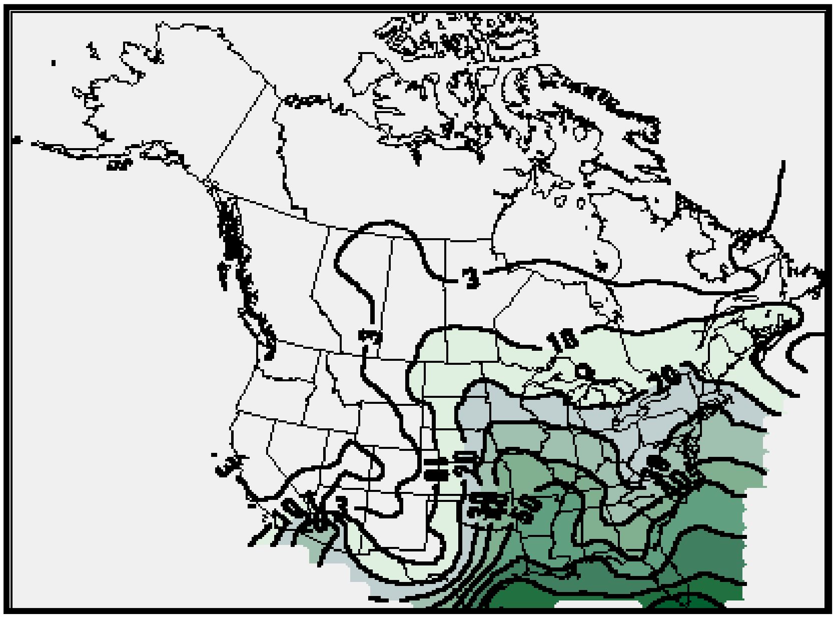

Figure 5. Average July frequency of the Moist Tropical weather type, 1961-1990. From SSC webpage, accessed Jan. 2008.

The production of SSC calendars for hundreds of stations across the North American continent has created a very large data set with high potential for application to study of climate and climate change, and many have already utilized such data in a variety of fields, including many of those listed above for synoptic-scale classification systems in general. Recent work by a team including the author at the University of Virginia (Knight et al. 2008) presents the first national climatology of the changing frequencies in SSC types based on the redeveloped classification system.

Earlier, an air mass climatology was completed for the United States using the SSC1 (Kalkstein et al. 1998). The study analyzed changes both in the frequency and character of air masses over the period 1948 through 1993. Using a standard least squares regression ($\alpha = 0.05$), a significant decrease in the frequency of the transition days over much of the country was observed. Of the 109 stations included in the study, decreasing transition frequency was observed at 94, and this trend was statistically significant at 24. They also noted an increase in MT frequency in the summer months, and decrease in MT in the winter. Table 1 shows the compilation of their frequency results. The region of maximum decrease stretched across many of the western states, where transition days were found to be decreasing at a rate greater than 1% per decade at many stations (Figure 6). Kalkstein et al. also evaluated trends in the within-air-mass meteorological variables. Although their work regarding changes to the character of air masses is of some interest for the present study, they suggested that those trends may be too conservative, because an air mass whose character has significantly evolved may have more days re-classified as a different SSC type. Further, they did not analyze long-term changes within the characteristics of transition days themselves.

Sheridan (2002) completed a preliminary national climatology using the SSC2 in his Ph.D. dissertation work. The results were fairly consistent to those of Kalkstein et al. 1998: A continent-wide decrease in transition frequency, a year-round increase in tropical air masses, and a decrease in polar air masses in all season except autumn. The rates of the transition decline matched those of Kalkstein et al. (1998) as well, with a broad region of decreases on the order of 1% per decade over the western portion of the country, with a maximum of 2.5% per decade in the Great Basin area.

Knight et al. (2008) used regression analysis and a change-point detection algorithm to determine long-term trends in air mass frequency over the United States, expanding the SSC frequency analysis. Their improvement to previous studies, the inclusion of the change point algorithm, demonstrated not only in which direction frequencies were headed, but also over what time period the changes were occurring. A consistent break point in trends was hypothesized to suggest a sharp change in the larger-scale Northern Hemisphere climate. While the Knight et al. study was completed over a sparser network than those of Kalkstein et al. (1998) and Sheridan (2002), their findings on air mass frequency were consistent with those of the two previous studies: an overall increase in warm, moist air masses, a decrease in cold, dry air masses, and a widespread decrease in transition frequency (Figure 7).

	Winter			Summer		
	+	−	Δ	+	−	Δ
DM	10	5	0.36	3	21	−0.16
DP	6	1	0.30	0	5	−0.32
DT	1	0	−0.08	5	0	0.18
MM	2	1	0.05	5	1	0.58
MP	12	7	0.20	5	1	−0.79
MT	0	7	−0.53	15	3	0.37
TR	0	24	−0.62	0	12	−0.71

Table 1. Trends in air mass frequency using the SSC 1 over the continental U.S., 1948–1993. From Kalkstein et al., 1998. + and – show the total number of statistically significant (α=0.05) increases and decreases amongst 109 stations across the country. Δ shows the mean change in frequency across all stations (%/decade), adjusted for overall frequency at each station.

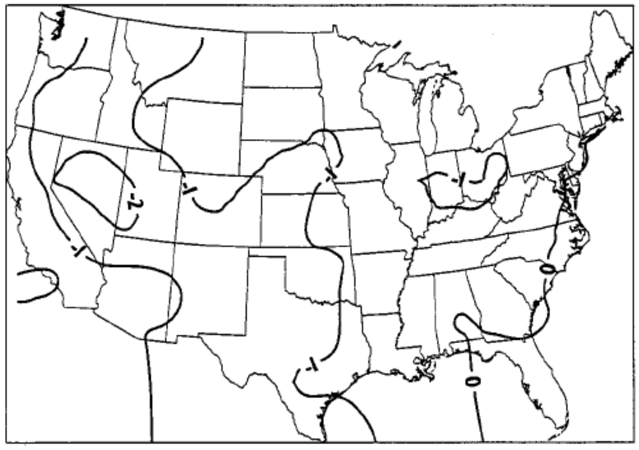

Figure 6. Trends in the frequency of the transition type from Kalkstein et al. (1998) for winter months 1948–1993, expressed as percent per decade.

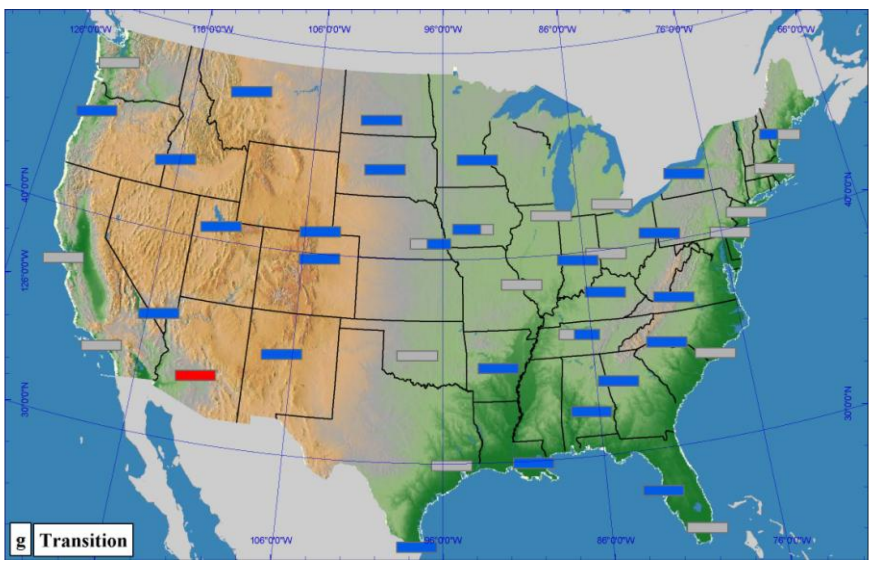

Figure 7. Trends in the frequency of the transition type (entire year) from Knight et al. (2008). Each horizontal bar denotes time over the period 1948–2005 with time increasing from left to right. Red indicates statistically significant positive trends, blue statistically significant negative trends, and gray no trend. A statistically significant change point is present where two colors are adjacent.

I.3 Hypothesis

The decrease in transition frequency over the past approximately half-century is a widespread, robust, and reproducible indicator of changes to the United States climate and, perhaps, large-scale atmospheric circulation. There are several potential interrelated connections between circulation dynamics and reduced transition frequency:

1. A decrease in the hemispheric or global speed of circulation and increased residence time of air masses;
2. A repositioning of the core of strongest upper-atmosphere winds away from the study region;
3. A decrease in the number, intensity, and/or spatial extent of fronts; and/or
4. Biases in measurements and/or the SSC methodology.

While all of these potential causes of the decrease in transition frequency merit attention in this research, amongst them I believe that the repositioning of the core of strongest winds away from the study region (Strong and Davis 2007) is most related to the decrease in transition over the United States. This jet core is typically located along the boundary of the cyclonic circulation surrounding the pole (Frauenfeld and Davis 2003). Therefore, my main hypothesis is that the decline in transition frequency can be attributed to changes in the position and shape of the circumpolar vortex over the past half century. Meteorological data will be analyzed to provide a link between transition activity and vortex trends. Additionally, I intend to evaluate the validity of the SSC as a tool for identifying transitions in synoptic-scale meteorology. Teleconnection frequency is known to be related to transition frequency; however, this analysis will be conducted independent of a teleconnection "framework." Previous research in this area may be used to supplement understanding of the circulation trends toward the later phases of the research.

I.4 Literature Review

Many factors may be linked to changes in the atmospheric circulation and the decrease in transition frequency, including changes in the Northern Hemisphere circumpolar vortex, adjustments to cyclone and anticyclone tracks, modifications of state variables at the surface, external forcings, and shifts in teleconnection patterns. These factors are all part of a complex system of feedback and balances that often impact one another. In the following sections, I briefly review relevant research in each field. A complete literature review is available in an appendix – this review is a summary of the full version.

I.4.1 Circumpolar Vortex

Throughout the year, the position, strength, and shape of the jet stream(s) over North America determine much of the synoptic-scale climate variability. The strongest feature of the polar jet in both hemispheres is located along the equatorward boundary of the circumpolar vortex (Frauenfeld and Davis, 2003). As noted by Frauenfeld and Davis (2003) and others, study of the circumpolar vortex provides a overall view of the hemispheric circulation, and variations thereof are related to air mass advection, surface and upper level temperatures, and precipitation. Accordingly, the dynamics of the Northern Hemisphere circumpolar vortex (henceforth, vortex) should be related to spatial and temporal variance in transition.

Work of Burnett (1993), Frauenfeld and Davis (2003) and Angell (2006) suggest a contraction of the Northern Hemisphere circumpolar vortex in recent decades that follows an expansion of the vortex through roughly 1970. The studies demonstrate decreasing vortex size at multiple levels of the atmosphere throughout the seasons, although not all seasons show a statistically significant decline at all levels. The magnitude of the change was estimated by Angell (2006) at 1.5% reduced area per decade. Increasing jet stream probabilities and speeds over the upper mid-latitudes support the theory of a contracting and intensifying vortex. For the United States in particular, jet stream probabilities and wind speeds are increasing north of the mean vortex position over the period 1958–2007 (Strong and Davis 2007). Rohli et al. (2005) and Wrona and Rohli (2007) examined vortex trends using GIS software and found no statistically significant trends in vortex shape or size for most seasons. The contrast between their work and that of Frauenfeld and Davis (2003) and Angell (2006) may arise from differing map projections and methods (Wrona and Rohli 2007).

The contrasting results of several recent studies suggest that analysis of vortex trends is highly method-dependent. Because of the agreement between Frauenfeld and Davis (2003) and Angell (2006), and the hypothesis of Rohli et al. (2005) that increasing mid-latitude temperatures should be associated with decreasing vortex area, it seems that relationships between the vortex and transition frequency should be examined. The work of Rohli et al. (2005) and Wrona and Rohli (2007) formally identify a second important feature of the vortex that may be related to transition activity: the shape (represented through their circularity ratio). As enhanced meridional flow in the vortex suggests increased pole-to-equator exchange of momentum and heat, circularity should be related to cyclogenesis, and thus, transition. Over larger spatial domains, then, transition frequency may be related to vortex position and shape. Analysis of the vortex enables investigation of how a repositioning of the core of strongest winds may move transition occurrence away from the study region.

I.4.2 Cyclone & Anticyclone Tracks

Study of changes to storm track activity often relies on examination of cyclone and anticyclone climatologies over periods of several decades or longer. As no single measure of such activity exists, studies in this area often present a range of methods that may yield considerably different results. Changes in cyclone and anticyclone activity should mirror changes in transition frequency, as the transition type is designed to identify shifts between these two main features of atmospheric circulation.

For the Northern Hemisphere, many studies have identified a decrease in cyclone and/or anticyclone activity over the mid-latitudes (30°–60° N) and/or an increase in activity over the high latitudes (60°–90° N) over the past several decades (e.g., Reitan, 1974; Zishka and Smith, 1980; Whittaker and Horn, 1982; Harman, 1987; Changnon et al., 1995; McCabe et al., 2001; Paciorek et al., 2002). These findings are consistent with observations to changes to the circumpolar vortex discussed above. Of course, changes in cyclone and anticyclone activity are not restricted to homogeneous trends across space. Differences in topography, proximity to oceans, lakes, and seas, and other physical factors cause significant spatial gradients in cyclone and anticyclone frequencies. The large size and varying landscape of the United States result in different portions of the country with very dissimilar synoptic climate regimes. These changes are also certainly related to long-term changes in the semi permanent features of the atmosphere, such as the subtropical high in the North Atlantic (e.g., Davis et al., 1997), and the associated teleconnections (discussed below).

In general, there is good agreement with respect to decadal-scale changes in United States cyclone and anticyclone activity over the past fifty years. With fewer cyclones, anticyclones, and periods of transition between them, it seems unsurprising that transition frequency in the SSC has declined. Fewer cyclones and anticyclones may be indicative of an overall slowing of the circulation and/or changes in the meridionality of flow, and could result in fewer fronts.

I.4.3 Surface Variables

While it is probable that the changes in transition frequency are related to large-scale patterns in the dynamics of synoptic-scale systems in the atmosphere, it is possible that changes to meteorological variables at the surface may drive the observed changes in the SSC climate, as the SSC is solely based on surface observations. Therefore, any change to the three variables used for transition identification (diurnal dew point temperature change, diurnal pressure change, and diurnal wind shift) will impact the output classification from the SSC. Granted, such changes can and should be related to some combination of local forcing and changes in the large-scale dynamics. Examination of trends in dew point temperature range, pressure range, and wind range should help to explain the linkages between shifts in the circulation and transition frequency.

There is mixed evidence to support changes to the diurnal dew point profile at stations across the country (e.g., Knappenberger et al. 1996; Schwartzman et al. 1998; Gaffen and Ross 1999; Robinson 2000). To the best of the author's knowledge, no literature describes long-term changes in the amplitude of diurnal pressure or wind changes across the United States. However, previous work does suggest that there are observable, daily patterns in these variables (pressure: Spar 1952, Brier 1965, Haurwitz 1965, Mass et al. 1991, Dai and Wang 1999; wind: Hering and Borden 1962, Bonner 1968, Bonner and Paegle 1970, Dai and Deser 1999) at many locations which should not be neglected from this study. Further, Klink (1999) observes an increase in mean monthly maximum wind speeds and decrease in mean minimum wind speeds at many stations throughout the United States over the period 1961 to 1990 – it is uncertain how this finding may be translated to trends in the daily wind range. Collectively, study of the surface variables should help to improve understanding whether there are fewer or weaker fronts at present compared with fifty years ago. Should fewer or weaker fronts exist today, the distributions of daily change data should reflect the pattern with fewer cases in the tails. Spatial analysis of daily change variables may indicate shifts in the primary regions of frontal and transition activity.

I.4.4 External Forcings

Human activity has left a significant footprint on many of the Earth's environments and systems. Amongst them, changes to the composition of the atmosphere and landscape are of high concern for atmospheric scientists, as these adjustments have the potential to shift the energy balance that drives circulation at all scales. More specifically, external forcings may be at least partially responsible for changes in circulation speed and shape as well as in frequency, intensity, and location of frontal activity. Changing global temperature patterns arising from increasing concentrations of greenhouse gasses may alter cyclone frequency and intensity, resulting from a decreasing surface level equator-to-pole temperature gradient, increasing equator-to-pole temperature gradient aloft, and increasing moisture availability (e.g., Trenberth et al., 2007 (IPCC AR4), Held 1993). As suggested previously, a widespread decrease in cyclone activity across the Northern Hemisphere middle latitudes should be well-captured by a change in the transition frequency across the United States, as storm tracks have tended toward higher latitudes in recent decades. However, as high uncertainty remains concerning the dynamical link between increasing greenhouse gas concentrations and extratropical cyclone activity, it will be difficult to relate changes in transition frequency to greenhouse gas changes alone.

The land surface is also an important element of the entire atmospheric system that controls the frequency and distribution of cyclone, and thus transition activity. Considerable changes to the landscape of the United States have occurred over the last few centruies at both the local and regional scale. Over the most recent century, these changes have been manifested in two principal areas: agriculture and urban development. At both scales, human adjustments to the landscape have been related to modifications of climate via changes to the energy balance, roughness factors, and other variables (e.g., Loose and Bornstein 1977; Gaffen and Bornstein 1987; Copeland et al. 1996; Bonan

1997; Bornstein and Lin 2000; Souch and Grimmond 2006; Brazel et al. 2007). As with greenhouse gasses, however, considerable debate exists as to how these alterations may impact atmospheric circulation.

I.4.5 Teleconnections

The semi-regular patterns of the redistribution of the atmosphere's mass across Earth's surface are known as teleconnections. At present, several teleconnections are known to have an impact on climate in the Northern Hemisphere. The North Atlantic Oscillation (NAO), Southern Oscillation (SO), and Pacific-North America (PNA) teleconnections are amongst those thought to exert the greatest influence (e.g., Barnston and Livezey, 1987; Hurrell et al. 2003). Shifts in teleconnections are often identifiable in changes to regional temperature and precipitation (e.g., Leathers et al., 1991) as well as in changes to air mass frequency (e.g., Sheridan, 2003), and are often related to the size and shape of the vortex (e.g., Frauenfeld and Davis 2003). The SSC has been included in analyses of air mass-teleconnection relationships; first by Sheridan (2003), with a statistically significant relationship found between weather-type frequencies and the PNA and NAO patterns, and more recently by Knight et al. (2008), with identification of an air-mass signal indicative of a warmer, moister climate across the United States.

The shift in atmospheric mass between the Icelandic Low and Bermuda High known as the North Atlantic Oscillation (NAO, e.g., Sheridan 2003, Ostermeier and Wallace 2003, Rogers 1990, Barnston and Livezey 1987, Walker and Bliss 1932) results in changes to the strength of the westerlies across the Atlantic and to the climate of the eastern United States. Sheridan (2003) finds decreasing transition frequencies across the southeastern states under the positive (steeper pressure gradient) phase of the NAO. Both Sheridan (2003) and Knight et al. (2008) observe significant correlations with many of the SSC air mass types. This pattern of variability also is identified in the first principal component of hemispheric annual variability, sometimes referred to as the Arctic Oscillation (e.g., Barnston and Livezey 1987, Thompson and Wallace 2000), or Northern Hemisphere Annular Mode (NAM, e.g., Ostermeier and Wallace 2003). The NAO, AO, and NAM indices have trended toward unusually high values over the past three decades (e.g., Hurrell 1995; Thompson and Wallace 2000; Ostermeier and Wallace 2003).

The second major pattern of variability in the Northern Hemisphere winter is the Pacific-North America (PNA) pattern in mid-tropospheric geopotential heights over the Pacific Ocean and much of North America (e.g., Leathers et al. 1991). Variations in PNA alter the ridge-trough structure that persists over these regions, which consequentially significantly impact surface climate across much of the country (e.g., Henderson and Robinson 1994, Leathers et al. 1991, Skeeter and Parker 1985). Sheridan (2003) and Knight et al. (2008) both observe significant correlations between the PNA index and transition frequencies over the past several decades. The PNA index has remained relatively high (enhanced meridional flow) since the late 1950's (e.g., Mitchell 2004; Leathers and Palecki 1992; Balling and Lawson 1982; Kalnicky 1974).

Low-frequency changes in Pacific SSTs and the regular oscillations of pressure across the southern Pacific were first related by Bjerknes (1969; Horel and Wallace, 1981). Combined, these processes represent the modern-day El Niño/Southern Oscillation phenomenon (ENSO). Changes in the Pacific Ocean SSTs and the related shifts in atmospheric mass over the Pacific exert a major influence on the climate of North America because of their impacts on the radiation balance, partitioning of energy, and transfer of momentum. Most of the significant impacts are related to enhanced convective activity in the tropics arising from the increased SSTs during warm episodes. In the United States, warm (El Niño) years have been associated with many changes to the surface climate, including more frequent east coast winter storms (Hirsch et al., 2001; Eichler and Higgins, 2006), stronger westerlies in the mid-latitudes (Namias, 1976), and increased frontal activity along the Gulf coast (Douglas and Englehart, 1981). The abundance of impacts suggests a high potential for an ENSO-transition relationship. Knight et al. (2008) observe a widespread negative correlation an ENSO index and transition frequency. The ENSO record is highly variable over the past several decades, but is suggestive of a bias toward more El Niño events in the most recent decades (Trenberth, 1990).

The Pacific Decadal Oscillation has impacts on both temperature and precipitation across North America. The positive phase has been related to anomalously dry conditions across the northern tier of the United States, anomalously wet conditions in the southwest, above-average temperatures in northwestern North America, and below-average temperatures in the southeast (Mantua and Hare 2002). In their review of existing literature on the PDO, Mantua and Hare (2002) describe the phenomenon as a blend of two semi-independent patterns of SST variability in the North Pacific, while acknowledging that its mechanisms are unclear. The relationship between PDO and SSC frequencies has not been examined to date.

In summary, the semi-regular oscillations in atmospheric waves, and related changes in surface pressure and other variables clearly play an important role on the climate of North America, and demonstrate an influence on the frequency of SSC types, including transition. It is recognized that these teleconnections do not operate independently on the circulation, but rather often evolve and influence each other and other elements of the atmospheric system. Their varying effects at least partially represent changes in the overall speed and shape of large-scale atmospheric circulation features, and may help to shed light on the number and strength of fronts and residence times of air masses over certain regions.

I.4.6 Summary

The large literature on changes to the United States climate and circulation over the past half-century demonstrates several probable links with the decreasing frequency of the transition weather type of the Spatial Synoptic Classification observed over the same time period:

1. The poleward recession of the circumpolar vortex may have decreased transition frequency over the study domain by shifting the zone of highest transition occurrence northward.

2. The decrease in cyclone and anticyclone frequencies suggests fewer boundaries between air masses, and/or a longer residence time of air masses over the continent.

3. Changes in the diurnal profile of the transition indicator variables have not been fully documented. However, there is some evidence for changes in the diurnal patterns that could adjust the probability of obtaining transition classification.

4. External forcings of the land and atmosphere have been significant over the past fifty years, including modifications that may impact the larger-scale circulation and/or local-scale dynamics in a manner that influences frontal movement and other transitional weather types.

5. Teleconnection patterns significantly impact regional climate, including air mass advection and transitional weather frequencies.

Although each of these five factors strongly indicate that the decadal-scale trend in the transition weather type is related to aspects of climate change, I believe that the trends in the vortex are principally responsible for the decrease in transition frequency. The vortex shifts should be evident via changes in the climatic variables employed by the SSC, motivating the hypothesis and methods.

I.5 References

Angell JK, 2006. Changes in the 300-mb North Circumpolar Vortex, 1963–2001. *Journal of Climate,* **19**, 2984–2994.

Balling Jr., RC, Lawson MP, 1982. Twentieth century changes in winter climatic regions. *Climatic Change*, **4** (1), 57–69.

Barnston AG, Livezey RE, 1987. Classification, Seasonality, and Persistence of Low-Frequency Atmospheric Circulation Patterns. *Monthly Weather Review*, **115**, 1083–1119.

Bjerknes J, 1969. Atmospheric Teleconnections from the Equatorial Pacific. *Monthly Weather Review*, **97** (3), 163–172.

Bonan GB, 1997. Effects of Land Use on the Climate of the United States. *Climatic Change*, **37**, 449–486.

Bonner WD, 1968. Climatology of the Low Level Jet. *Monthly Weather Review*, **96** (12), 833–850.

Bonner WD, Paegle J, 1970. Diurnal variations in boundary layer winds over the south-central United States in summer. *Monthly Weather Review*, **98** (10), 735–744.

Bornstein R, Lin Q, 2000. Urban heat islands and summertime convective thunderstorms in Atlanta: three case studies. *Atmospheric Environment*, **34** (3), 507–516.

Brazel AJ, Chambers FB, Kalkstein LS, 1992. Summer energy balance on West Gulkana Glacier, Alaska, and linkages to a temporal synoptic index. *Z. Geomorph.,* **86** (Suppl.), 15–34.

Brazel A, Gober P, Lee SJ, Grossman-Clarke S, Zehnder J, Hedquist B, Comparri E, 2007. Determinants of changes in the regional urban heat island in metropolitan Phoenix (Arizona, USA) between 1990 and 2004. *Climate Research*, **33**, 171–182.

Brier G, 1965. Diurnal and semidiurnal atmospheric tides in relation to precipitation variations. *Monthly Weather Review*, **93** (2), 93–100.

Burnett AW, 1993. Size variations and long-wave circulation within the January Northern Hemisphere Circumpolar Vortex: 1946–1989. *Journal of Climate*, **6,** 1914–1920.

Changnon D, Noel JJ, Maze LH, 1995. Determining cyclone frequencies using equal-area circles. *Monthly Weather Review*, **123,** 2285–2294.

Copeland JH, Pielke RA, Kittel TGF, 1996. Potential climatic impacts of vegetation change: A regional modeling study. *Journal of Geophysical Research*, **101,** 7409–7418.

Dai A, Deser C, 1999. Diurnal and semidiurnal variations in global surface wind and divergence fields. *Journal of Geophysical Research*, **104**, 109–125.

Dai A, Wang J, 1999. Diurnal and semidiurnal Tides in Global Surface Pressure Fields. *Journal of the Atmospheric Sciences***, 56** (22), 3874–3891.

Davis RE, 1991. A synoptic climatological analysis of winter visibility trends in the mideastern United States. *Atmospheric Environment (Urban Atmosphere)*, **25B**, 165–175.

Davis RE, Hayden BP, Gay DA, Phillips WL, Jones GV, 1997. The North Atlantic Subtropical Anticyclone. *Journal of Climate*, **10,** 728–744.

Dilley FB, 1992. The statistical relationship between weather-type frequencies and corn (maize) yields in southwestern Pennsylvania, USA. *Agricultural and Forest Meteorology*, **59**, 149–164.

Dixon PG, Mote TL, 2003. Patterns and causes of Atlanta's Urban Heat-Island Precipitation. *Journal of Applied Meteorology*, **42**, 1273–1284.

Dolney TJ, Sheridan SC, 2006. The relationship between extreme heat and ambulance calls for the city of Toronto, Ontario, Canada. *Environmental Research*, **101**, 94–103.

Douglas V, Englehart PJ, 1981. On a Statistical Relationship between Autumn Rainfall in the Central Equatorial Pacific and Subsequent Winter Precipitation in Florida. *Monthly Weather Review*, **109,** 2377–2382.

Eicher T, Higgins W, 2006. Climatology and ENSO-Related Variability of North American Extratropical Cyclone Activity. *Journal of Climate*, **19** (10), 2076–2093.

Fovell RG, Fovell MC, 1993. Climate Zones of the Conterminous United States Defined Using Cluster Analysis. *Journal of Climate*, **6**, 2103–2135.

Frauenfeld OW, Davis RE, 2003. Northern Hemisphere circumpolar vortex trends and climate change implications. *Journal of Geophysical Research*, **108,** D14.

Gaffen D, Bornstein RD, 1988. Case Study of Urban Interactions with a Synoptic Scale Cold Front. *Meteorology and Atmospheric Physics*, **38,** 185–194.

Gaffen D, Ross RJ, 1999. Climatology and Trends of U.S. Surface Humidity and Temperature. *Journal of Climate*, **12,** 811–828.

Garardin MP, Berglund E, Tardif J, Monson K, 2005. Radial growth of tamarack (Lariz laricina) in the Churchill area (Manitoba) in relation to climate and larch sawfly (Pristiphora erichsonii) herbivory. *Arctic, Antarctic, and Alpine Research*, **37**, 206–217.

Harman JR, 1987. Mean Monthly North American Anticyclone Frequencies, 1950–79. *Monthly Weather Review*, **115**, 2840–2848.

Haurwitz B, 1965. The diurnal pressure oscillations. *Arch. Meteor. Geophys. Biolkimat. A*, **14**, 361–379.

Held IM, 1993. Large-Scale Dynamics and Global Warming. *Bulletin of the American Meteorological Society,* **74** (2), 228–241.

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** (3), 307–323.

Hering WS, Borden Jr. TR, 1962. Diurnal Variations in the Summer Wind Field over the Central United States. *Journal of the Atmospheric Sciences,* **19**, 81–86.

Hirsch ME, DeGaetano AT, Colucci SJ, 2001. An East Coast Winter Storm Climatology. *Journal of Climate,* **14**, 882–899.

Hondula DM, Sitka LJ, Davis RE, Knight DB, Gawtry S, Stenger PJ, 2009. A Back-Trajectory and Air Mass Climatology for the Northern Shenandoah Valley, USA. *International Journal of Climatology (online version available April 2009).*

Horel JD, Wallace JM, 1981. Planetary-Scale Atmospheric Phenomena Associated with the Southern Oscillation. *Monthly Weather Review*, **109**, 813–829.

Hurrell JW, 1995. Decadal Trends in the North Atlantic Oscillation. *Science,* **269**, 676–679.

Hurrell JW, Kushnir Y, Ottersen G, Visbeck M, 2003. An Overview of the North Atlantic Oscillation. *Geophysical Monograph 134*, *American Geophysical Union*.

Kalkstein LS, Corrigan P, 1986. A synoptic climatological approach for geographical analysis: Assessment of sulfur dioxide concentrations. *Annals of the Association of American Geographers*, **76**, 381–395.

Kalkstein LS, Tan G, Skindlov JA, 1987. An Evaluation of Three Clustering Procedures for Use in Synoptic Climatological Classification. *Journal of Climate and Applied Meteorology*, **26,** 717–730.

Kalkstein LS, Dunne PC, Vose RS, 1990. Detection of Climatic Change in the Western North American Arctic Using a Synoptic Climatological Approach. *Journal of Climate*, **3** (10), 1153–1167.

Kalkstein LS, MC Nichols, CD Barthel, JS Greene, 1996. A New Spatial Synoptic Classification: Application to Air-Mass Analysis. *International Journal of Climatology*, **16** (9), 983–1004.

Kalkstein LS, SC Sheridan, DY Graybeal, 1998. A determination of character and frequency changes in air masses using a spatial synoptic classification. *International Journal of Climatology*, **18** (11), 1223–1236.

Kalnay E, et al., 1996. The NCEP/NCAR 40-Year Reanalysis Project. *Bulletin of the American Meteorological Society*, **77** (3), 437–471.

Kalnicky RA, 1974, Climatic Change since 1950. *Annals of the Association of American Geographers*, **64** (1), 100–112.

Klink K, 1999. Trends in mean monthly maximum and minimum surface wind speeds in the coterminous United States, 1961 to 1990. *Climate Research*, **13**, 193–205.

Knappenberger PC, Michaels PJ, Schwartzman PD, 1996. Observed changes in the diurnal temperature and dewpoint cycles across the United States. *Geophysical Research Letters*, **23** (19), 2637–2640.

Knight DB, Davis RE, Sheridan SC, Hondula DM, Sitka LJ, Deaton M, Lee TR, Gawtry SD, Stenger PJ, Mazzei F, Kenny BP, 2008. Increasing frequencies of warm and humid air masses over the conterminous United States from 1948 to 2005. *Geophysical Research Letters*, **35** L10702.

Leathers DJ, Graybeal D, Mote T, Grundstein A, 2004. The Role of Airmass Types and Surface Energy Fluxes in Snow Cover Ablation in the Central Appalachians. *Journal of Applied Meteorology*, **43** (12), 1887–1899.

Leathers DJ, Mote TL, Grundstein AJ, Robinson DA, Felter K, Conrad C, Sedywitz L, 2002. Associations between continental-scale snow cover anomalies and air mass frequencies across eastern North America. *International Journal of Climatology*, **22** (12), 1473–1494.

Leathers DJ, Palecki MA, 1992. The Pacific/North American Teleconnection Pattern and United States Climate. Part II: Temporal Characteristics and Index Specification. *Journal of Climate,* **5**, 707–716.

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**, 517–528.

Livezey RE, Chen WY, 1983. Statistical field significance and its determination by Monte Carlo techniques. *Monthly Weather Review*, **111**, 46–59.

Loose T, Bornstein D, 1977. Observations of Mesoscale Effects on Frontal Movement Through and Urban Area. *Monthly Weather Review*, **105** (5), 563–571.

Mantua NJ, Hare SR, 2002. The Pacific Decadal Oscillation. *Journal of Oceanography*, **58**, 35–44.

Mass CF, Steenburgh J, Schultz DM, 1991. Diurnal Surface-Pressure Variations over the Continental United States and the Influence of Sea-level Reduction. *Monthly Weather Review*, **119**, 2814–2830.

McCabe GJ, Clark MP, Serreze MC, 2001. Trends in Northern Hemisphere Surface Cyclone Frequency and Intensity. *Journal of Climate*, **14**, 2763–2768.

Mitchell JFB, Johns TC, Gregory JM, Tett SFB. Climate response to increasing levels of greenhouse gases and sulphate aerosols. *Nature*, **376**, 501–504.

Morabito M, Crisci A, Grifoni D, Orlandini S, Cecchi L, Bassci L, Modesti PA, Gensini GF, Maracchi G. Winter air mass based synoptic climatological approach and hospital admission for myocardial infarction in Florence, Italy. *Environmental Research*, **102**, 52–60.

Namias J, 1976. Some Statistical and Synoptic Characteristics Associated with El Niño. *Journal of Physical Oceanography*, **6**, 130–138.

Ostermeier GM, Wallace JM, 2003. Trends in the North Atlantic Oscillation–Northern Hemisphere Annular Mode during the Twentieth Century. *Journal of Climate*, **16**, 336–341.

Paciorek CJ, Risbey JS, Ventura V, Rosen RD, 2002. Multiple Indices of Northern Hemisphere Cyclone Activity, Winters 1949–99. *Journal of Climate*, **15**, 1573–1590.

Power HC, Sheridan SC, Senkbeil JC, 2006. Synoptic climatological influences on the spatial and temporal variability of aerosols over North America. *International Journal of Climatology*, **26**, 723–741.

Rainham DGC, Smoyer-Tomic KE, Sheridan SC, Burnett RT, 2005. Synoptic weather patterns and modification of the association between air pollution and human mortality. *International Journal of Environmental Health Research*, **15**, 347–360.

Retian CH, 1974. Frequencies of Cyclones and Cyclogenesis for North America, 1951–1970. *Monthly Weather Review*, **102**, 861–868.

Robinson PJ, 2000. Temporal Trends in United States Dew Point Temperatures. *International Journal of Climatology*, **20**, 985–1002.

Rogers JC, 1990. Patterns of Low-Frequency Monthly Sea-level Pressure Variability (1899–1986) and Associated Wave Cyclone Frequencies. *Journal of Climate*, **3**, 1364–1379.

Rohli RV, Wrona KM, McHugh MJ, 2005. January Northern Hemisphere Circumpolar Vortex Variability and its relationship with Hemispheric Temperature and Regional Teleconnections. *International Journal of Climatology*, **25**, 1421–1436.

Schwartzman PD, Michaels PJ, Knappenberger PC, 1998. Observed changes in the diurnal dewpoint cycles across North America. *Geophysical Research Letters*, **25** (13), 2265– 2268.

Senkbeil JC, Sheridan SC, 2007. The sensitivity of tree ring growth to air mass variability and the Pacific Decadal Oscillation in coastal Alabama. *International Journal of Biometeorology*, **51**, 483–492.

Sheridan SC, 2000. The redevelopment of an air-mass classification scheme for North America, with applications to climate trends and teleconnections. PhD dissertation, University of Delaware.

Sheridan SC, 2002. The redevelopment of a weather-type classification scheme for North America. *International Journal of Climatology*, **22** (1) 51–68.

Sheridan SC, 2003. North American Weather-Type Frequency and Teleconnection Indices. *International Journal of Climatology*, **23**, 27–45.

Skeeter BR, Parker AJ, 1985. Synoptic control of regional temperature trends in the coterminous United States between 1949 and 1981. *Physical Geography*, **6**, 69–84.

Souch C, Grimmond S, 2006. Applied climatology: urban climate. *Progress in Physical Geography*, **30** (2), 270–279.

Spar J, 1952. Characteristics of the semidiurnal pressure wave in the United States. *Bulletin of the American Meteorological Society*, **33**, 438–441.

Spatial Synoptic Classification homepage, accessed April 2008. http://sheridan.geog.kent.edu/ssc.html

Strong C, Davis RE, 2007. Winter jet stream trends over the Northern Hemisphere. *Quarterly Journal of the Royal Meteorological Society*, **133**, 2109–2115.

Thompson DWJ, Wallace HM, 2000. Annular Modes in the Extratropical Circulation. Part I: Month-to-Month Variability. *Journal of Climate*, **13**, 1000–1016.

Trenberth KE, 1990. Recent Observed Interdecadal Climate Changes in the Northern Hemisphere. *Bulletin of the American Meteorological Society*, **71** (7), 988–993.

Trenberth KE, Jones PD, Ambenje P, Bojariu R, Easterling D, Klein Tank A, Parker D, Radimzadeh F, Renwick JA, Rusticucci M, Soden B, Zhai P, 2007. Observations: Surface and Atmospheric Climate Change. In: *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon S, Qin D, Manning M, Chen Z, Marquis M, Avery KB, Tignor M, Miller HL (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Walker GT, Bliss EW, 1932. World Weather V. *Mem. Royal Meteorological Society*, **4**, 53–84.

Whittaker LM, Horn LH, 1982. Geographical and Seasonal Distribution of North American Cyclogenesis, 1958–1977. *Monthly Weather Review*, **109**, 2312–2322.

Wrona KM, Rohli RV, 2007. Seasonality of the northern hemisphere circumpolar vortex. *International Journal of Climatology*, **27**, 697–713.

Yarnal B, 1993. *Synoptic Climatology in Environmental Analysis*. Belhaven Press: London.

Zishka KM, Smith PJ, 1980. The Climatology of Cyclones and Anticyclones over North America and Surrounding Ocean Environs for January and July, 1950–77. *Monthly Weather Review*, **108** (4), 387–401.

II. Decadal-Scale Trends in U.S. Transition Frequencies and Daily Weather Variability

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Abstract

Frontal passages represent an important component of the atmospheric circulation with respect to surface systems but are difficult to objectively identify and analyze in the context of decadal-scale climate change. In recent years, synoptic-scale weather classification has continued to emerge as a tool for investigating regional and global alterations to the Earth's atmosphere. One such system, the Spatial Synoptic Classification (SSC) uses surface weather observations to identify six air mass types and one transition category, the latter of which attempts to categorize days with a distinct change from one air mass to another. Thus the SSC offers a unique opportunity to

examine the climatology of frontal passages. The frequency of the transition type has significantly declined across United States over the second half of the twentieth century, potentially revealing a climatic adjustment toward fewer frontal passages that is not well-documented to date.

We link the decline in winter transition frequency to decreasing high-frequency moisture and pressure variability by examining the largest within-day dew point temperature and pressure changes. In the upper Midwest, the decrease in moisture variability is related to increasing dew point temperatures amongst the driest air masses. Accordingly, the decrease in transition frequency in this region is related to a weakening of transitions and reclassification in the SSC. Farther west, the decline is associated with a shift in the larger-scale circulation via a northward displacement of the circumpolar vortex and resultant decrease in both moisture and pressure variability. Although interdecadal variability in circulation regimes may be responsible for the trends, our results are consistent with global climate model projections associated with increasing surface temperatures.

II.1 Introduction

Unraveling the nature and causes of changes in climate variability, rather than mean conditions, is becoming an increasingly emphasized research area. Most of the focus has been on variability related to extremes (e.g., heat waves (Meehl & Tebaldi 2004), drought (Rind et al. 1990), heavy precipitation (Karl & Knight 1998)), but it is also possible that climate change can be observed and understood through more regularly-observed patterns in the weather. Most precipitation is associated with frontal passages, for example, and a long-term trend in the frequency, intensity, or magnitude of fronts might significant impact hydrological processes and human and natural systems. The decreasing frequency of the transition type in the Spatial Synoptic Classification (Kalkstein 1998, Knight et al. 2008) suggests that such a change in frontal passage activity is occurring. The goal of this research is to determine the underlying causes of the decrease in transitional days in the United States by examining temporal shifts in the distributions of short-term dew point, pressure, and wind variability.

Air mass and weather-type identification systems offer a useful rubric to consider climate and weather by accounting for multiple variables simultaneously. Although the greatest benefits of such an approach are probably in examining relationships between the atmosphere and surface environment, these systems also can be applied to climate change. Using one such air mass approach, Knight et al. (2008) identified increasing frequencies of warm, moist, air masses and decreasing frequencies of cool, dry air masses across the United States over approximately the past five decades. Such findings cannot point directly to a particular causative change in the circulation, but they do present a more comprehensive summary of climatic changes than one might obtain from trends in the means of individual variables.

The decline in transition frequency is amongst the most notable results of the SSC trend analyses published to date; however, the underlying cause of the decline has yet to be examined. As transition days are probably most often associated with frontal passages, we speculate that the decrease across the United States could be related to any one of a number of factors including: fewer fronts, increased persistence of air masses, weaker fronts, fronts (or air masses) with a smaller spatial extent, and fronts that move more slowly. A result suggesting temporal trends in any of those factors could provide a new perspective on the impact of climate change over the past several decades.

Most of the work related to temporal trends in daily weather variability has focused on surface temperature and precipitation. Twenty-four-hour temperature variability for the United States has decreased over the period 1911–1992 and for several other Northern Hemisphere regions over different time periods (Karl et. al 1995). In China, a decrease in wintertime daily temperature variability over the period 1954–2000 has been linked to a decreasing frequency of low temperature extremes (Gong & Ho 2004). Further, extreme single-day precipitation events are increasingly contributing to total precipitation amounts (Karl et. al 1995). We anticipate that trends in daily dew point temperature variability are consistent with the results above given the relationship between temperature and saturation vapor pressure. Trends in both dew point temperature and pressure variability should be closely tied with shifts in the hemispheric circulation, for which a large literature exists.

Throughout the year, the position, strength, and shape of the jet stream(s) over North America determine much of the synoptic-scale climate variability. Jet stream position is coupled to the air mass climatology of individual stations, as those to the north of the polar front jet have greater exposure to polar air masses, and those to the south, tropical. The strongest feature of the jet stream in both hemispheres is located along the southern boundary of a polar vortex, the region in the upper atmosphere of maximum meridional geopotential height gradient (Frauenfeld & Davis 2003). A contracting winter polar vortex has been observed in recent decades (Davis & Benkovic 1992, Burnett 1993, Frauenfeld & Davis 2003), although some research suggests no temporal trends (Rohli et al. 2005). Jet stream probabilities have been increasing over Canada, consistent with a contracting vortex (Strong & Davis 2007). For the region of interest in the present study, troughing has increased over the eastern Pacific, ridging increased over western North America, and little to no trend has been observed over eastern North America (Frauenfeld & Davis 2003). Increased meridionality in the long wave midlatitude circulation pattern suggests a slower propagation of systems across the continent, and a general northward shift in the vortex suggests a displacement of storm tracks to the north – both factors that would likely decrease U.S. transition frequencies.

Transition frequency patterns should also be associated with trends in cyclone and anticyclone activity. As no single best measure of such activity exists, research on this topic often employs different methods. However, for the Northern Hemisphere many studies point to a common pattern: decreases in cyclone activity in the mid-latitudes (30ºN–60º N) and a corresponding increase in the high latitudes (60ºN–90º N) over the past several decades (Changnon et al. 1995, McCabe et al. 2001, Paciorek et al. 2002). Collectively, these results may indicate changes in the speed and/or meridionality of hemispheric flow, but certainly suggest decreasing transition frequencies as fewer cyclones likely would result in fewer boundaries between air masses differing in dew point temperature, pressure, and wind.

The observed decreases in temperature variability and cyclone activity are consistent with model projections of a warming climate in which: (1) reduction in the latitudinal temperature gradient requires fewer cyclones to transport energy between the equator and poles (Held 1993, Yin 2005), (2) increased moisture in the atmosphere causes the cyclones that do exists to become more ‘efficient’ transporters of energy, and thus, more intense (Lambert 1995, Carnell and Senrio 1998, Brayshaw 2005), and (3) feedback mechanisms related to snow and ice cover enhance warming trends at high latitudes (Trenberth et al. 2007 (IPCC AR4)).

We examine the linkages between transition frequency and short-term variability of dew point, sea-level pressure, and wind (the variables used by the SSC to identify transition days) for winter months in the contiguous United States 1950–2007 in an effort to place the declining transition frequencies in the context of larger-scale climate change.

II. 2 Data and Methods

Daily SSC calendars and corresponding six-hour meteorological data are utilized for a spatial network of 63 first-order weather stations across the contiguous United States over the period December 1950–February 2007 (Table 1 and Figure 1). We limit the analysis to winter (DJF), the season when transition frequencies are highest and frequency declines are greatest (Knight et al. 2008, Sheridan 2002). The meteorological parameters employed by the SSC are surface air temperature (ºC), dew point temperature (ºC), sea-level pressure (mb), u- (west-east) and v- (south-north) components of the horizontal wind vector, cloud cover (1/10th's), diurnal temperature range, diurnal dew point temperature range, diurnal sea-level pressure range, and diurnal wind shift.

The SSC uses sliding seed days to identify the mean characteristics of weather types for specific locations. First, seed days are selected for four two-week windows throughout the year, with one two-week period falling during the hottest time of the year, another during the coolest, and two during midpoints between the warmest and coolest periods. Once the characteristics for each of six basic air mass types for each two-week window are determined for each variable, a polynomial is fit to the sum of the actual meteorological data throughout the year and the linearly-fit departures for each air mass. Thus, for each air mass and for each day of the year there is an expected value for each variable.

The procedure used to identify transition seed days differs slightly and considers only three variables: the diurnal dew point temperature range, diurnal sea-level pressure range, and largest diurnal wind shift (all of observations at 04:00, 10:00, 16:00, and 22:00

local time). High values for each of these variables should be associated with a major change in the overall weather. If all three of these parameters exceed 1.3 standard deviations above the mean, the day is eligible to become a “transition seed day.” This threshold of 1.3 standard deviations was selected to ensure that transition frequencies were similar to those of the SSC1, in which the transition frequency was deemed acceptable (Sheridan, 2002).

After the seed days were established for the original station (Wilmington, Delaware), a seed day transfer procedure was applied with the goal of decreasing differences in the SSC climatologies between adjacent stations. The seed day transfer procedure placed an emphasis on using days on which the same air mass was observed at adjacent stations, which increased the overall spatial cohesiveness of the SSC coverage.

To classify each day, a z-score is calculated for each variable of each air mass on a daily basis as the difference between the actual and theoretical values squared divided by the variance. These scores are summed across all twelve variables, and the air mass with the lowest sum is selected as that day’s SSC classification. After this primary classification, a secondary method checks whether or not the day should be identified as transition. The procedure is repeated as above, except here only the three transition variables are evaluated. If the new transition z-score sum for the transition type is lower than the transition z-score sum for the air mass type designated from the primary classification, the day is re-classified as transition. If it is greater, the day retains its original classification. This procedure is repeated for every day throughout the record, to generate an SSC calendar for each station. Complete details on the SSC procedure may be found in Sheridan (2002).

Linear regression is used to establish the transition frequency trends over the entire period of record at each station. In the event that more than 30 days are missing from the SSC record for a given year, the year is excluded from the analysis. In general, the SSC calendars and corresponding meteorological records are very complete for the period of record, with fewer than 5% of all days missing or incomplete. At only seven stations were any years removed from analysis, and amongst six of those, no more than one year was removed. Because of the relatively small sample size (57 years), we apply a bootstrapping technique which resamples the data 1,000 times. The general principle of bootstrapping is to generate a distribution of estimates for a statistical parameter of interest. The distribution provides a quantitative measure of the robustness of a particular estimate. The parameter of interest in this research is the linear regression slope *b*. In each resampling iteration, 57 pairs of the independent (year) and dependent (transition frequency) variables are drawn with replacement. A simple linear regression slope is calculated for each of these randomly generated sets of 57 pairs. The observed trend in the original data is considered statistically significant if the 2.5th and 97.5th percentile regression slopes from the bootstrap trials have the same sign. (This method is adapted from Efron & Tibshirani (1986) and applied to all regression models in this research).

To determine which of the three transition variables is driving the trend toward lower transition frequencies, we first consider the year-to-year distributions of these variables at each station. For transition frequency to decrease, the number of days with large shifts in one, two, or all three of the parameters must also be decrease. We attempt to determine which of the three are declining by counting the number of days with large changes in the weather each winter. In this preliminary analysis, we consider a "large shift" to be greater than or equal to 90% of that expected for an average winter transition day in the SSC's identification procedure. The number of days meeting the 90% criteria is summed annually for each station. These data are useful in identifying which of the range variables may be limiting transition frequencies on a year-to-year basis. For example, it is unlikely that any trends in pressure range are related to trends in transition frequency if only a small fraction of days with large pressure shifts are transition days.

We next consider the trends in the upper percentiles (70^{th}, 80^{th}, 90^{th}) of the variables deemed to be limiters of transition frequency. We also examine the upper (80^{th}, 90^{th}) and lower (10^{th}, 20^{th}) percentiles of signed values of the changes (rather than the absolute value) between the earliest (04:00 local time) and latest (22:00) observation each day. The 24-hour change between 04:00 on one day and 04:00 on the following day would not be an appropriate variable to consider because SSC identification is based only on weather observations on the day of interest. In total, at this step we have a maximum of 21 potential predictor variables of transition frequency (70^{th}, 80^{th}, and 90^{th} percentiles of dew point, pressure, and wind range, and 10^{th}, 20^{th}, 80^{th}, and 90^{th} percentiles of dew point, pressure, and wind change).

To identify a variable as a predictor of transition frequency, we apply a series of regression models. In the first, the independent variable is year and the dependent variable is one of the 21 noted above. Should the dependent variable demonstrate a statistically significant trend over time we then regress transition frequency upon that variable. If that relationship is also statistically significant, we then examine the temporal trend in residuals from the second model. In cases where the residuals demonstrate no significant trend, the variable is considered a predictor of transition frequency and a likely link to the physical cause of the overall decline. As an example, transition frequencies and the 90th percentile dew point temperature change are both significantly declining at Fargo, ND, and these two variables are significantly related (Figure 2). The residuals from regressing transition frequency upon the 90th percentile dew point temperature change demonstrate no temporal trend, suggesting that decreasing dew point variability is related to the declining transition frequency at Fargo (Figure 2). Following this analysis, we then attempt to link trends in the change variables to trends in the underlying raw data – our results might connect decreases in the upper percentiles of dew point temperature range to increasing minimum dew point temperatures, for example.

To place the trends in transition frequency and daily weather variability in the context of the larger-scale circulation, we utilize monthly Northern Hemisphere circumpolar vortex data from Frauenfeld & Davis (2003). The vortex data are intended to represent the region of strongest westerly flow and are generated from NCEP/NCAR reanalysis geopotential height fields by tracking the north–south shifts of the region of maximum meridional height gradient along longitudinal transects. A mean monthly northern, center, and southern vortex position is calculated for three layers of the atmosphere at 5°-spaced meridians; we consider the position of their center 500 hPa height contours over the domain 60ºW–150ºW, which includes the entire conterminous

United States and extends into the eastern Pacific. The vortex data are available from winter 1950–51 through 2001–02. At each station, we generate 18 single regression models relating transition frequency to the winter average vortex position in each 5° band over the domain.

II. 3 Results

Wintertime (DJF) transition frequencies vary between 5–15% across the United States on average, with the most transitions observed in the north and east and the fewest in the southern Plains and Southwest (Figure 3). Decreasing winter transition frequencies are observed at 37 of the 63 stations and increasing winter transition frequencies are not observed (Figure 4). On average, the transition frequency at stations with a significant trend is decreasing by 0.88%/decade (note: a 1%/decade trend refers to the change in frequency of transition days compared to all days, i.e., a frequency decline from 15% to 14% rather than 15% to 14.85%). We observe two areas of maximum decline: one in the upper Midwest and the other in the northern Rockies. In these regions, the rates of decrease approach 2%/decade. At Boise, Idaho, for example, the winter transition frequency decreased from approximately 15% in the late 1950's to 6-8% in the most recent years. The trends are generally consistent over the period of record, with a few stations showing a greater rate of decline during the 1960's than in later decades.

At many stations across the country, most winter days with a large shift in either dew point temperature or pressure are identified as transitions in the SSC (Figure 5). Only half of days with a large shift in the wind, however, are transition days, as the number of large wind shift days is generally much higher than the number of transition days. Accordingly, trends in dew point temperature and pressure variability are more related to the trends in transition frequency than temporal patterns in wind variability because the number of days with large shifts in those two variables limits the number of transition days whereas the number of days with large shifts in the wind does not. We exclude the wind variability from the remainder of the study. At Fargo, North Dakota, for example, 100% of the days with a large dew point temperature change during the winter are transition days in many years. The same is true for pressure change during nearly all years in the record. In the case of wind shift, however, there are no years within which 60% or more days with a large change are transition days (Figure 6).

Dew Point Temperature Variability

Decreases in the upper percentiles of dew point temperature range are evident across the northern half of the country. In the case of the 90^{th} percentile, the maximum changes are observed in the upper Midwest and in the vicinity of Nevada (Figure 7). When the 80^{th} and 70^{th} percentiles are considered, more stations show significant trends, but the region of maximum decline remains consistent.

A different spatial pattern emerges when we examine the directional dew point temperature change between 4 a.m. and 10 p.m. local time. In the lowest percentiles (10^{th} and 20^{th}), very few stations demonstrate a significant trend over time, and those with significant trends are located in the upper Midwest and scattered through the West. These trends are positive, suggesting that the sharpest drops in dew point have been moderating over time. In the upper percentiles of directional dew point temperature change, the number of stations with trends toward more moderate changes is much more widespread. The trend is significant at several eastern stations in the 80^{th} percentile. The 90^{th} percentile dew point temperature change map closely resembles the 90^{th} percentile dew point temperature range map, with the region of maximum decline located in the upper

Midwest. Phoenix, Arizona, demonstrates a significant decreasing trend in the low percentiles and significant increasing trend in the upper percentiles, opposite the rest of the network.

Temporal patterns in daily dew point temperature range and daily dew point temperature change provide strong evidence of decreasing dew point variability across many northern and western stations. There is a significant relationship between the upper percentiles of dew point temperature range and transition frequency at most of the 37 stations with a transition trend, and at 20 of those stations the residuals of transition frequency demonstrate no temporal trend (Figure 7). In other words, decreasing dew point variability accounts for the decrease in transition frequency at over half of the stations in the analysis, including many of those with the greatest declines in transition frequency.

Significant positive trends in the lowest percentiles of dew point are present across much of the region of greatest decline in dew point variability. For the 10^{th} percentile 4 a.m. dew point temperature, for example, the increase approaches 1ºC/decade in the upper Midwest (Figure 8).

Sea-Level Pressure Variability

Large changes in sea-level pressure are becoming more moderate across the northern Rocky Mountains as measured by both pressure range and pressure change (Figure 9). The changes are most consistently observed at four stations: Spokane, Washington, Missoula, Montana, Boise, Idaho, and Pocatello, Idaho, but some evidence for decreasing pressure variability is evident at a few other stations in the West and Midwest. No stations demonstrate increasing wintertime pressure variability.

In the case of pressure range, significant decreases are seen in the 70th and 80th percentiles at the four stations noted above. Further, several stations across the southwest and Four Corners area show decreases in either the 70th or 80th percentile pressure range, but generally not both. The stations of Elko, Nevada, Salt Lake City, Utah, and Grand Junction, Colorado, show no trends in any upper percentile of pressure range, separating "northern" and "southern" regions of decreases in pressure range.

When directional changes are considered, the spatial pattern in the trends is relatively similar to that observed using range only. No trends are evident in the 10th percentile (sharp drops in pressure), but in the 20th percentile the four principle stations noted previously demonstrate significant increases and moderation. Similarly, the upper percentiles show trends toward moderation at several western stations. The 90th percentile pressure changes are significantly decreasing at 11 locations in the west including the three in Nevada, Utah, and Colorado that showed no trends in pressure range, possibly supporting a notion of decreasing pressure variability across the entire west (Figure 9). While such a conclusion cannot be reached by considering any single method employed in this research, the combination of results points toward a reduction in variability across much of the west, excluding the immediate Pacific coast.

Compared with dew point temperature, a small number of stations exhibit trends in pressure variability. The residuals of transition frequency regressed with the 90th percentile pressure change show no temporal trend at six stations between the northwest and southern Midwest (Figure 9). We note that at the stations in the northwest the minimum dew point temperatures were not increasing, possibly indicating that changes in pressure variability there are forcing the trends in dew point variability and transition frequency.

At most stations there are no trends in any component of the distribution of sea-level pressure, indicating that the trends in the change variables are not related to increasing minimums as was the case for dew point temperature at certain stations.

Circumpolar Vortex impacts on Transition Frequency

Statistically significant regression models relating vortex position to transition frequency are present at 52 of 63 stations (Figure 10). A positive relationship indicates that transition frequencies are elevated with a mean vortex position in the higher latitudes, or a contracted state. Similarly, an inverse relationship indicates that transition frequencies are greater when the vortex is farther south. In general, the variance explained by winter average vortex position is 30% or less; however, these models each have only one independent variable. The stations with strongest relationship between vortex activity and transition frequency are located throughout the Rocky Mountain west and across the southeastern tier of the U.S. For reference, the mean winter vortex position over North America is sinusoidal with a northernmost extent along the Pacific coast at approximately 50º N and southernmost extent at approximately 42º N near Lake Erie. There is considerable year-to-year variability in the average winter position, with a standard deviation greater than 4º across the west decreasing to roughly 2.5º in the east.

Since the 1970's, the vortex has been significantly contracting across the United States with the greatest trend in western part of continent (Frauenfeld & Davis 2003).

We observe a high degree of spatial consistency in transition-vortex relationships. Vortex position over the eastern Pacific (125º–140º W) is positively correlated to transition frequencies across the Midwest and northeast, as well as at Elko, NV and Cedar City, UT (grey circles in Figure 10). There is an inverse relationship between vortex position over the United States and transition frequency at most other stations. In general, transition frequency is best-correlated with the vortex activity nearby or to the west, although a few exceptions are present (e.g., Albuquerque, NM and Spokane, WA). At 21 stations, the residuals of the regression between vortex position and transition frequency demonstrate no temporal trend.

II. 4 Discussion

Our analysis uncovered a widespread decrease in dew point variability. Decreases in the upper percentiles of both dew point temperature range and dew point temperature change may occur for either of two reasons: either the moisture content before a transition event has changed relative to the moisture content following, or the number of boundaries between moist and dry air masses has decreased. We can attribute decreasing variability in the Midwest to the former, based on the significant increase in low percentile dew point temperatures. Increasing moisture amongst the driest air masses is consistent with Kalkstein et al. (1998), who identified increasing temperature and dew point temperature amongst western arctic air masses using a synoptic classification approach similar to the SSC. The western arctic is a common source region for anticyclones in the upper Midwest during the winter months (Klein 1957). The increasing moisture content of Arctic air masses may be related as far west as Grand Junction, CO, as a 'secondary track' of polar anticyclones follows a trajectory across Idaho, but we are not convinced that increasing moisture content amongst arctic air masses is responsible for the changes observed at Reno and Las Vegas, NV, and nearby stations. If Arctic air masses were partially responsible for the increase at those locations, the signature should also be evident across stations in Idaho and Montana, where there are generally no trends in any percentile of dew point temperature.

Increasing moisture content of the driest Arctic air masses is a probable cause for decreasing transition frequency at stations across the upper Midwest. We also observe a link between increasing low dew point temperatures and decreasing transition frequencies at stations across Nevada, Utah, and Colorado, but a physical explanation based solely on moisture properties of air masses is difficult to derive.

Decreases in pressure variability also appear to be related to decreasing transition frequencies, including stations where the minimum dew point temperatures are not increasing. However, as there are no significant trends in any components of the pressure distribution, we do not believe that the number of high pressure days relative to low pressure days has changed over the past several decades or that the intensity of high pressure systems and low pressure systems has changed. For the variability to decline, the rate of change between high and low values of pressure must have diminished over the past several decades, analogous to an increase in the wavelength of a periodic function with no change in amplitude.

As an example, the winters of 1974–5 and 1994–5 at Missoula, Montana are not statistically different in terms of pressure distribution (using a 2-tailed Kolmogorov-Smirnov test) but the 90th percentile pressure changes for the years are markedly different (10.5 mb/day and 6.6 mb/day, respectively). The daily pressure time series for these two years support the notion of increased persistence (Figure 11). Compared with winter 1974–75, 1994–95 demonstrates relatively few isolated high or low pressure days; when high or low pressure is observed, it is typically observed for several consecutive days. By contrast, more single-day high or low pressure events are observed in winter 1974–75.

The vortex relationships offer insight into the synoptic-scale patterns linked with the decline in transition frequency. The positive relationship between the vortex position over the Pacific and transition frequency across the northern and eastern states indicates a linkage with the Aleutian low, one of the centers of action of the Pacific-North American teleconnection pattern (e.g., Wallace & Gutzler 1981). In phases when the low is weaker, the corresponding trough over the eastern U.S. also tends to be weaker. As a result, the trough in the eastern U.S. does not extend as far to the south, shifting the region of maximum cyclone activity into the Northeast. It is unclear why the vortex position over the Pacific, rather than the western U.S., is more highly correlated with transition frequency at Elko, Nevada, and Cedar City, Utah. Analysis of the configuration of the vortex during high and low transition frequency winters confirms that the shape of the Pacific trough is a better discriminator than the extent of the ridge over the West, but we are unable to conclude why this may be using seasonally averaged vortex data. It is possible that a relationship exists with the subtropical jet that our data are unable to represent.

With respect to the upper Midwest, however, the tendency for greater ridging in the west in recent years should increase the probability of Arctic air masses following a trajectory over the Dakotas and Minnesota. In the dew point data, then, we might expect to see greater variability caused by decreasing minimum temperatures because of more frequent extremely dry air masses. However, this is the opposite of our observation of decreasing variability and increasing minimum dew points. One theory we noted above was the increasing moisture content within arctic air masses concurrent with increasing temperatures (Kalkstein 1990). Accordingly, if air masses with an arctic source region are being more commonly observed in the upper Midwest, low dew point temperatures would not decrease.

The strong inverse relationship between the magnitude of the ridge over the interior west and the transition frequency at nearby stations is unsurprising. With an enhanced ridge, the Pacific storm track is diverted to the north, reducing transition types related to the passage of low pressure centers. Additionally, cold fronts associated with polar air masses are less likely to be observed because the polar air masses are restricted to regions north of the ridge. Instead, subsidence is common (Leathers et al., 1991) and the greater amplitude of the wave pattern suggests generally more persistent features. With an enhanced ridge, moist Pacific and Gulf air can more easily be advected into the region and northward into the Rockies, likely resulting in the increases in low percentile dew point temperatures. This effect would be most pronounced at the driest and southernmost locations, which may explain why stations such as Salt Lake City, Grand Junction, and Denver demonstrate a trend whereas those in Idaho, with typically higher mean and minimum dew point temperatures, do not. These results do not necessarily contradict decreasing precipitation over the west with an enhanced mid-troposphere ridge (Leathers et al. 1991). Because many locations are so dry, the increase in the minimum dew points may not lead to more frequent saturation of air masses.

Decreasing pressure variability in the West is also consistent with increased ridging as long waves in the atmosphere propagate more slowly than short waves. However, with an increased ridge, we expected to find an increase in mid-to-upper percentiles of observed sea-level pressure because of more frequently observed high pressure days, which was not the case. Our current hypothesis is that with meridional flow cyclogenesis is more likely with increased upper-level divergence and low pressure systems that develop in the West are more likely to persist locally because of the displaced polar jet well to the north. Time series like those in Figure 11 support this hypothesis.

In contrast to the western half of the country, meridional flow is associated with elevated transition frequencies across the east. For the mid-Atlantic region, a more southerly vortex over the Midwest elevates transition frequencies. This may be caused by more common intrusions of polar air masses as well as increased cyclogenesis downstream of the Rockies with more meridional flow. It is unclear why there is a relationship between the vortex position over the Midwest and several stations upstream. Similarly to the mid-Atlantic, an enhanced trough over the east coast is associated with more transition activity in the southeast.

II. 5 Conclusion

Decreasing transition frequencies across much of the United States are associated with declining variability in dew point temperature and sea-level pressure. At least a portion of the variance can be explained by the position of the Northern Hemisphere circumpolar vortex. Increasing meridionality in the vortex over western North America in recent years has led to a moderation of daily weather variability, such that in recent years very few sharp changes are observed. We suggest that the persistence of air masses in this region has increased over the past few decades. In the upper Midwest, the reduced transition frequencies are related to increasing low percentile dew point temperatures (i.e., moistening of the driest days), consistent with global warming projections of enhanced warming in the Arctic (e.g., IPCC AR4). Dew point temperature and pressure variability do not seem to be linked with decreases in transition frequency across much of the east.

This application of a synoptic-scale weather classification system to study decadal-scale trends in climate change may provide a new perspective on the impacts of circulation changes on daily weather variability. For the upper Midwest, the difference between moist and dry air masses in the winter has moderated over the past half century. In the West, the number of transitional boundaries observed over a given time frame has decreased, and this trend is probably related to increased residence time of air masses. As frontal passages are one of the major precipitation delivery mechanisms, the changes we observe related to the decline in transition days may substantially impact hydrologic cycles and surface systems.

II. 6 Table and Figures

(on following pages)

Station	ID	Lat	Lon
Albuquerque, NM	ABQ	35.05	106.60
Amarillo, TX	AMA	35.23	101.70
Atlanta, GA	ATL	33.65	84.42
Austin, TX	AUS	30.30	97.70
Billings, MT	BIL	45.80	108.53
Bismarck, ND	BIS	46.77	100.75
Boise, ID	BOI	43.57	116.22
Boston, MA	BOS	42.37	71.03
Burlington, VT	BTV	44.47	73.15
Buffalo, NY	BUF	42.93	78.73
Columbia, SC	CAE	33.95	81.12
Cedar City, UT	CDC	37.70	113.10
Chattanooga, TN	CHA	35.03	85.20
Cleveland, OH	CLE	41.42	81.87
Casper, WY	CPR	42.92	106.47
Corpus Christi, TX	CRP	27.77	97.50
Covington, KY	CVG	39.05	84.67
Washington - National, DC	DCA	38.85	77.04
Dodge City, KS	DDC	37.77	99.97
Denver, CO	DEN	39.75	104.87
Duluth, MN	DLH	46.83	92.18
Des Moines, IA	DSM	41.53	93.65
Elko, NV	EKO	40.83	115.78
El Paso, TX	ELP	31.80	106.40
Newark, NJ	EWR	40.70	74.17
Fargo, ND	FAR	46.90	96.80
Fresno, CA	FAT	36.77	119.72
Ft. Smith, AR	FSM	35.33	94.37
Ft. Wayne, IN	FWA	41.00	85.20
Spokane, WA	GEG	47.63	117.53
Grand Junction, CO	GJT	39.12	108.53
Greensboro, NC	GSO	36.08	79.95
Jackson, MS	JAN	32.32	90.08
Jacksonville, FL	JAX	30.50	81.70
Las Vegas, NV	LAS	36.08	115.17
Los Angeles, CA	LAX	33.93	118.40
North Platte, NE	LBF	41.13	100.68
Miami, FL	MIA	25.82	80.28
Milwaukee, WI	MKE	42.95	87.90
Missoula, MT	MSO	46.92	114.08
Minneapolis - St. Paul, MN	MSP	44.88	93.22
New Orleans, LA	MSY	29.98	90.25
Oklahoma City, OK	OKC	35.40	97.60
Chicago, IL	ORD	41.98	87.90
Norfolk, VA	ORF	36.90	76.20
Portland, OR	PDX	45.60	122.60
Philadelphia, PA	PHL	39.88	75.25
Phoenix, AZ	PHX	33.43	112.02
Pocatello, ID	PIH	42.92	112.60
Pierre, SD	PIR	44.38	100.28
Richmond, VA	RIC	37.50	77.33
Reno, NV	RNO	39.50	119.78
Roanoke, VA	ROA	37.32	79.97
San Diego, CA	SAN	32.73	117.17
San Antonio, TX	SAT	29.53	98.47
Seattle - Tacoma, WA	SEA	47.45	122.30
San Francisco, CA	SFO	37.62	122.38
Springfield, MO	SGF	37.23	93.38
Salt Lake City, UT	SLC	40.78	111.97
St. Louis, MO	STL	38.75	90.37
Syracuse, NY	SYR	43.12	76.12
Tallahassee, FL	TLH	30.38	84.37
Tampa, FL	TPA	27.97	82.53

Table 1. Network of first-order weather stations used in analysis. Latitude coordinates are in degrees north and longitude coordinates are in degrees west.

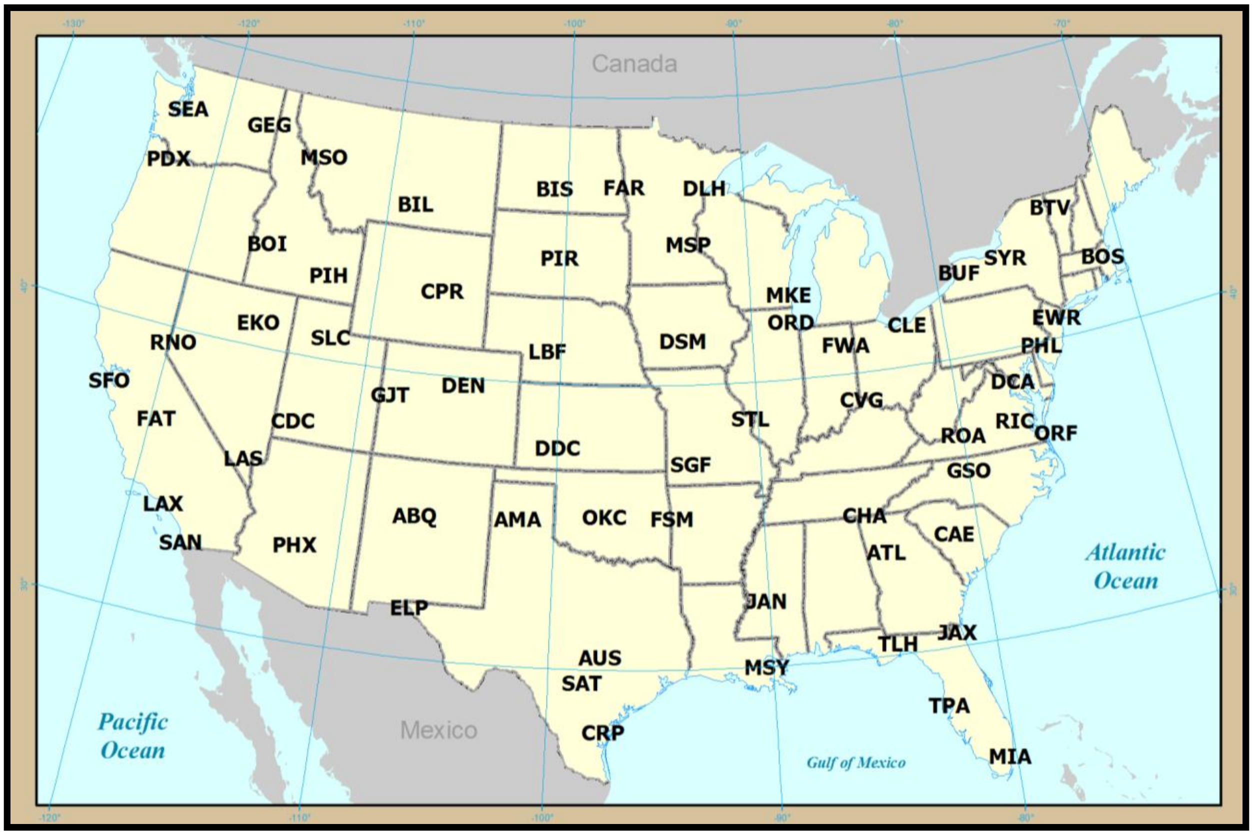

Figure 1. Network of first-order weather stations used in analysis. Station names corresponding to ID codes on the map are in Table 1.

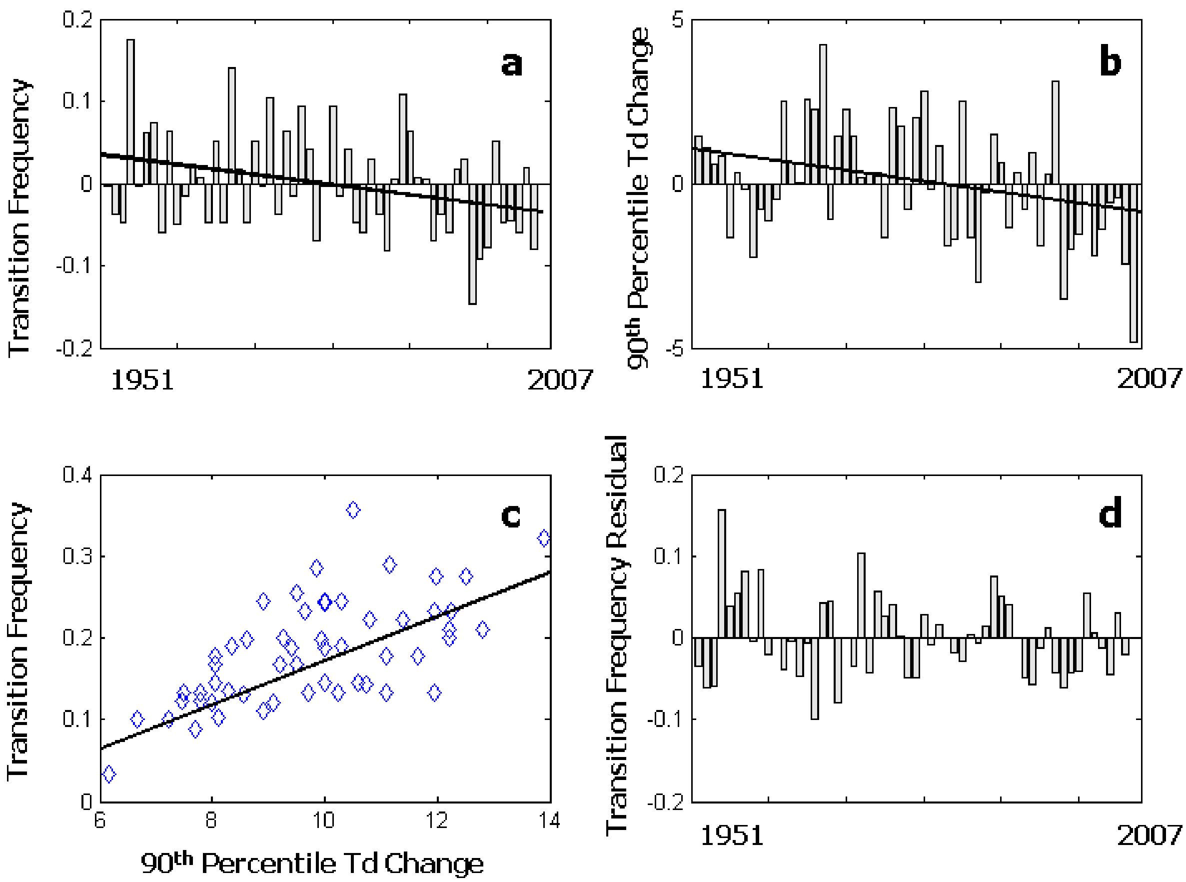

Figure 2. a) Winter (DJF) transition frequencies at Fargo, ND, 1951 – 2007 relative to mean over period of record. Black line demonstrates statistically significant trend at $\alpha < 0.05$. b) As in (a) but for the 90th percentile winter dew point temperature change. c) Comparison of year-by-year transition frequencies and 90th percentile dew point temperature change. Black line demonstrates statistically significant relationship. d) Residuals from regression in (c) (no significant trend).

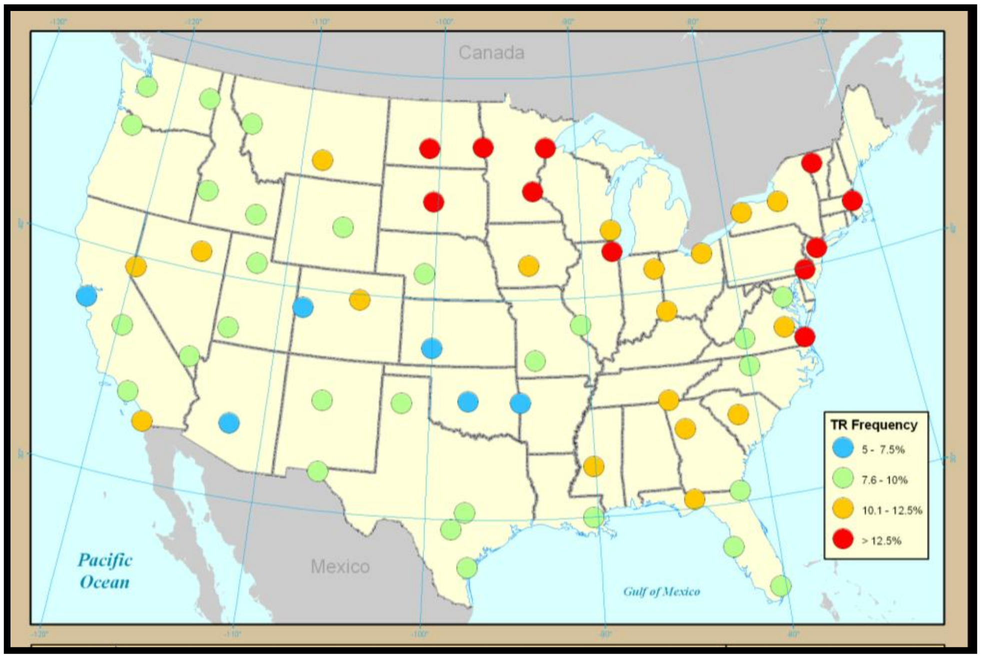

Figure 3. Mean winter (DJF) Spatial Synoptic Classification transition type frequency for the period Dec. 1950–Feb. 2007.

Figure 4. Bootstrapped linear regression trends in winter (DJF) Spatial Synoptic Classification transition type frequency for the period Dec. 1950–Feb. 2007. Stations with an downward pointing triangle exhibit significantly decreasing frequencies; grey dots indicate no trend.

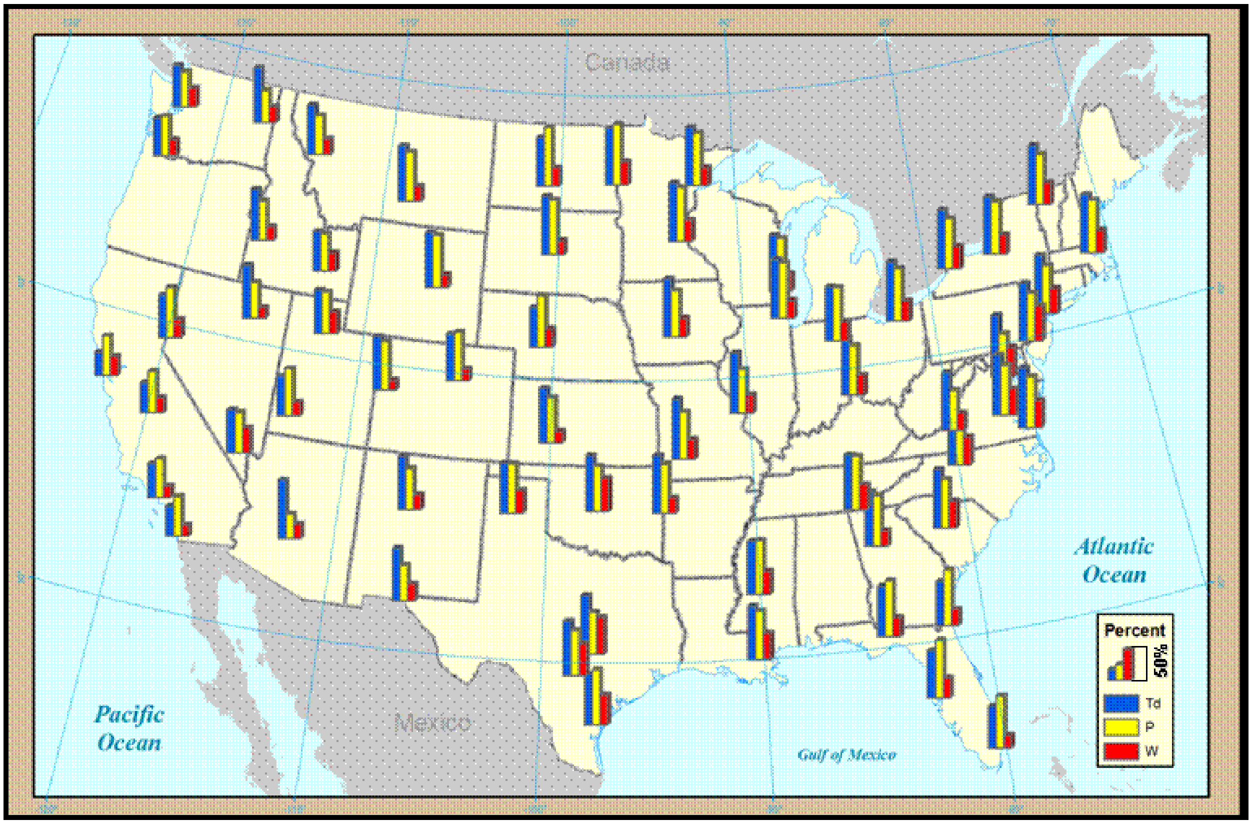

Figure 5. Average percentage of winter days (DJF) with a large change in dew point temperature (blue), pressure (yellow), and wind (red) that are transition days. A large change is defined as a difference between 4 a.m. and 10 p.m. that is greater than or equal to 90% of the expected value on a transition for each day of the year in the Spatial Synoptic Classification. The height of the red bar in the legend represents a value of 50%.

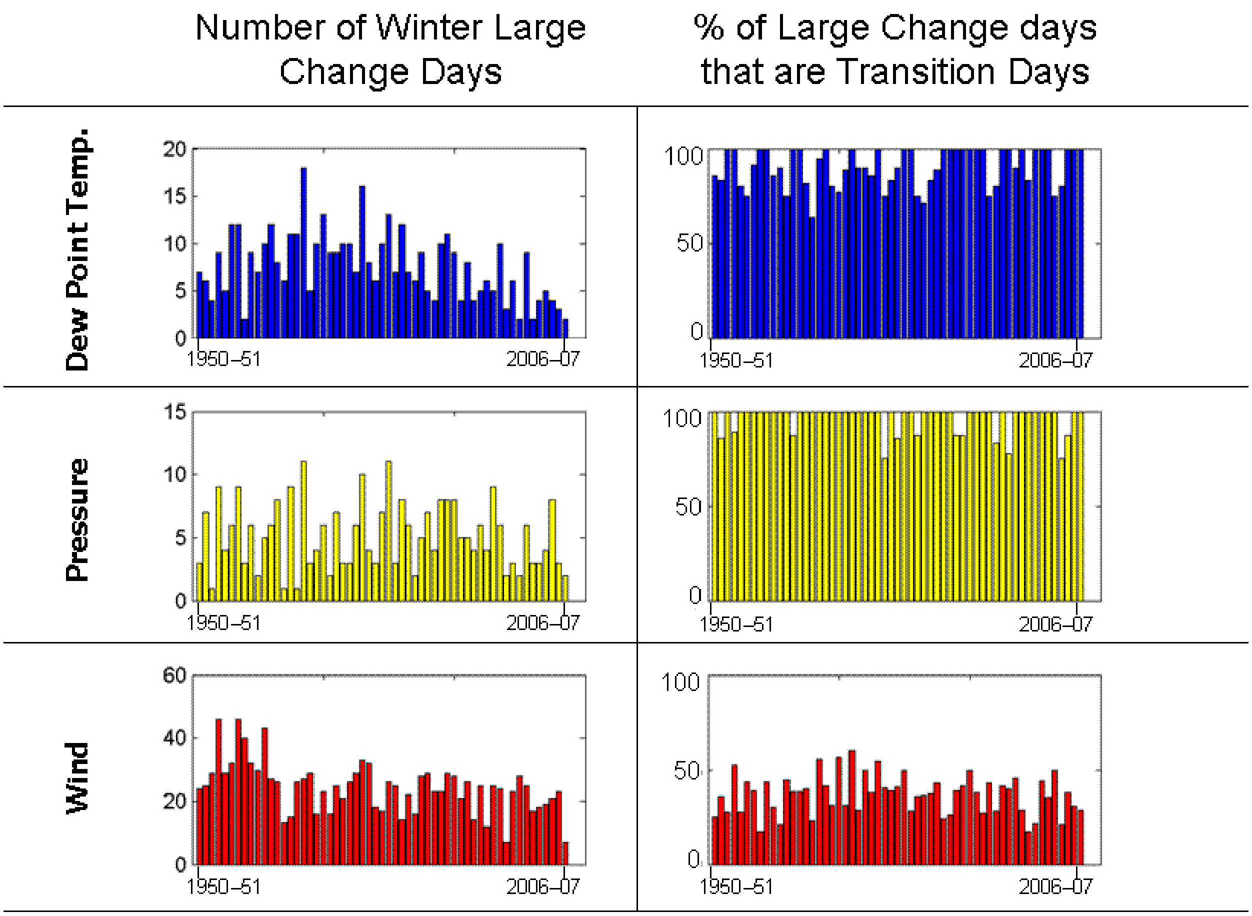

Figure 6. Left panels: Number of winter days at Fargo, ND on which the dew point range (blue), pressure range (yellow), and wind range (red) exceeds 90% of the expected winter seed day value for transition days, Dec. 1950–Feb. 2007. Right panels show the percentage of large change days that are transition days, color scheme corresponding to that on the left.

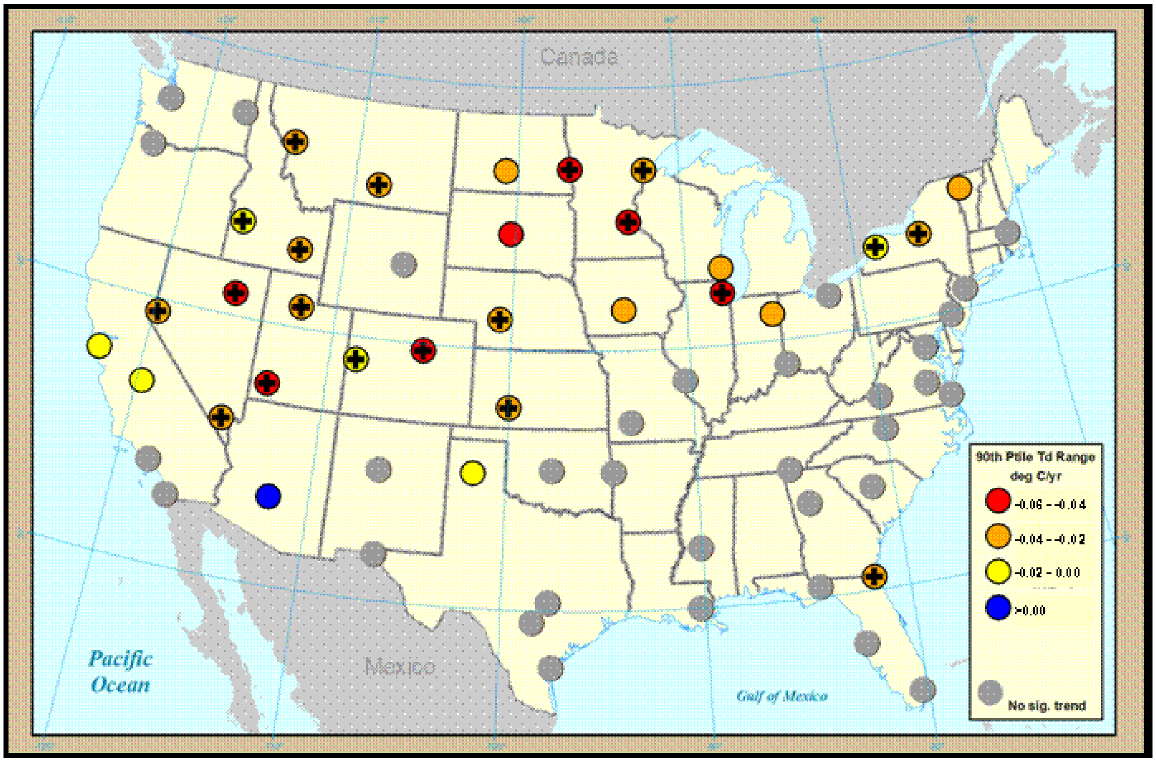

Figure 7. Trends in the 90th percentile winter (DJF) dew point range for the period Dec. 1950–Feb. 2007. The dew point range is defined as the absolute value of the difference between the maximum and minimum dew points observed at 4 a.m., 10 a.m., 4 p.m., and 10 p.m. local time. A plus sign denotes stations at which the residuals of the regression between the 90th percentile dew point range and transition frequency have no significant trend (see Figure 2). 0

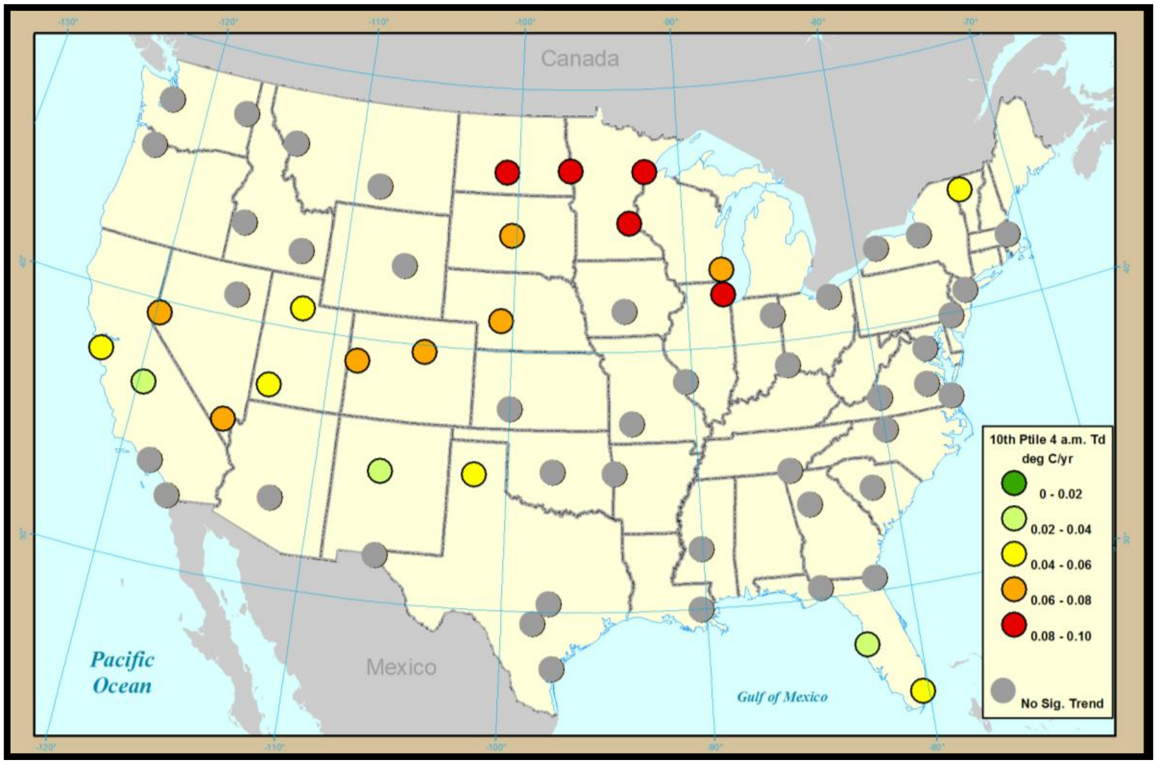

Figure 8. Trends in the 10th percentile winter (DJF) 4 a.m. local time dew temperature for the period Dec. 1950–Feb. 2007.

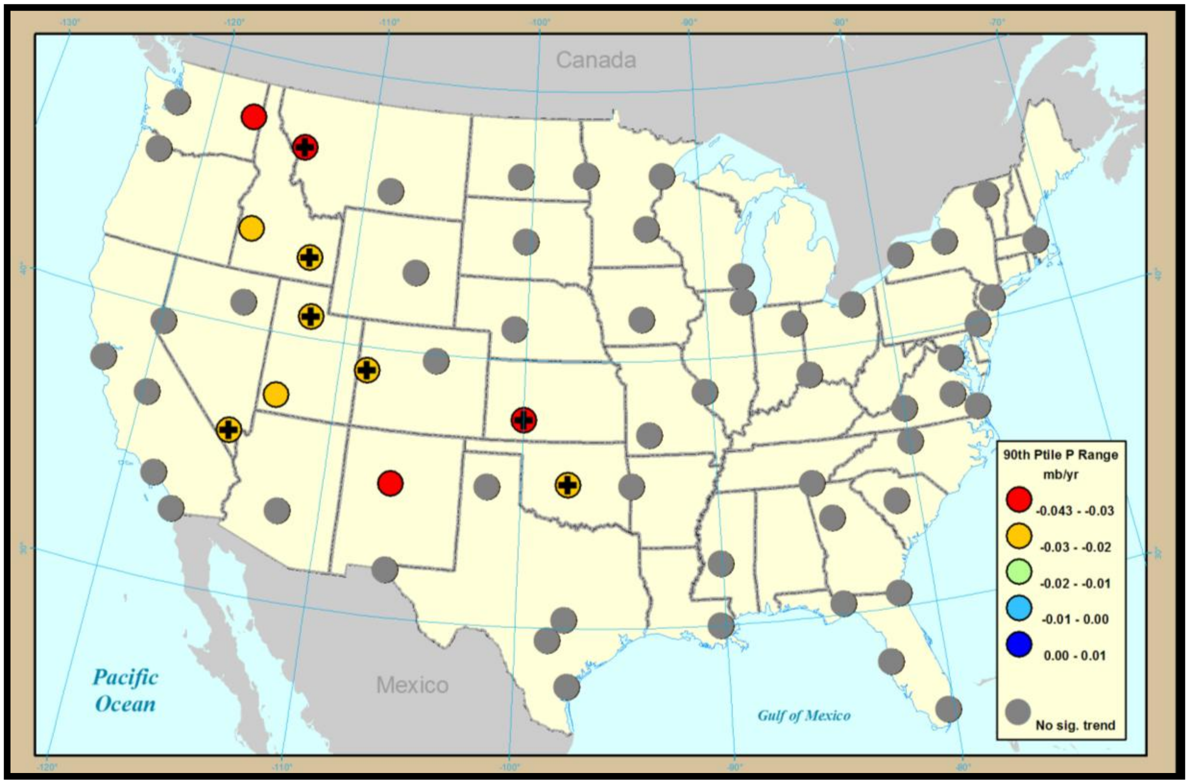

Figure 9. Same as Figure 7, but for the 90th percentile winter (DJF) pressure change, defined as the difference between the 4 a.m. and 10 p.m. local time sea level pressure.

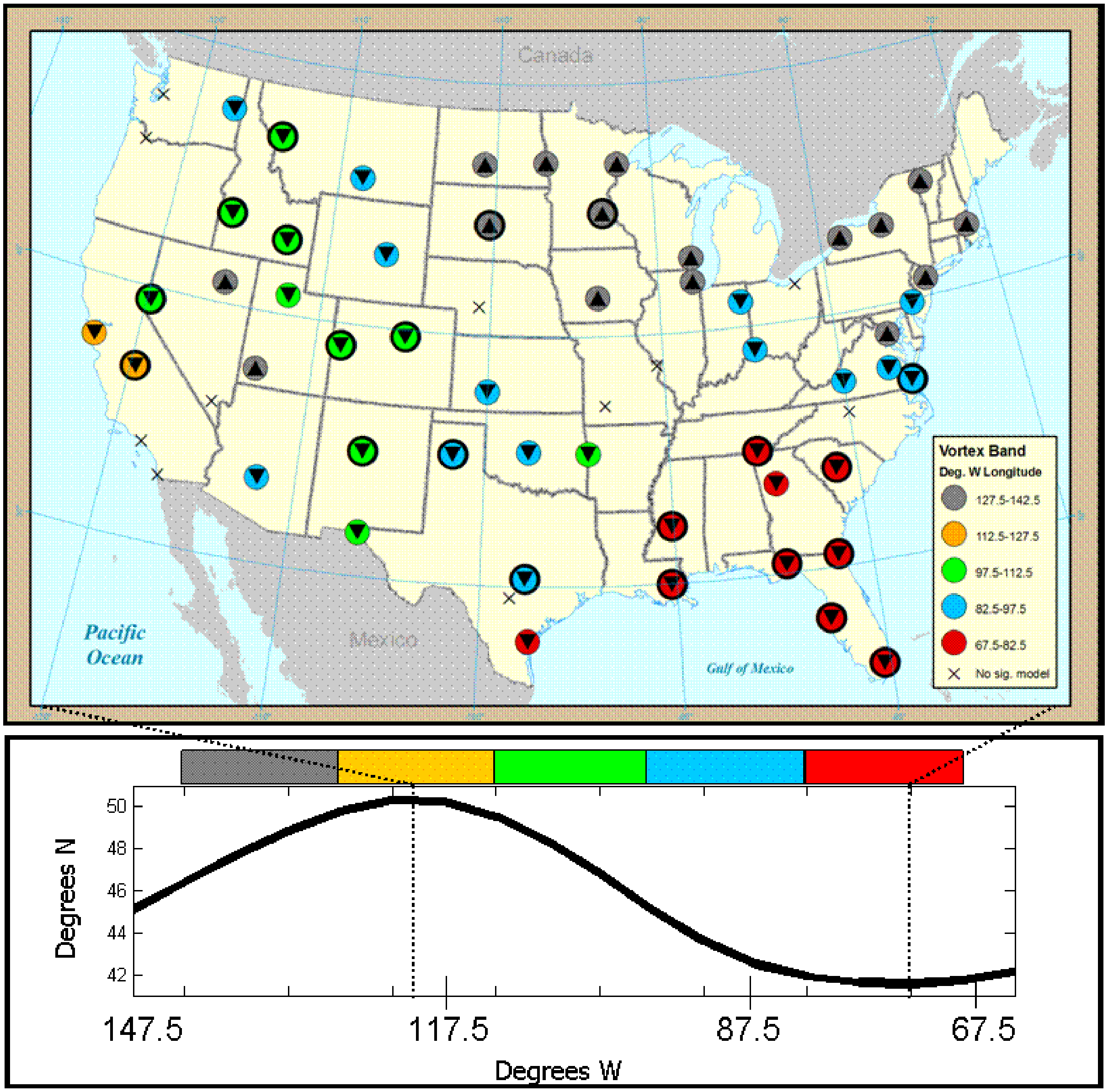

Figure 10. Relationships between winter (DJF) Spatial Synoptic Climatology transition frequency and the latitudinal position of the Northern Hemisphere circumpolar vortex. A dot indicates a significant relationship between vortex position and transition frequency; the color corresponds to the 15º longitude band with the highest correlation (average vortex shape shown in lower plot with matching colors). The triangle indicates the direction of the relationship between the vortex position and transition frequency – a positive relationship (north-pointing triangle) indicates higher transition frequencies when the vortex is more northerly. Black outlines around the colored dots identify stations where the residuals of the regression between vortex position and frequency demonstrate no significant trend. For example, the transition frequency at Denver, Colorado is most correlated to vortex activity between 97.5 and 112.5ºW and the relationship is inverse such that transition frequencies are higher when the vortex is farther south.

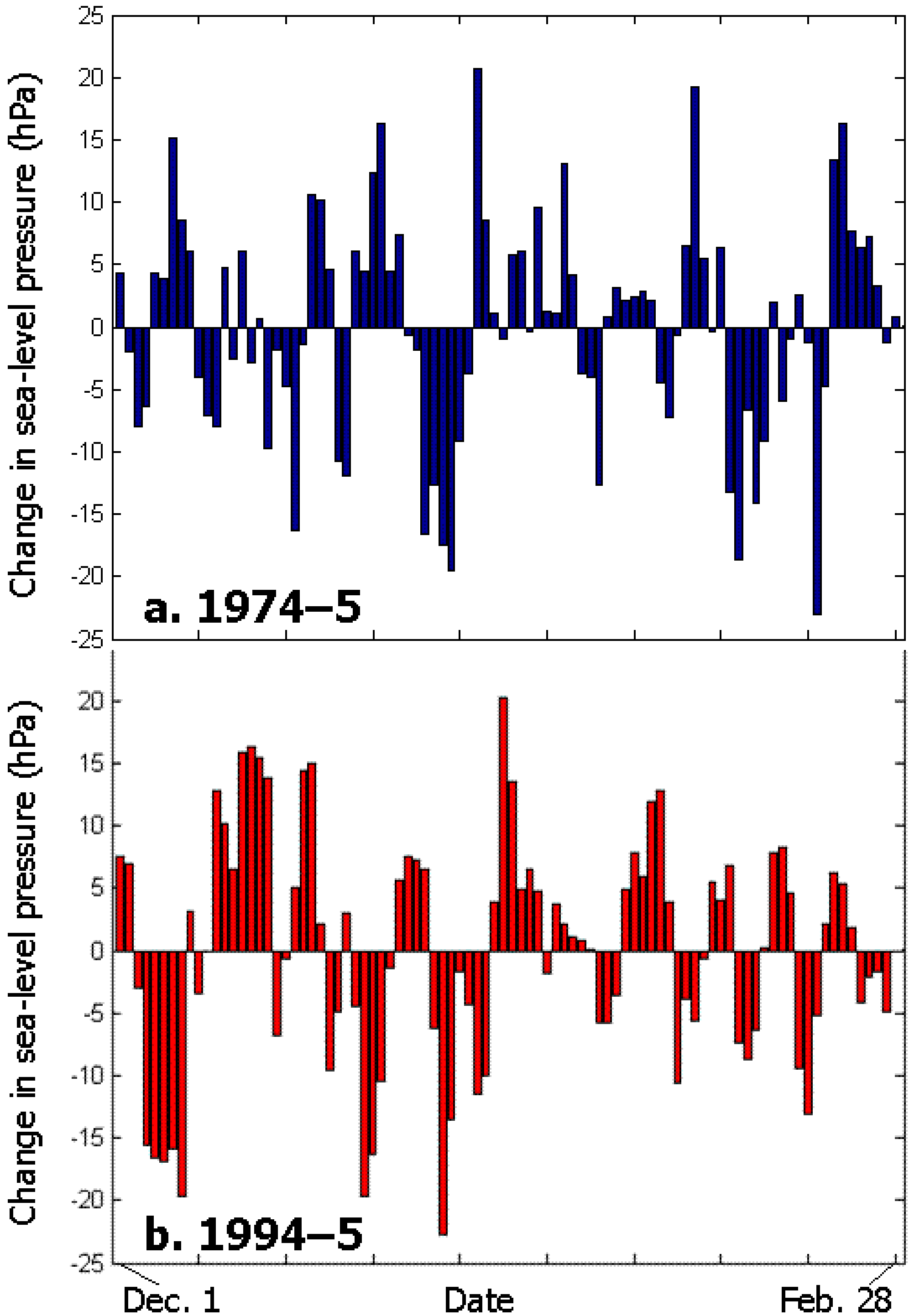

Figure 11. Daily sea level pressure relative to seasonal average at Missoula, Montana for winters (DJF) a) 1974–5 and b) 1994–5. Measurements are at 10 p.m. local time.

II. 7 References

Brayshaw D (2005) Storm tracks under climate change. Proc 2005 Br Council on Climate Change, 6 pp

Burnett AW (1993) Size variations and long-wave circulation within the January Northern Hemisphere Circumpolar Vortex: 1946–1989. J Clim 6: 1914–1920

Carnell RE, Senrio CA (1998) Changes in the mid-latitude variability due to increasing greenhouse gases and sulphate aerosols. Clim Dynamics 14: 369–383

Changnon D, Noel JJ, Maze LH (1995) Determining cyclone frequencies using equal-area circles. Mon Weather Rev 123: 2285–2294

Davis RE, Benkovic SR (1994) Spatial and temporal variations of the January circumpolar vortex over the Northern Hemisphere. Int J Clim 14: 415–428

Efron B, Tibshirani R (1986) Bootstrap methods for standard errors, confidence intervals, and other measures of statistical accuracy. Statistical Science 1: 54–75

Frauenfeld OW, Davis RE (2003) Northern Hemisphere circumpolar vortex trends and climate change implications. J Geophys Res D 108: ACL 7-1

Gong DY, Ho CH (2004) Inter-seasonal variability of wintertime temperature over east Asia. Int J Climatol 24: 131-144

Held IM (1993) Large-Scale Dynamics and Global Warming. Bull. Am. Meteorol. Soc. 74: 228–241

Kalkstein LS, Dunne PC, Vose RS (1990) Detection of Climatic Change in the Western North American Arctic Using a Synoptic Climatological Approach. J Clim 3: 1153–1167

Kalkstein LS, SC Sheridan, Graybeal DY (1998) A determination of character and frequency changes in air masses using a spatial synoptic classification. Int J Clim 18: 1223–1236

Karl TR, Knight WR, Plummer N (1995) Trends in high-frequency climate variability in the twentieth century. Nature 377: 217–220

Karl TR, Knight RW (1998) Secular trends of precipitation amount, frequency, and intensity in the United States. Bull. Am. Meteorol. Soc. 79: 1107–1119

Klein WH (1957) Principal tracks and mean frequencies of cyclones and anticyclones in the Northern Hemisphere. Research Paper 40, U.S. Weather Bureau, 60 pp

Knight DB, Davis RE, Sheridan SC, Hondula DM, Sitka LJ, Deaton M, Lee TR, Gawtry SD, Stenger PJ, Mazzei F, Kenny BP (2008) Increasing frequencies of warm and humid air masses over the conterminous United States from 1948 to 2005. Geophys Res Lett 35: L10702

Lambert SJ (1995) The effect of enhanced greenhouse warming on winter cyclone frequencies and strength. J Clim 8: 1447–1452

Leathers DJ, Yarnal B, Palecki MA (1991) The Pacific/North American Teleconnection Pattern and United States Climate: Part I: Regional Temperature and Precipitation Associations. J Clim 4: 517–528

McCabe GJ, Clark MP, Serreze MC (2001) Trends in Northern Hemisphere Surface Cyclone Frequency and Intensity. J Clim 14: 2763–2768

Meehl GA, Tebaldi C (2004) More Intense, More Frequent, and Longer Lasting Heat Waves in the 21st Century. Science 305: 994–997

Paciorek CJ, Risbey JS, Ventura V, Rosen RD (2002) Multiple Indices of Northern Hemisphere Cyclone Activity, Winters 1949–99. J Clim 15: 1573–1590

Rind D, Goldberg R, Hansen C, Rosenzweig C, Ruedy R (1990) Potential Evapotranspiration and the Likelihood of Future Drought. J Geophys Res D: 95, 9983–10004

Rohli RV, Wrona KM, McHugh MJ (2005) January Northern Hemisphere Circumpolar Vortex Variability and its relationship with Hemispheric Temperature and Regional Teleconnections. Int J Clim 25: 1421–1436

Sheridan SC (2002) The redevelopment of a weather-type classification scheme for North America. International Journal of Climatology 22: 51–68

Strong C, Davis RE (2007) Winter jet stream trends over the Northern Hemisphere. Q J R Meteorol Soc 133: 2109–2115

Trenberth KE, Jones PD, Ambenje P, Bojariu R, Easterling D, Klein Tank A, Parker D, Radimzadeh F, Renwick JA, Rusticucci M, Soden B, Zhai P (2007) Observations: Surface and Atmospheric Climate Change. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Avery KB, Tignor M, Miller HL (eds) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Wallace JM, Gutzler DS (1981) Teleconnections in the geopotential height field during the Northern Hemisphere Winter. Mon Weather Rev 109: 784–812

Yin JH (2005). A consistent poleward shift of the storm tracks in simulations of 21st century climate. Geophys Res Lett 35: L18701

III. A Preliminary Winter Transition Type Climatology for the United States, 1951–2007

III.1 Introduction

Unlike the six air mass types of the Spatial Synoptic Classification (Sheridan 2002), the SSC's transition category represents a wide array of synoptic-scale atmospheric features. This is by design, as the category is supposed to capture all varieties of changes in the weather, such as cold front and warm front passages. In previous and ongoing research, however, the transition category is often excluded from some analyses because of the suite of differing meteorological conditions it likely represents (e.g., Hondula et al., 2009). This caveat especially hinders the usefulness of the transition category in applied climatological studies, as surface systems potentially respond differently based on the direction of change that is occurring. Further, a validation of the transition category as a true identifier of significant weather changes will support more widespread use of the SSC. Currently it is unknown whether the transition category acts as a "catch-all" for the air mass identification, labeling days that are not easily classified into one of the six air mass types as transitions.

The goal of this component of the research is to identify sub-types within the transition category, and in doing so, evaluate the validity of the SSC as a means for identifying frontal passages and other significant synoptic-scale patterns associated with changing weather conditions. We further examine trends in the sub-types in an effort to more thoroughly understand the nature of the widespread decline in transition frequency observed over the past several decades (e.g., Knight et al. 2008).

III.2 Data and Methods

SSC calendars and corresponding meteorological data at each of 63 stations across the contiguous United States are considered for winter (DJF) 1950–51 through winter 2006–07. The mean daily dew point temperature change and pressure change between 4 a.m. and 10 p.m. local time is determined for each station. Each transition day is then assigned to one of four sub-types based on how the dew point and pressure change compare with the mean (e.g., Td increase relative to mean and P decrease relative to mean). These variables are selected because they are likely the best two predictors of transition type of the three variables used by the SSC to identify transitions. Note that we use the signed change rather than the absolute value "range" employed in the SSC. Accordingly, each winter transition day throughout the record is assigned to one of the four possible combinations of Td and P change. These sub-type calendars are used to generate a spatial climatology of transition types. We generate composite 850 millibar geopotential height fields for each sub-type at each station using NCEP/NCAR Re-analysis data (Kalnay et al. 1996) and examine daily weather maps (NOAA) for the centroid day of each quadrant at each station to develop a framework for the synoptic-scale patterns associated with each transition type. Average geopotential height differences between 4 a.m. and 10 p.m. local time for each subtype are contoured using the IDW algorithm in ArcMap (ESRI) with equal contour intervals.

We also consider trends in sub-type frequencies to determine if any specific transition patterns have become proportionally more or less common over time. For each region, we calculate the frequency of each transition type out of the total number of transition days and then employ linear regression to identify significant temporal trends. Because the total set of transition days is relatively small for each station (on average there are 5-15 transition days per winter), the sample size does not accommodate the generation of meaningful trends in the subtypes at individual stations, particularly for any subtypes that would be less frequently observed. Accordingly, we aggregate stations based on year-to-year patterns in transition frequency through hierarchical cluster analysis with Ward's method. Ward's method was chosen to create regions with similar numbers of station (Kalkstein et al. 1987). We then consider the trends in the subtypes on a regional basis.

To examine how the overall hemispheric circulation might influence the proportioning of transition subtypes, we use seasonal mean Northern Hemisphere 500mb circumpolar vortex data for the domain 60º–150º W (from Frauenfeld and Davis 2003). The vortex position is determined at three separate pressure surfaces by identifying the latitude of the regional of maximum geopotential height gradient across 5º longitude bands and is available from winter 1950–51 through 2001–02. We regress the frequency time series of each subtype for each region against the 500mb vortex position in each of the 18 5º-wide longitude bands that comprise the study domain.

III.3 Results and Discussion

Across the network, a majority of transition days fall into the two categories where the sign of the dew point temperature change and pressure change are opposite (Figure 1). Many of these days should be associated with cold and warm front passages. An example of the split of transition days is shown for Las Vegas, NV (Figure 2). For example, 21% of all transition days are in the lower-right quadrant with increasing dew point temperature and decreasing pressure, consistent with warm frontal passages. In addition for the tendency for more points to be located in the upper-left and lower-right quadrants, we observe a "hole" in the data centered near the origin. This is expected, as days that exhibit little dew point temperature change and little pressure change are likely not classified as transition in the SSC. Any points that do fall near the origin must be days with a large wind shift.

Each of the four transition types potentially represents a different synoptic weather pattern associated with a change from one air mass type to another. In the upper-right hand quadrant of Figure 2 are days with both increasing pressure and dew point temperature ("moist high"). Moving clockwise, days in the second quadrant are consistent with a farm frontal passage ahead of a low pressure center. The lower-left hand quadrant is characterized by decreasing dew point temperature and pressure ("dry low"). Finally, the fourth quadrant is consistent with cold frontal passages with falling dew point temperatures and increasing pressure. Below, we summarize the spatial variability in the subtype frequencies (Figures 3–6) and discuss the likely weather patterns associated with each (Figures 7–10).

Transition days on which the dew point temperature change and pressure change both increase are most commonly observed in the southwestern United States (1-2 cases per year) and rarely observed in the east (Figure 3). At Pacific coast stations, this pattern may emerge when one high pressure center moving west-to-east from the ocean replaces one that has persisted to the east. In the antecedent air mass the clockwise flow around the high advected dry air to the stations, whereas the new air mass may be positioned such that moist air is advected, or the air mass itself is generally moister. For example, at Seattle these days are associated with increasing high pressure to the southwest of the station, which would result in the advection of moist air directly from the ocean. (e.g., Figure 7a). Farther inland, in many cases we observed a persistent low pressure center that was not associated with precipitation being replaced by a Pacific air mass following a west-to-east or northwest-to-southeast trajectory (e.g., Figure 7b). Although much of the precipitation may fall west of the Four Corners area because of orographic effects, the air mass still may retain greater moisture than a low pressure center that has had no access to a moisture source for several days. This type is less common in the east because low pressure centers there have greater access to moisture from the Gulf of Mexico and Atlantic Ocean and maritime air masses from the Pacific have likely moderated and dried upon descent on the lee side of the Rockies.

Warm fronts are often associated with a decrease in pressure as a low pressure center approaches and an increase in dew point temperature. Our transition sub type with falling pressure and increasing moisture matches this pattern and is most commonly observed in the upper Midwest and Northeast, with a secondary maximum at San Diego

(Figure 4). In these regions the type is present on 7-8 days each winter, whereas elsewhere it is present 1-3 days per winter. The average geopotential height contours confirm an approaching low as the major feature of this subtype (Figures 8a and 8b). Our synoptic analysis also revealed cases associated with falling pressure and increasing moisture in the north that were not associated with low pressure centers, but instead were days when a high pressure center began to move east of the stations. The resulting wind shift and advection of moister air from the south around the west side of the high pressure center combined with the decreasing sea-level pressure results in a “false” warm front signal. The potential for this signal is supported by the high frequency of dry polar air masses across the north (Sheridan 2002). Because these days exhibit a large shift in both pressure and dew point as the air mass moves south and is moderated, it may not be entirely inappropriate to consider them transition days. Further, even if they are to be classified as transition days, it may be preferential to classify them differently than those purely associated with low pressure centers. At stations farther south, the geopotential height pattern more closely matches that expected with an approaching low – increasing pressure well to the west and decreasing pressure to the immediate west and at the station (e.g., Figure 8b). The composite maps do not reveal a consistent paradigm for the secondary maximum in southern California, suggesting that either a variety of synoptic-scale patterns or more localized influences such as a land-sea breeze may result in this type of transition classification.

Days on which the dew point temperature and pressure both drop are relatively rare across the entire country, with less than one case observed on average each winter.

The maximum frequency is observed across the west coast, Southwest, and east coast (Figure 5), approximately matching the spatial distribution of the number of lows observed during winter months (Klein 1957). Most often this transition type occurs when a low pressure center moves toward the east and the associated cold front passes the station late in the day (e.g., Figures 9a and 9b). The position of the stations is roughly coincident to the center of decreasing pressure in the east-west direction, indicating that the lowest pressures were present late in the day. Accordingly, on these days the low arrived close to 10 p.m. We believe that this type is infrequently observed because it requires proximity to low pressure centers and passage of the cold front. While the low pressure center may be confined to a small geographic area on the order of a few hundred miles, its associated cold front may extend across a larger area. As a low pressure center moves across the country, many stations will experience a significant shift in dew point temperature associated with the cold front, but a much smaller number will also experience a significant shift in pressure. Amongst those that do, this type is only observed when the front passes late in the day. We also noted several cases where this type was observed in the Southwest related to zonal movement of a high off the Pacific Ocean. When the anticyclone is located near the coast, moist air may be advected inland. As the high moves inland, over the desert, the moisture supply is cut off and the air advected northward around the west side of the high will be especially dry. The continued movement of the high to the east will result in decreasing pressure and decreasing dew point at stations located to its west.

Finally, days associated with a drop in dew point and increase in pressure represent a common transition occurrence, occurring on average between 5 and 8 times at stations in the east (Figure 6). Like the previous type, many of these days are identified as cold front passages (e.g., Figure 10a). However, this type is observed much more frequently, likely because of the larger spatial extent of anticyclones (and, thus, potential for increasing high pressure), As noted above, polar air masses often follow a trajectory over the upper Midwest and into the eastern half of the United States, and as such are much less frequently observed in the west. As we expect a cold front to be on the leading edge of such an air mass, it is logical that this transition type is most common across the east. Cyclogenesis downstream of the Rockies may also contribute to total cold front passage count in the east, particularly in the south where polar fronts are rarely observed (e.g., Figure 10b).

One of the major factors related to the identification of subtypes appears to be the timing and positioning of a cyclone as it approaches or passes the station. Although different synoptic mechanisms can lead to particular subtypes, in the case of the traditional cyclone model, we can imagine at least three of the types being identified depending on where the system is located relative to the station. If the station and low pressure center are on a similar latitude, and the low approaches but does not pass the station before 10 p.m., we observe a decrease in pressure and increased in dew point temperature. As discussed for the case where dew point and pressure both decrease, should the low just move past the station, a different subtype will be observed. The passage of a low to the north of a station early in the day will result in cold front classification. Accordingly, the same synoptic feature can lead to at least three of the four subtypes. This is not necessarily a weakness of the SSC or the subtype identification system because both are designed to classify the weather over discrete 24-hour periods.

We identify nine regions of similar year-to-year transition frequency time series using hierarchical cluster analysis with Ward's method (Figure 11). Most of the regions are very spatially coherent, with the exception of the Northwest region that includes the stations of Cheyenne, Wyoming, and Lincoln, Nebraska. The northwest region appears to include stations that would fall along a southerly displaced polar vortex with a ridge in the west. Trends in regionally aggregated subtypes are more common in the more frequently observed transition types (increasing dew point/decreasing pressure and decreasing dew point/increasing pressure) than in the two others (Table 1). No regional trends demonstrate increasing frequencies of any transition subtype.

Four regions demonstrate statistically significant trends in the proportion of at least two subtypes: Midwest, Northeast, Rocky Mountain, and Northwest (Table 1). No trends are evident in the other five regions. In general, there is consistent evidence for a decreasing proportion of transition days on which the dew point increases and pressure decreases (approaching low, e.g., Figure 12), and an increasing proportion of days on which the dew point falls and pressure rises (cold front passage, e.g., Figure 13). The sign of the trends in the other two subtypes vary by region.

	Transition Subtype			
Region/Extent	Td+, P+	Td+, P-	Td-, P-	Td-, P+
Midwest (80-110ºW)		-1.24	-0.38	1.63
Related Vortex Band		x	140-145 (-)	85-90 (+)
Northeast (70-80ºW)	-0.20			1.40
Related Vortex Band	65-70 (-)			75-80 (-)
Rocky Mountain (100-120ºW)		-1.13	0.99	
Related Vortex Band		140-145 (+)	115-120 (+)	
Northwest (100-120ºW)	1.01	-1.76		
Related Vortex Band	95-100 (+)	90-95 (-)		

Table 1. Trends in transition sub-type frequency divided by total transition days across four United States regions. For each region, the first line shows the regression slope B for $\alpha < 0.05$. Units are proportional percentage per decade (i.e., a value of 1.00 indicates an increase from 10% of total transition days to 11% over a ten-year span). The second line shows which, if any, 5º longitude vortex band position is best correlated with the proportional frequency and the sign of the relationship. A positive correlation indicates that the proportional frequency is higher when the vortex is displaced to the north. No trends are present for any subtypes in the other five regions, and an "x" indicates no significant relationship for a case presented in the table.

In the Midwest region the approaching low subtype is becoming less frequently observed relative to all transition days, although we observe no significant relationship with vortex position at any longitude. The subtype associated with falling dew point temperature and pressure is also decreasing in frequency, and there is a statistically significant relationship with vortex activity over the eastern Pacific. This type is more frequently observed when the Aleutian low is strengthened, an indicator of more meridional flow. The fourth subtype, which includes cold front passages, is increasing in proportional frequency. The trend is positively related to the latitude of the vortex.

Collectively, these results are consistent with a northward shift of cyclone tracks in the middle latitudes (McCabe et al., 2001) and a contacting vortex (Frauenfeld & Davis 2003). The subtypes associated with decreasing pressure require proximity to the low pressure center, as described above. As storm tracks shift to the north, the likelihood of low pressure centers passing over this region is decreasing, but the cold fronts associated with the lows may still be observed.

The proportion of two transition subtypes associated with increasing pressure in the Northeast has significantly changed over the study period. Because of the overall low frequency of days with a dew point and pressure increase (see Figure 3), however, we are most interested in the increasing trend in cold front passages. When the trough in the east is enhanced or displaced southward cold fronts account for a greater portion of all transition days. In addition to the storm track trend noted for the Midwest, this pattern might also be related to more frequent incursions of polar air across the eastern half of the country when the trough extends farther south.

Across the Rocky Mountain region, the approaching low subtype has decreased in frequency and the type associated with decreasing dew point temperature and pressure has become more common. The trend with approaching lows is probably not related to vortex activity over the Pacific, as the results first suggest, because the vortex position west of the continent has not demonstrated any significant trend. The positive relationship between the vortex position and approaching low frequency is unsurprising, as a more moderate Aleutian low indicates zonal flow, enabling storms to track into the United States instead of being diverted to the north around a large ridge. In the case of the subtype with decreasing dew point and pressure, we see proportionally more cases with an enhanced ridge, which has become more prevalent over the past two to three decades (Frauenfeld and Davis 2003). Subsequent analysis reveals that the actual number of cases on this subtype has not increased in this region, so the proportion is increasing simply because the number of approaching low cases is decreasing. The same theory is applicable in the Northwest region where we see a real decrease in approaching lows because of enhanced ridging and resultant increase in the proportion of another subtype.

III.4 Conclusion

The transition type of the SSC appears to be a reputable means of identifying synoptic-scale atmospheric patterns associated with shifts from one air mass type to another. We have identified four sub-types of transition days that may be used to enhance applications of the SSC to surface systems and environments. Using the subtypes, we have developed a preliminary transition climatology for the United States. Patterns resembling warm fronts/approaching lows and cold fronts account for a majority of transition days and are most frequently observed in the north and east, respectively.

Significant trends are present in the proportion of subtypes observed each winter in some regions of the United States. Using circumpolar vortex data, we have related these trends to adjustments in the circulation. In the Northwest and Rocky Mountain regions, increased ridging has led to fewer transition days associated with approaching lows, whereas in the Midwest and Northeast, we observe more cold front days but fewer approaching lows, indicative of a shift in storm tracks to the north. This shift in storm track patterns may result from the contracting vortex in the west, which impacts where cyclogenesis occurs. Although there may be station-specific features not revealed in this analysis, the results provide a baseline for an improved understanding of the way in which decadal-scale circulation changes impact the formation and persistence of synoptic-scale weather patterns.

III.5 Figures

(on following pages)

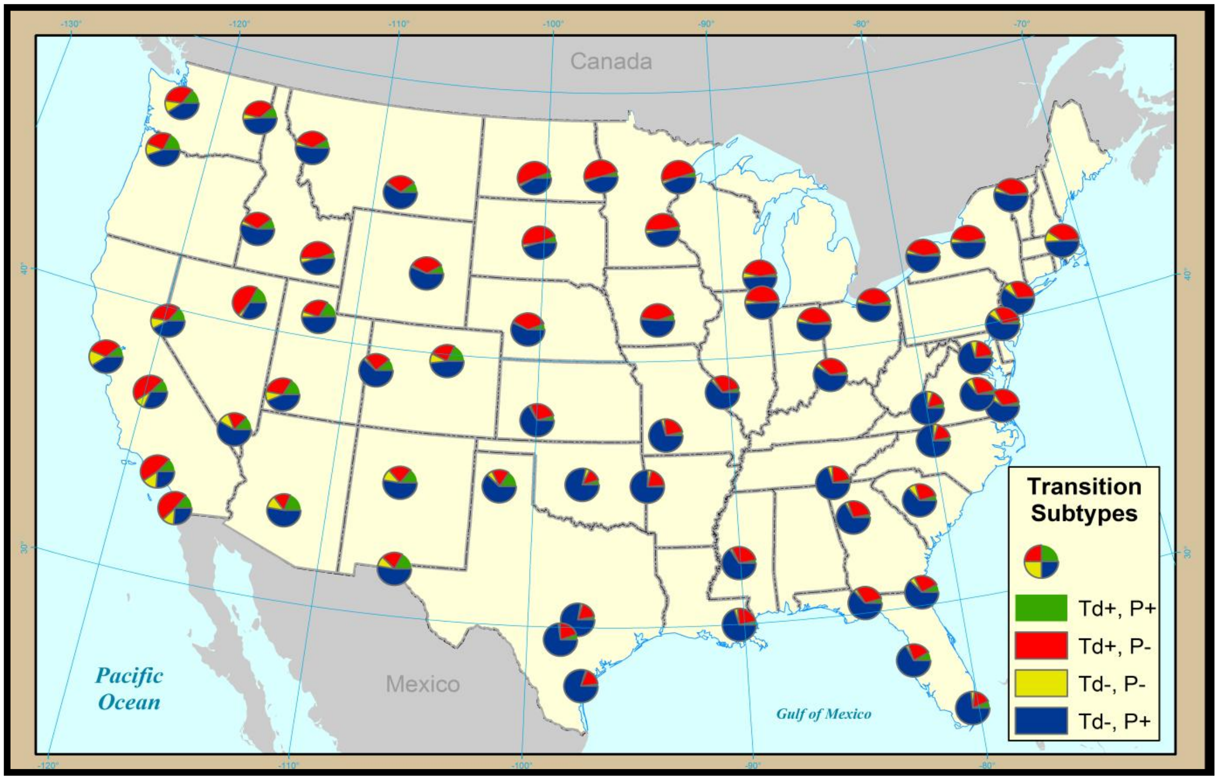

Figure 1. Relative frequency of four transition subtypes at each of 63 stations for winters, Dec. 1950–Nov. 2007. Transition subtypes are identified by the sign of the change in dew point temperature and sea-level pressure between 4 a.m. and 10 p.m. local time (relative to the average change over the same time period for all winter days). The total number of days in each subtype are shown in Figures 3–6.

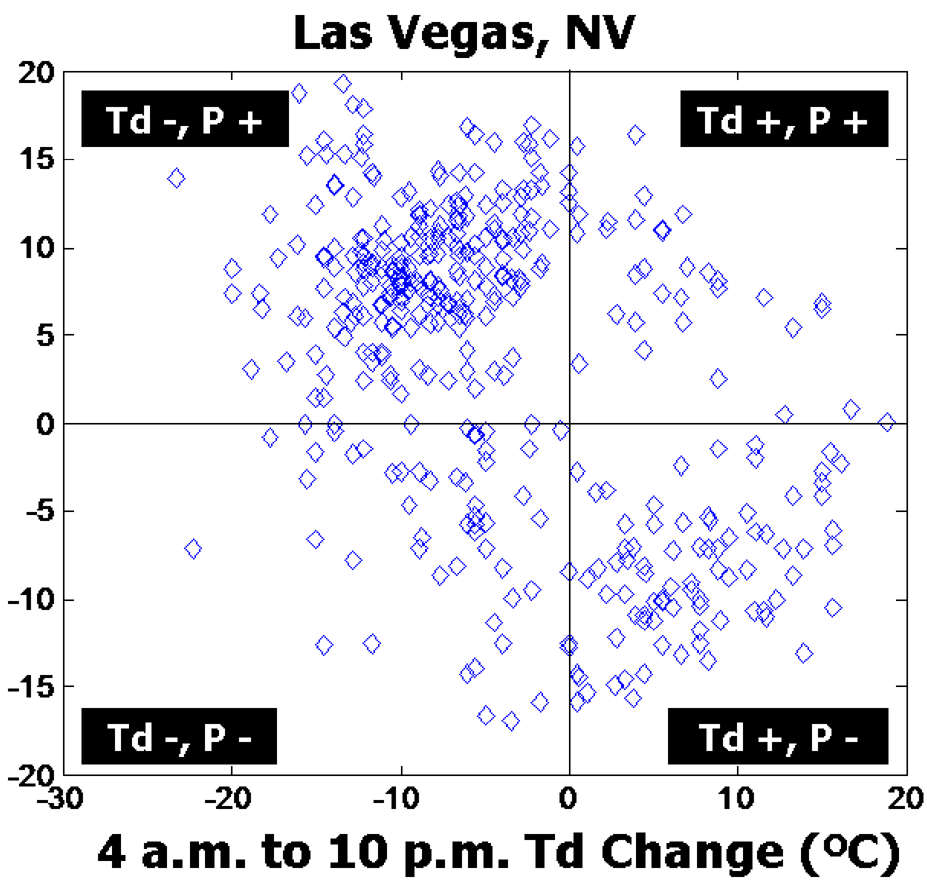

Figure 2. Winter transition days at Las Vegas, NV, Dec. 1950–Nov. 2007. Each diamond represents one day. Sea-level pressure (SLP) measured in hPa; dew point temperature (Td) measured in degrees C.

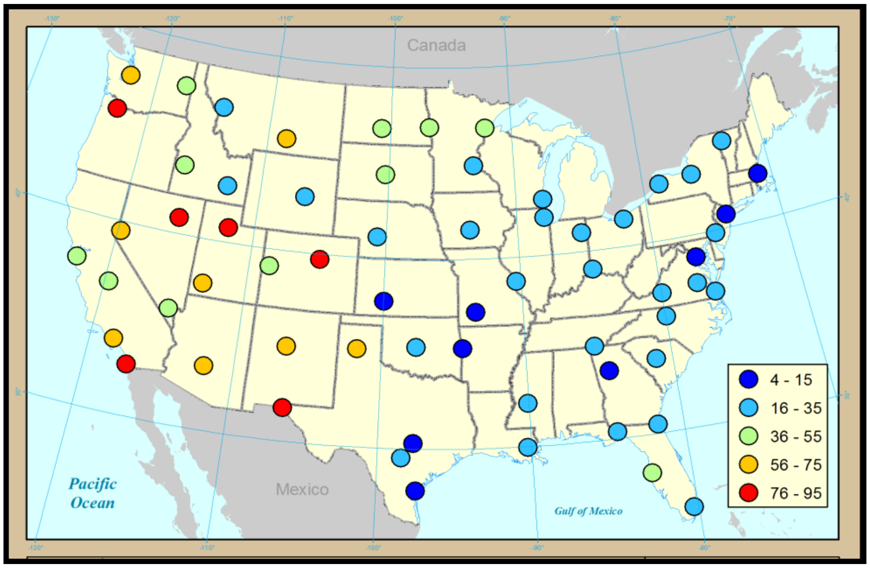

Figure 3. Count of winter transition days, Dec. 1950–Nov. 2007, on which the dew point temperature and pressure increased between 4 a.m. and 10 p.m. relative to the average daily change over the same time period.

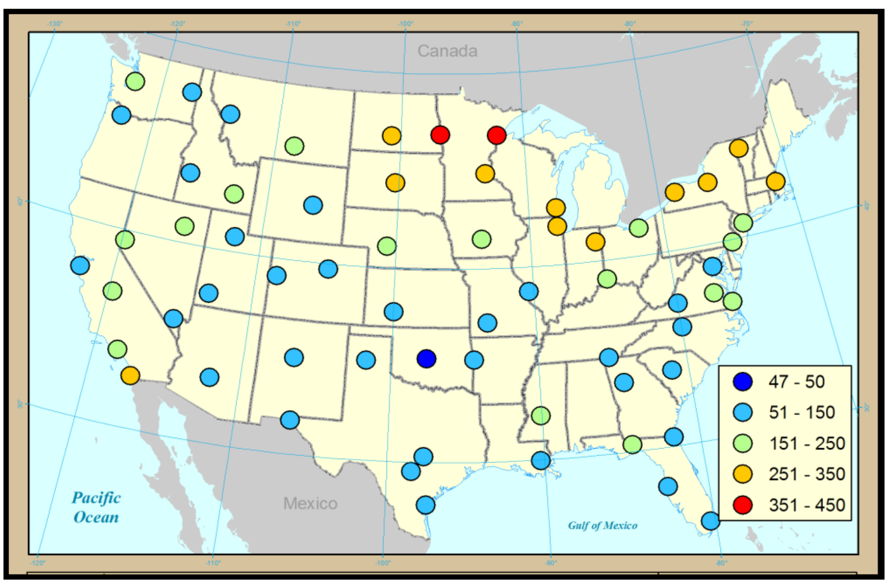

Figure 4. Count of winter transition days, Dec. 1950–Nov. 2007, on which the dew point temperature increased and pressure decreased between 4 a.m. and 10 p.m. relative to the average daily change over the same time period.

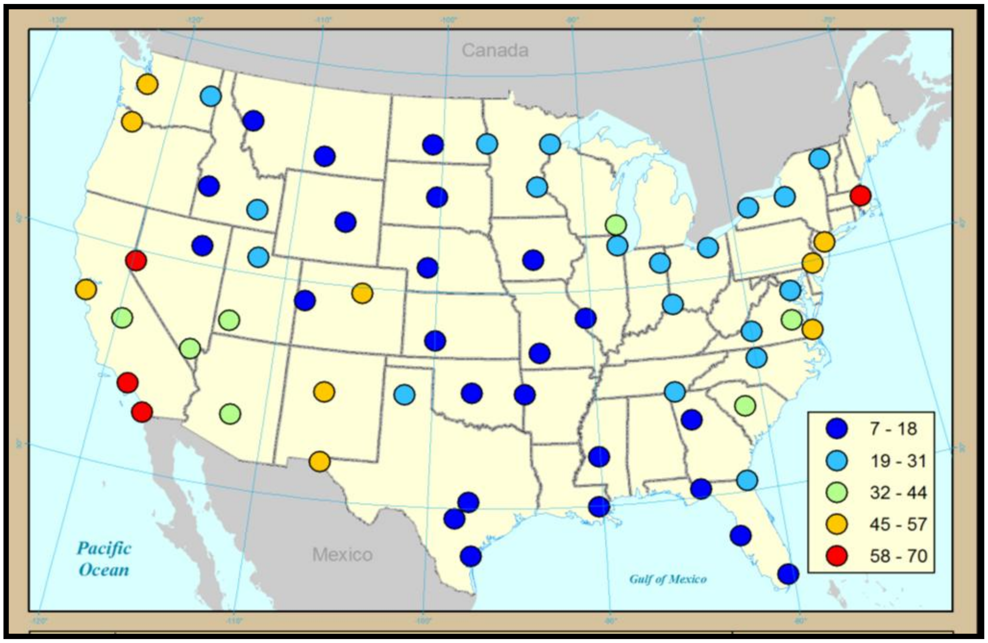

Figure 5. Count of winter transition days, Dec. 1950–Nov. 2007, on which the dew point temperature and pressure decreased between 4 a.m. and 10 p.m. relative to the average daily change over the same time period.

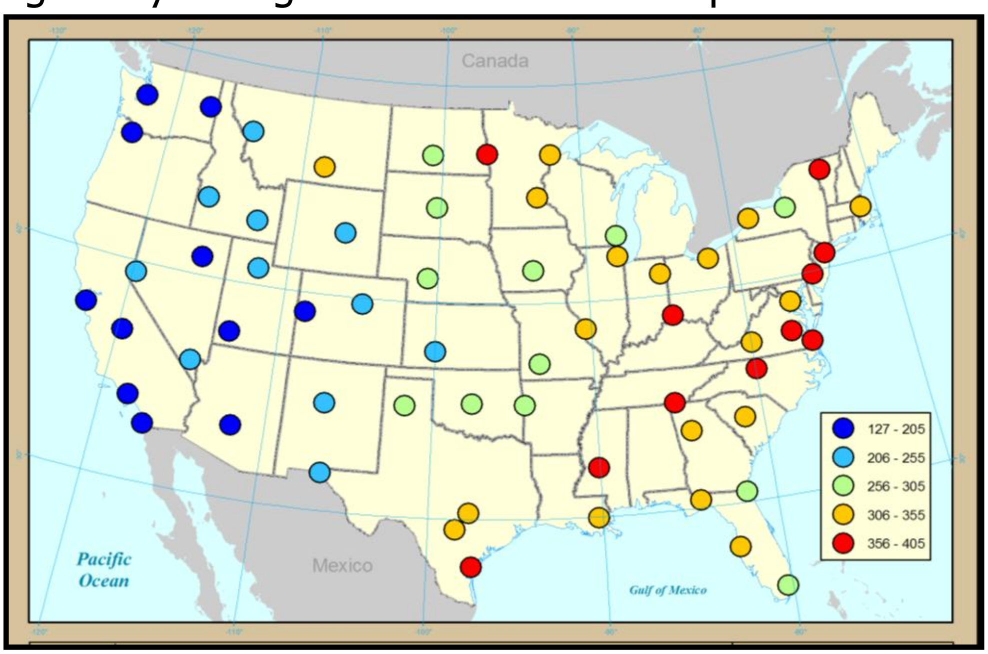

Figure 6. Count of winter transition days, Dec. 1950–Nov. 2007, on which the dew point temperature decreased and pressure increased between 4 a.m. and 10 p.m. relative to the average daily change over the same time period.

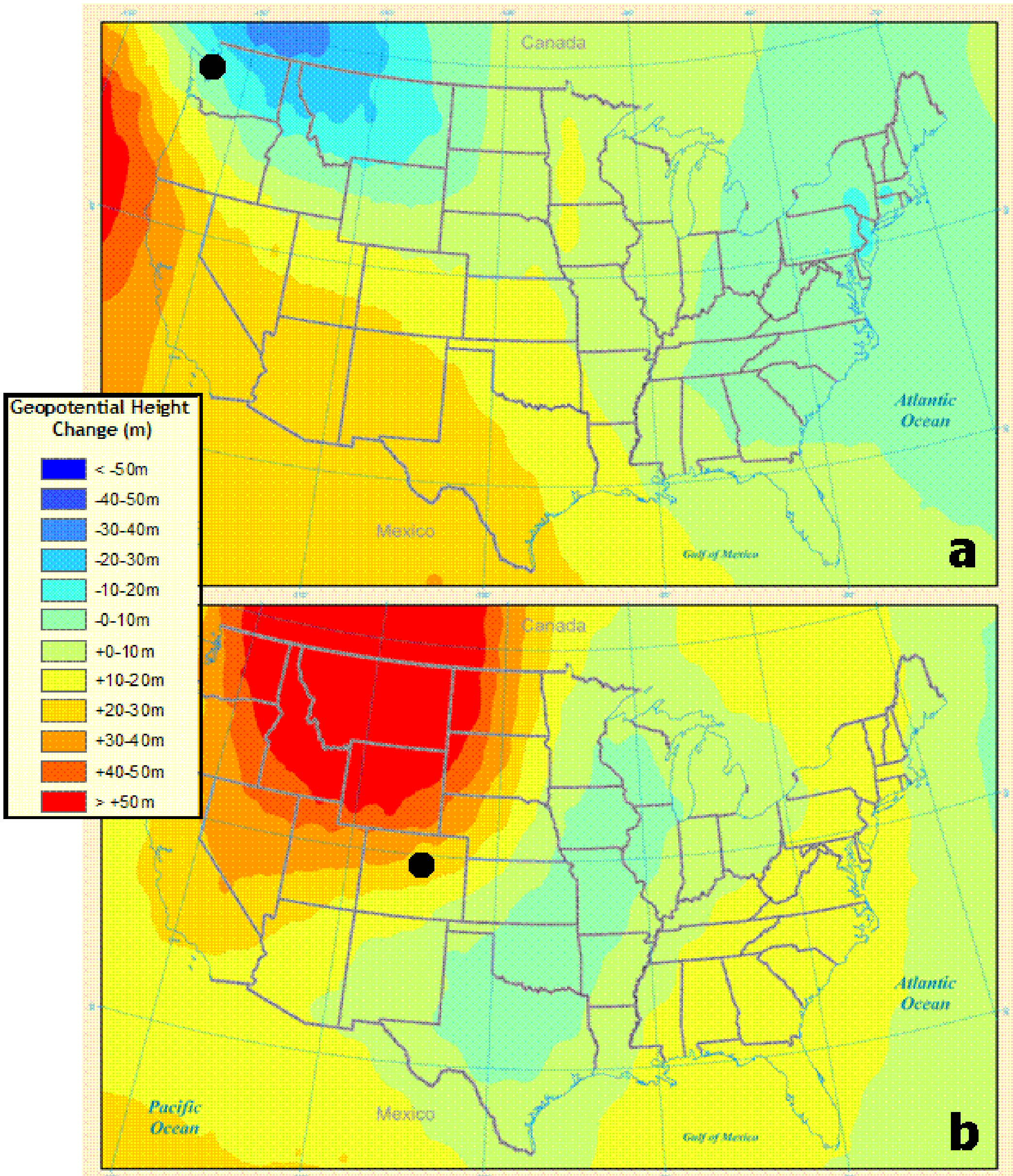

Figure 7. Average 850mb geopotential height change on transition days on which the dew point temperature and surface pressure increased, winters 1950– 51 through 2006–07 at a) Seattle, Washington, and b) Denver, Colorado. Stations denoted by circle.

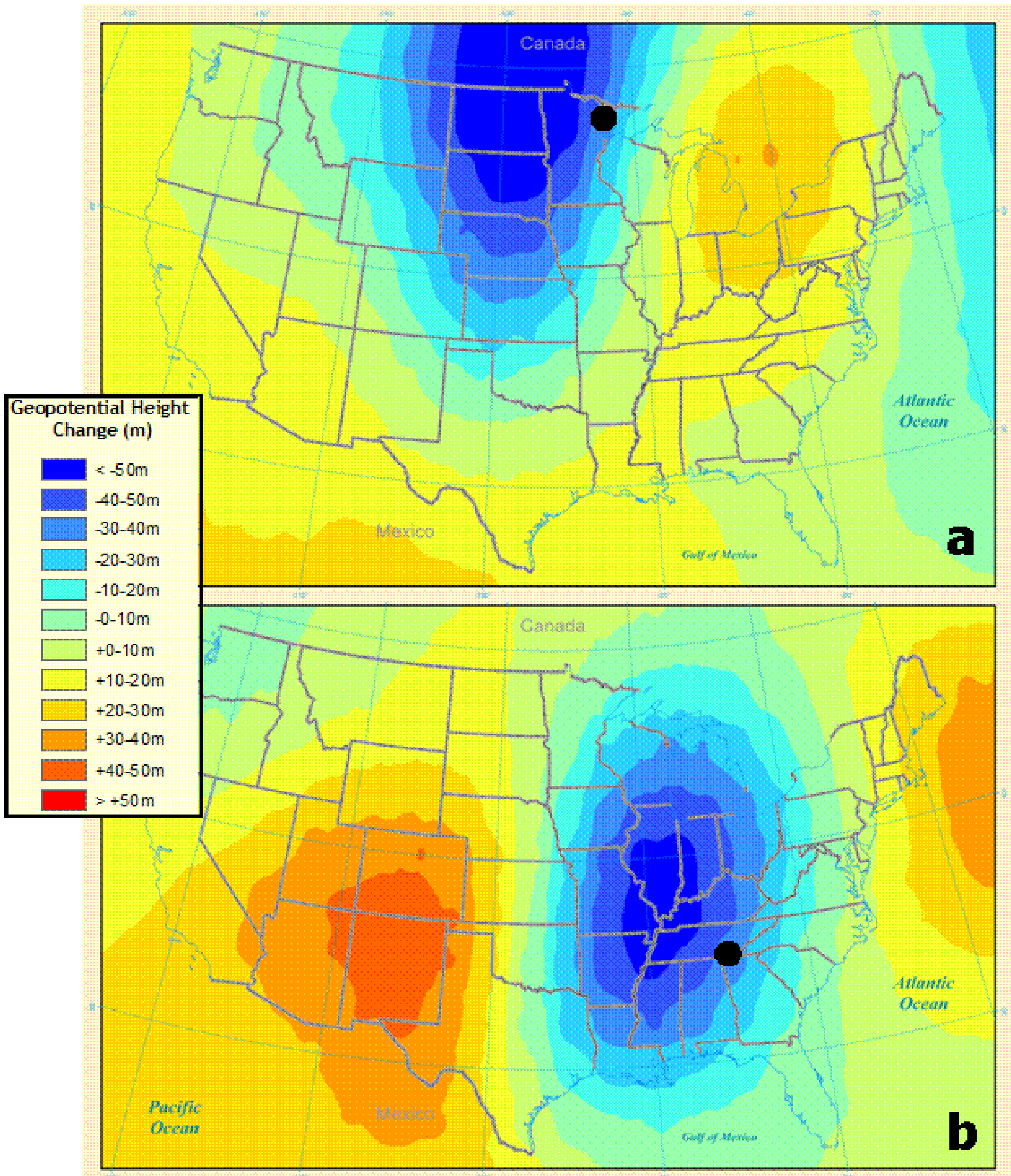

Figure 8. Average 850mb geopotential height change on transition days on which the dew point temperature increased and surface pressure decreased, winters 1950– 51 through 2006–07 at a) Duluth, Minnesota, and b) Chattanooga, Tennessee. Stations denoted by circle.

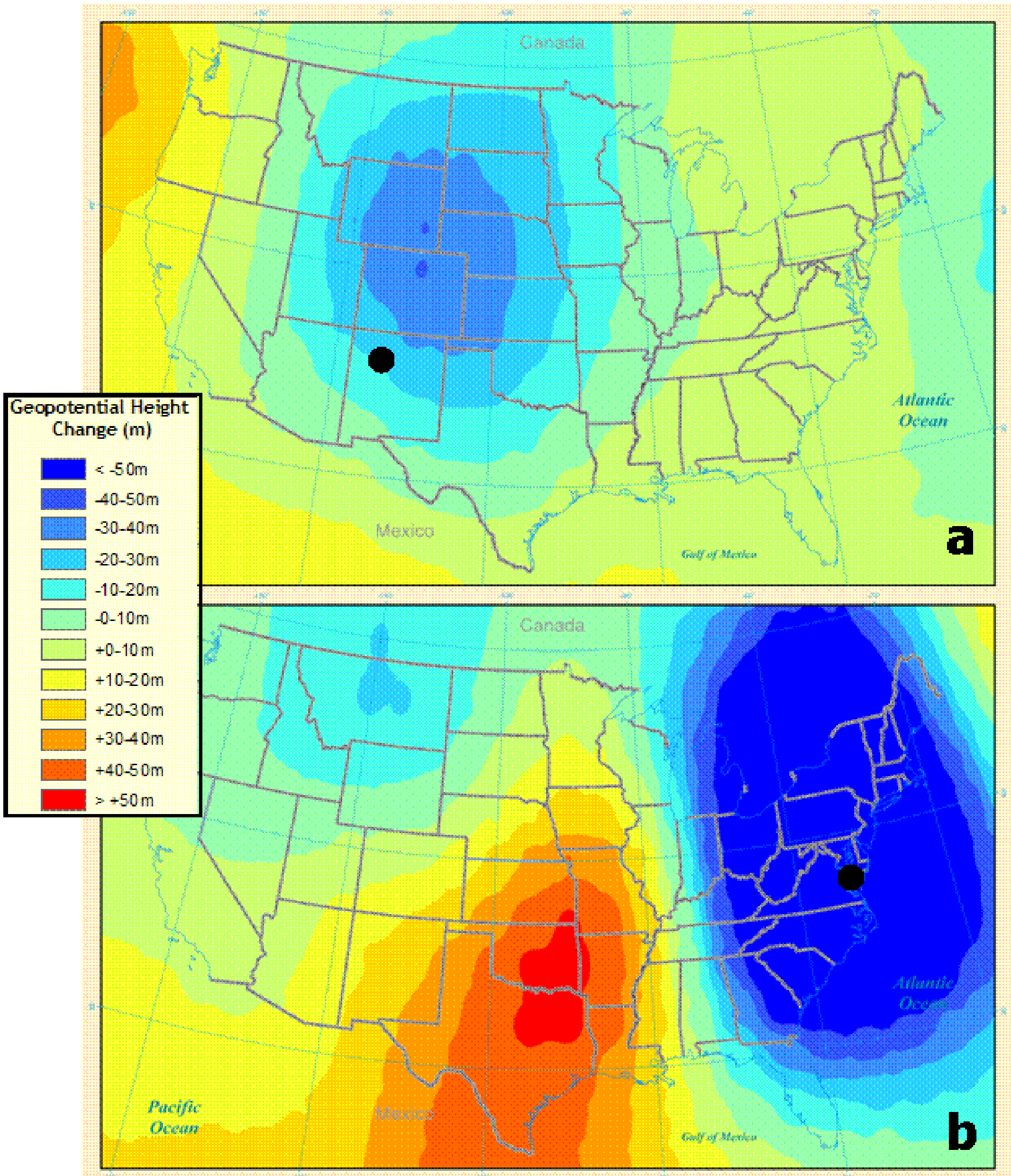

Figure 9. Average 850mb geopotential height change on transition days on which the dew point temperature and surface pressure decreased, winters 1950– 51 through 2006–07 at a) Albuquerque, New Mexico, and b) Norfolk, Virginia. Stations denoted by circle.

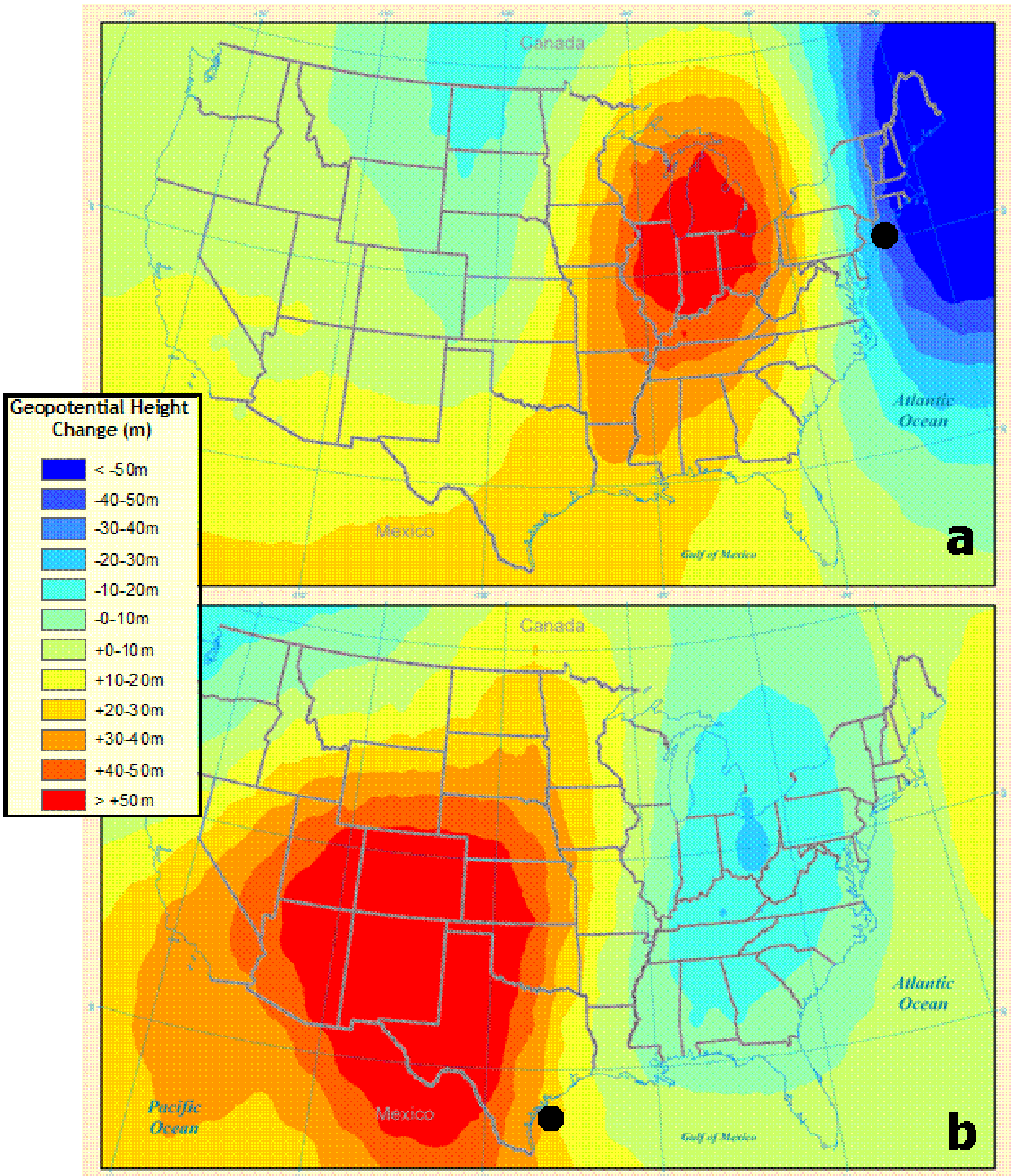

Figure 10. Average 850mb geopotential height change on transition days on which the dew point temperature decreased and surface pressure increased, winters 1950– 51 through 2006–07 at a) Newark, New Jersey, and b) Corpus Christi, Texas. Stations denoted by circle.

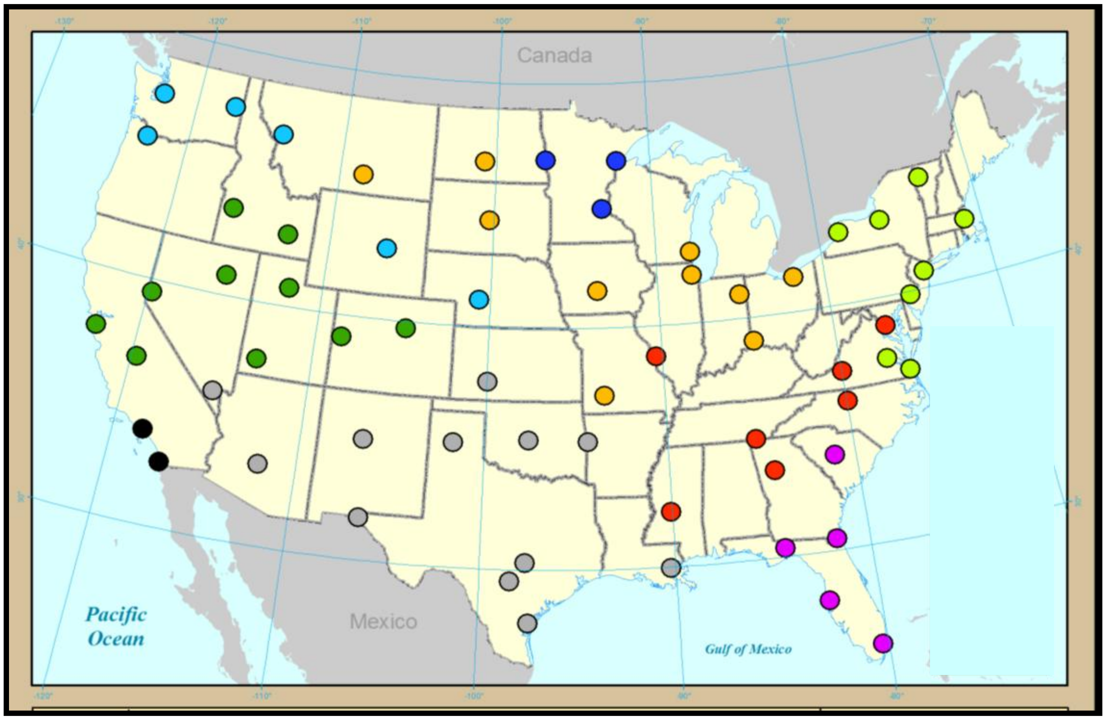

Figure 11. Hierarchical clustering solution grouping stations by annual winter transition frequency. Region names and colors: South-grey, East-red, Midwest-yellow, Northeast-light green, Rocky Mountain-dark green, Northwest-light blue, Upper Midwest-dark blue, Southeast-purple, Southern California-black.

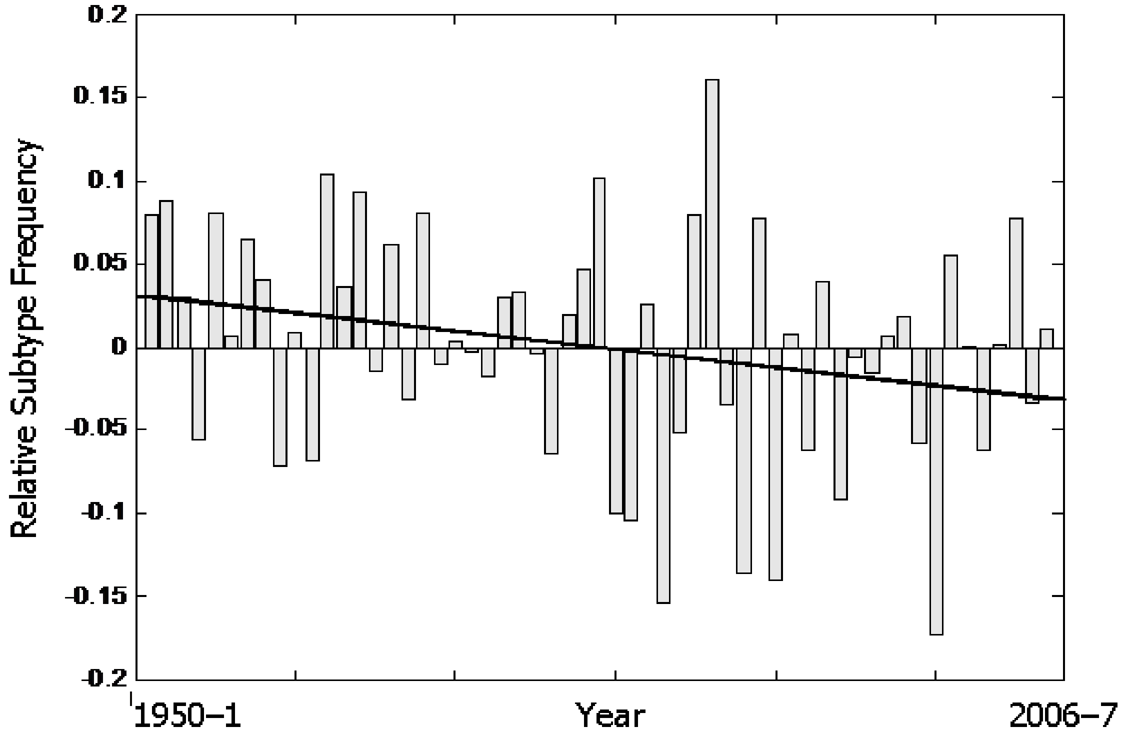

Figure 12. Annual relative frequency of wintertime (DJF) transition days on which the dew point temperature increased and the pressure decreased for the Rocky Mountain region, Dec. 1950–Feb 2007. The proportional frequency for each year is equal to the sum of all observed subtype days across all regional stations divided by the sum of all observed transition days. Values plotted are the difference from the mean proportional frequency (0.354). The solid black line represents a statistically significant trend ($\alpha<0.05$).

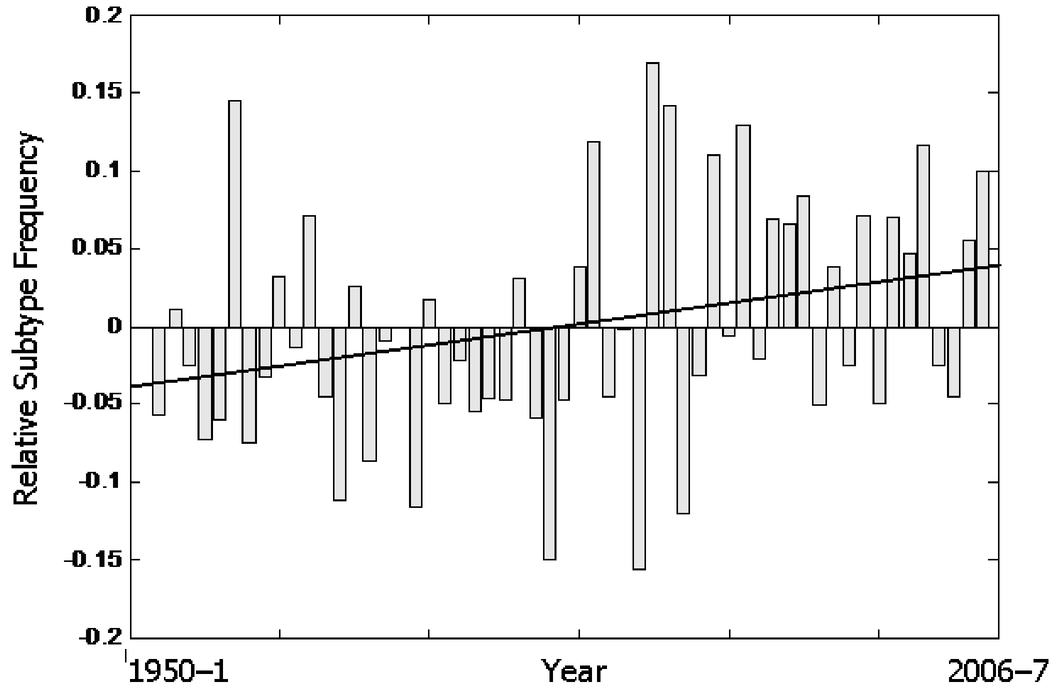

Figure 13. Annual relative frequency of wintertime (DJF) transition days on which the dew point temperature decreased and the pressure increased for the Northeast region, Dec. 1950–Feb 2007. The proportional frequency for each year is equal to the sum of all observed subtype days across all regional stations divided by the sum of all observed transition days. Values plotted are the difference from the mean proportional frequency (0.525). The solid black line represents a statistically significant trend ($\alpha<0.05$).

III. 6 References

ESRI. (2006) *ArcMap GIS*. Retrieved from http://www.esri.com

Frauenfeld OW, Davis RE, 2003. Northern Hemisphere circumpolar vortex trends and climate change implications. *Journal of Geophysical Research*, **108,** D14.

Hondula DM, Sitka LJ, Davis RE, Knight DB, Gawtry S, Stenger PJ, 2009. A Back-Trajectory and Air Mass Climatology for the Northern Shenandoah Valley, USA. *International Journal of Climatology (online version available April 2009).*

Kalkstein LS, Tan G, Skindlov JA, 1987. An Evaluation of Three Clustering Procedures for Use in Synoptic Climatological Classification. *Journal of Climate and Applied Meteorology*, **26,** 717–730.

Kalnay E, et al., 1996. The NCEP/NCAR 40-Year Reanalysis Project. *Bulletin of the American Meteorological Society*, **77** (3), 437–471.

Klein WH, 1957. Principal tracks and mean frequencies of cyclones and anticyclones in the Northern Hemisphere. Research Paper 40, U.S. Weather Bureau, 60 pp

Knight DB, Davis RE, Sheridan SC, Hondula DM, Sitka LJ, Deaton M, Lee TR, Gawtry SD, Stenger PJ, Mazzei F, Kenny BP, 2008. Increasing frequencies of warm and humid air masses over the conterminous United States from 1948 to 2005. *Geophysical Research Letters*, **35** L10702.

McCabe GJ, Clark MP, Serreze MC, 2001. Trends in Northern Hemisphere Surface Cyclone Frequency and Intensity. *Journal of Climate*, **14**, 2763–2768.

National Oceanic and Atmospheric Administration. *Daily Weather Map Series*. Accessed at http://www.hpc.ncep.noaa.gov/dailywxmap/ 2008–09.

Sheridan SC, 2002. The redevelopment of a weather-type classification scheme for North America. *International Journal of Climatology*, **22** (1) 51–68.

IV. Comparison of Spatial Synoptic Classification Transition Seed Day Characteristics and Observations

IV.1 Introduction

One of the goals of this research was to evaluate the ability of the SSC to accurately identify transition days. In the previous section we demonstrated a synoptic-based analysis for doing so; here, we apply a more mathematical approach to determine the differences between the SSC's seed day characteristics for transition types and observations.

Seed day selection indirectly determines the overall frequencies and seasonality of each SSC type, including transitions. If the seed day characteristics for a moist tropical air mass are warmer and moister than is common for moist tropical air at a particular location, the corresponding SSC frequency will differ considerably from reality. Similarly, the characteristics of air masses evolve throughout the season – air from a true moist tropical source region in the winter is likely cooler and drier than it is in the summer. The importance of proper seed day identification is equally critical for the transition type as it is for the six air masses.

As described in the overall thesis introduction, the weather types in the current SSC are identified based on "sliding" seed days. First, seed days are selected for four two-week windows throughout the year, one two-week window falling during the hottest time of the year, another during the coolest, and two during midpoints between the warm and cold periods. Once the characteristics for each air mass for each two-week window are determined for the same 12 variables (at 04, 10, 16, and 22 EST) as in the SSC1, a polynomial is fit to the sum of the actual meteorological data throughout the year and the linearly-fit departures for each air mass. Thus, for each air mass and for each day of the year there is an expected value for each of the 12 variables.

The procedure used to identify transition seed days differs slightly. Instead of considering the 12 meteorological variables as above, the transition procedure considers three: the diurnal dew point temperature range, diurnal sea-level pressure range, and largest diurnal wind shift (all of observations at 04, 10, 16, and 22 EST). High values for each of these variables should be associated with a major change in the weather. If all three of these parameters exceeded 1.3 standard deviations above the mean, the day was eligible to become a transition seed day. This threshold of 1.3 standard deviations was selected to ensure that transition frequencies were similar to those of the SSC1, in which the transition frequency was deemed acceptable (Sheridan, 2002).

After the seed days were established for the original station (Wilmington, DE), a seed day transfer procedure was applied with the goal of decreasing differences in the SSC climatologies between adjacent stations. The seed day transfer procedure placed an emphasis on using days on which the same air mass was observed at adjacent stations, which increased the overall cohesiveness of the SSC coverage (Thesis Introduction).

The seed days, then, must be reasonable values to which the meteorological data are compared to correctly identify weather types and develop logical seasonal and spatial patterns in weather type frequencies. In this section, we compare the expected and observed transition variables throughout the calendar year over the period December 1950–November 2007.

IV. 2 Methods

The seed day characteristics for the 63 stations in our network were obtained from Scott Sheridan (Kent State University). This data set contains twelve expected meteorological parameters for each of the weather types on each day of the year. We apply a 21-day equal-weighting moving average smoother to the expected dew point temperature range, pressure range, and wind range on transition days to remove effects of rounding present in the original data set. The observed dew point temperature range, pressure range, and wind range on transition days alone, as well as all days, are sorted by day of year. For each parameter, the mean observed value is calculated for each day of the year, and then a 41-day equal-weighting moving average smoother is applied to remove high-frequency variability. The smoother also ensures that if transition days were not observed on any particular day of the year over the entire record, there are no missing data in our comparison.

Two measurements of error are calculated for the three transition variables between the smoothed seed day characteristics and smoothed observations on transition days: average absolute error and bias. The absolute error is defined as the sum of the absolute values of the 365 differences between expected and observed values. The bias is defined as the sum of the actual values of the same 365 differences. Between the two, we obtain a sense of the overall goodness of fit and the tendency for seed days to over-estimate or under-estimate the intensity of transitions (Table 1). These data are plotted for each station (Figure 1). We also generate time series plots of the smoothed data to more closely examine the seasonality of the sliding seed days and observations. Examples of time series for select stations are shown in the text to complement the discussion.

IV. 3 Results and Discussion

In general, the two accuracy measures suggest that errors are relatively modest between seed day estimations and observations for all three transition indicator variables (Table 1). For reference, typical transition day dew point temperature changes are 5-10ºC, pressure changes 10-20 mb, and wind shifts 5-15 m/s. SSC estimations are above observed median transition day dew point temperature changes and pressure changes for all 63 stations, and negative and positive bias are both present with respect to wind shift.

	Td Abs. Error	Td Bias	P Abs. Error	P Bias	W Abs. Error	W Bias
Min	1.09	-3.02	0.61	-3.44	0.25	-1.22
Mean	2.13	-2.12	2.03	-2.01	0.55	-0.17
Max	3.02	-1.09	3.44	-0.40	1.23	0.68

Table 1. Comparative measures between transition seed day and observed dew point temperature range, pressure range, and wind range for a 63-station network across the United States. The absolute error is defined as the daily average absolute values of the difference between expected and observed values. The bias is defined as the average of the actual (positive or negative) values of the same differences. Units are ºC/day for dew point temperature (Td), mb/day for sea-level pressure (P), and (m/s)/day for wind (W). Negative bias represents overestimation of seed day values by the SSC.

Dew point temperature range errors are largest across the southern Midwest, where the dew point temperature range is overestimated by as much as 3ºC on average (Figure 1). At Amarillo, TX (Figure 2), and nearby stations, the errors are larger in the winter and summer than in the shoulder seasons. The observed dew point temperature range is nearly constant between day 0 and 150, when a sharp decrease is observed. Lower dew point temperature ranges persist through day 250, when a gradual ascent into winter begins. The expected dew point temperature range follows a more periodic shape, correctly capturing the winter maximum but failing to reach the summer minimum. This example highlights a shortcoming of the SSC seed day selection procedure in that it is limited to a sinusoidal pattern. Features like the “step function” near day 150 in Amarillo, accordingly, cannot be captured. Such patterns are observed at several stations in the southwest.

Errors in pressure range are greatest across the northern half of the country. However, the seasonal pattern in pressure range is very well represented in the SSC at all of these stations – an example is shown for Syracuse, NY (Figure 3). The departure between expected and observed values increases in the winter relative to the summer, but the overall shapes closely match. A more interesting case is that of Miami, FL (Figure 4), where the typical pressure range is smaller, and thus, the total error is small compared to Syracuse. At Miami, the expected and observed values are well-correlated until day 100, when the observed values fall gradually through the summer until a sharp spike near day 225 associated with the onset of hurricane season. We do not believe, however, the seed day characteristics should be changed to represent infrequent extreme events; the departure during the spring is of greater concern.

There are no readily visible spatial patterns in error associated with wind range. At many stations, wind range demonstrates minimal seasonality, and seed day profiles similarly do not anticipate seasonal changes. Syracuse, NY, is one of the stations with the greatest overall error, but this is simply because of consistent overestimation (Figure 2). Stations in hurricane-impacted areas show a late-summer spike in W range similar to Miami's P range profile.

IV. 4 Conclusion

Across much of the United States, the SSC sliding seed day characteristics for transition days are similar in magnitude and seasonality to observations. A few stations show non-periodic fluctuations, especially in dew point and pressure, that may encourage revision of the seed day catalogs. Most of the error associated with dew point and pressure arises from the seed day values being greater than the observations. However, if the seed day values were lowered, the transition frequency would increase as more days would be statistically "closer" to the transition type. The current system was designed to mirror the frequencies in the original SSC which the authors deemed acceptable (Sheridan 2002). Spatial gradients in error may also promote revision of the catalogs to more accurately represent the relative transition frequencies between stations. In general, the sliding seed day procedure appears to be successful in providing target values of dew point temperature range, pressure range, and wind range for identifying transition weather types.

IV. 5 Figures

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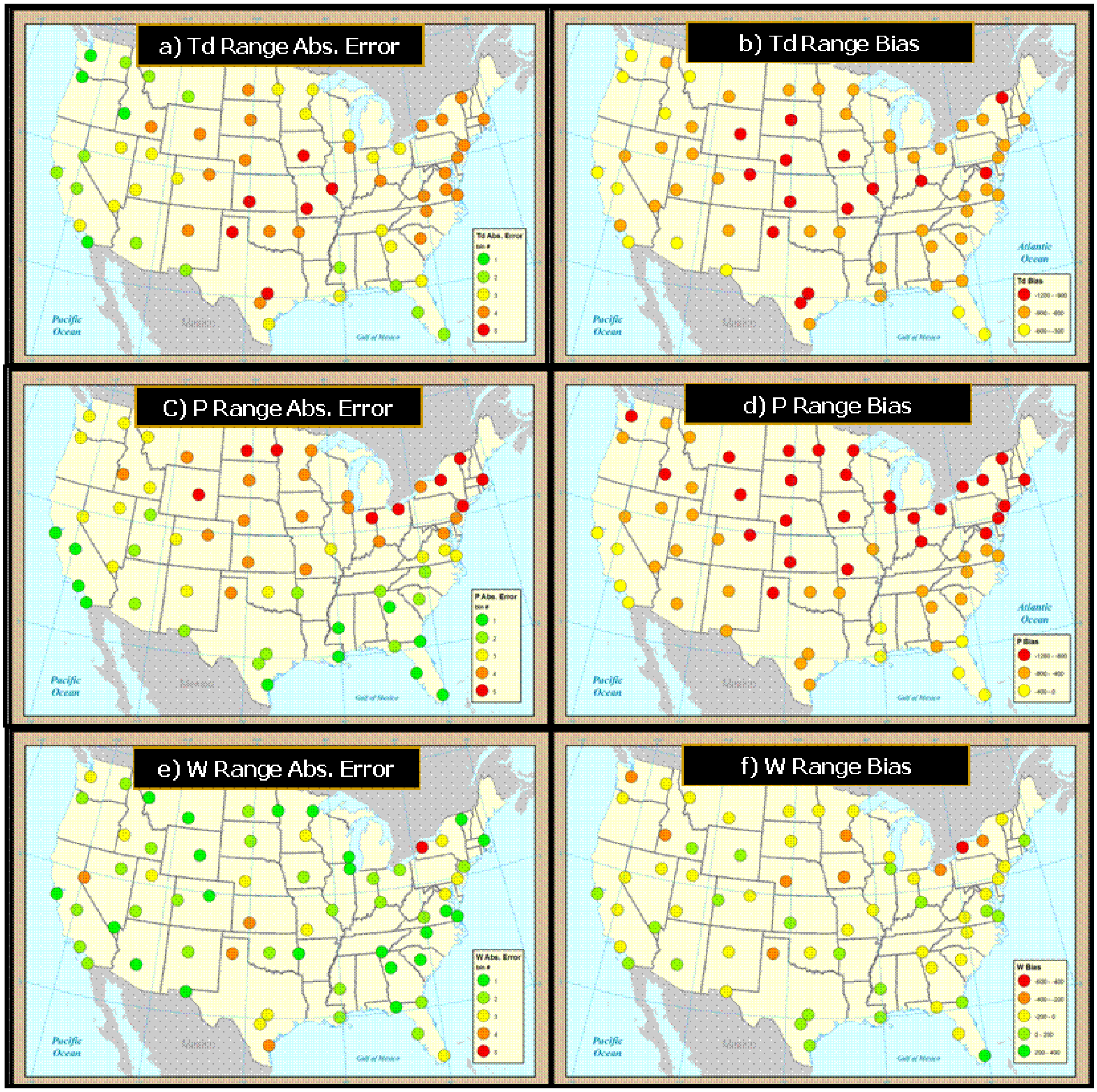

Figure 1. Absolute error and bias between 21-day smoothed SSC seed day and 41-day smoothed observed Td range, P range, W range, Dec. 1950–Nov. 2007. Color contours on absolute error plots (a,c,e) represent equally spaced intervals between the minimum and maximum value (red indicates greatest error). Color contours on bias plots (b,d,f) represent equally spaced intervals centered at zero (shades of green indicate observations above seed day values, shades of yellow and red indicate observations below seed days). Units in bias plots are deg C, mb, and m/s (total per year).

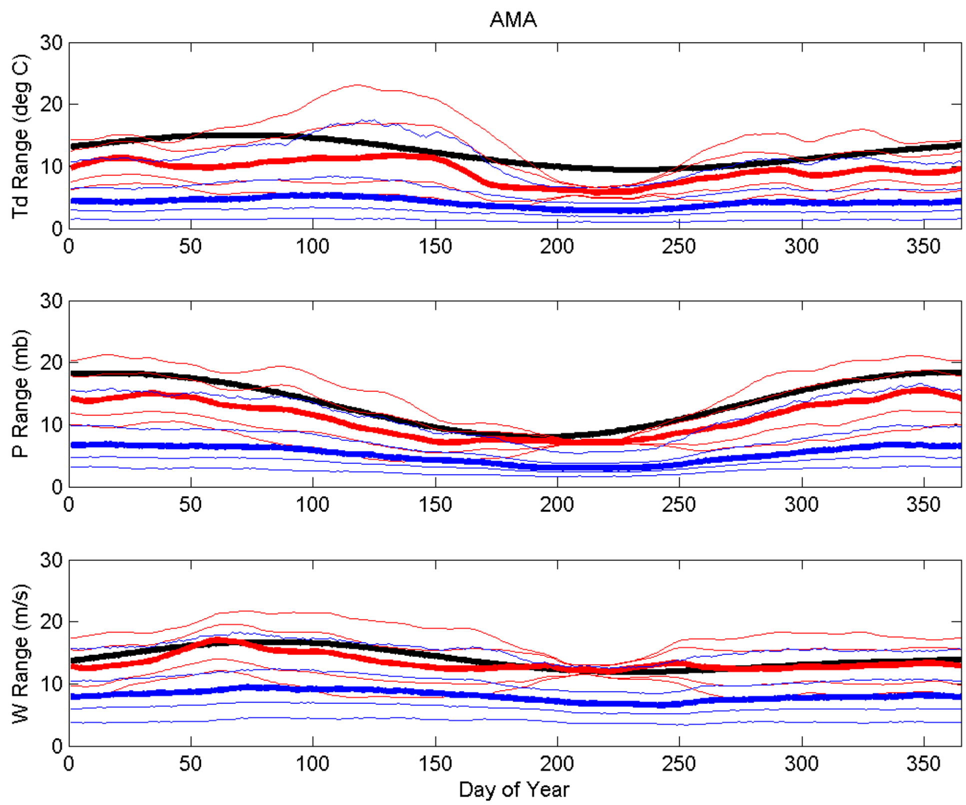

Figure 2. Comparison of seed day and observed Td Range, P Range, and W range at Amarillo, TX, Dec. 1950–Nov 2007. The black line represents the 21-day smoothed sliding seed day value for each variable. The thick red (blue) line represents the median 41-day smoothed observed value on transition (all) days. Thinner red and blue lines represent the 5th, 25th, 75th, and 95th percentiles for corresponding data.

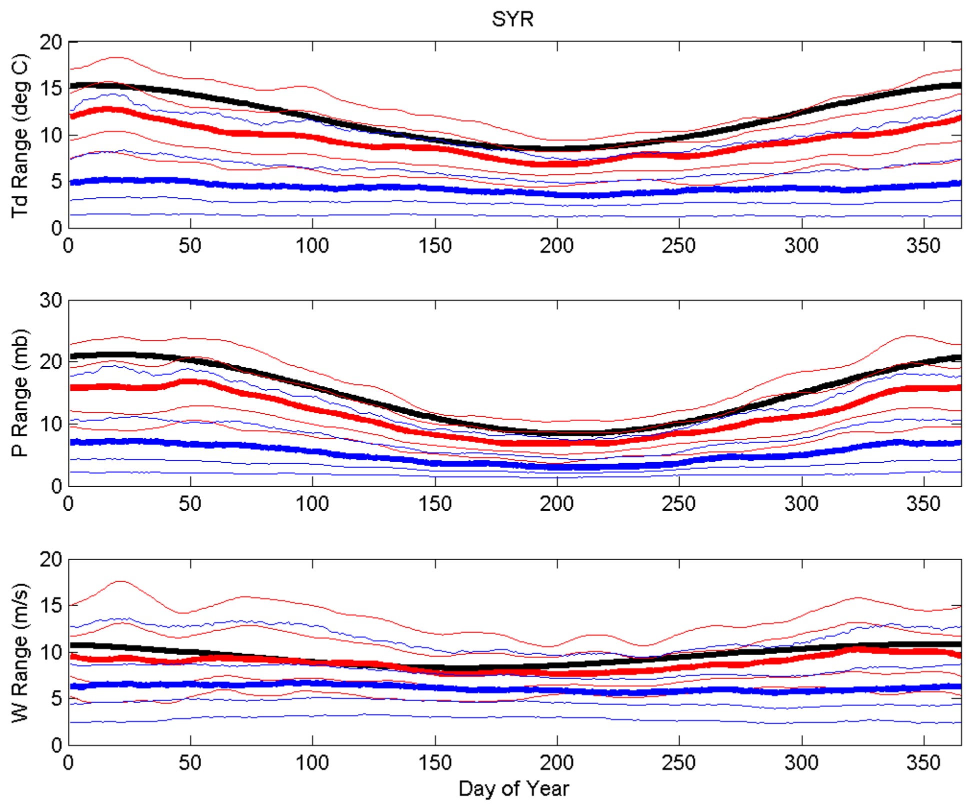

Figure 3. Comparison of seed day and observed Td Range, P Range, and W range at Syracuse, NY, Dec. 1950–Nov 2007. The black line represents the 21-day smoothed sliding seed day value for each variable. The thick red (blue) line represents the median 41-day smoothed observed value on transition (all) days. Thinner red and blue lines represent the 5th, 25th, 75th, and 95th percentiles for corresponding data.

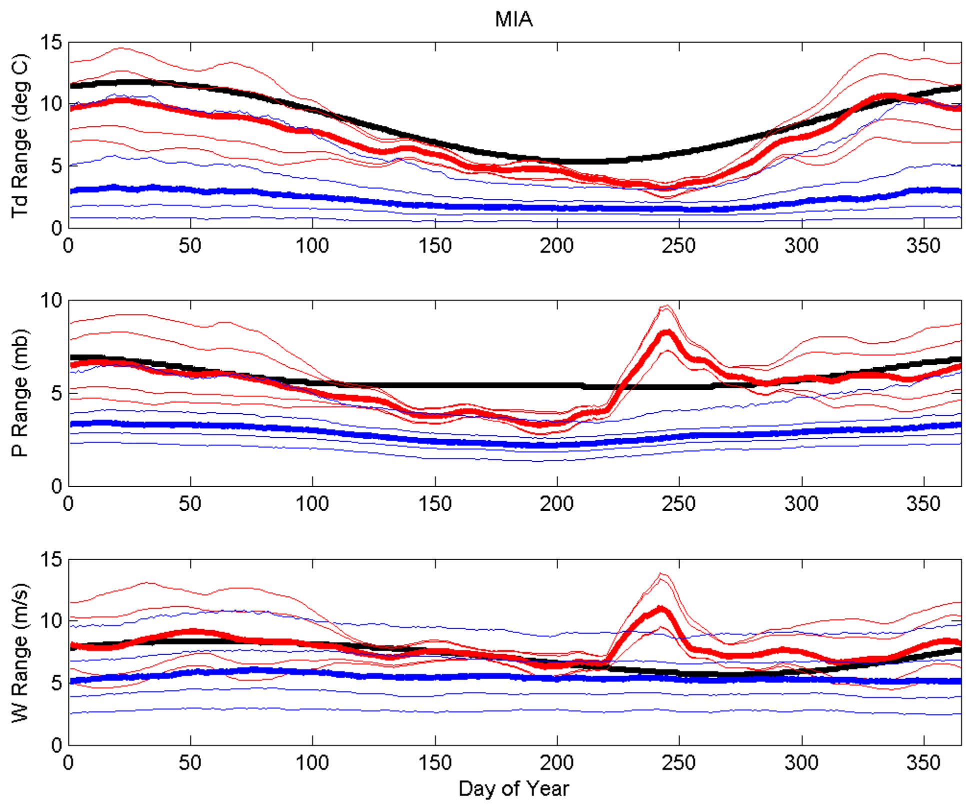

Figure 4. Comparison of seed day and observed Td Range, P Range, and W range at Miami, FL, Dec. 1950–Nov 2007. The black line represents the 21-day smoothed sliding seed day value for each variable. The thick red (blue) line represents the median 41-day smoothed observed value on transition (all) days. Thinner red and blue lines represent the 5th, 25th, 75th, and 95th percentiles for corresponding data.

V. SUMMARY AND FUTURE RESEARCH OPPORTUNITIES

The decline in transition frequencies over approximately the past half century indicates a shift in the climate toward more persistent synoptic-scale patterns in the western United States and weaker cold front passages across the east. The area of maximum frequency decline extends from the Great Basin through Minnesota and the Great Lakes region. As the configuration of circumpolar vortex has changed in recent decades to a more meridional wintertime pattern with enhanced contraction in the west, fewer frontal passages are observed. In the Upper Midwest, the dew point temperatures of the driest air masses have increased, resulting in weaker cold fronts at the leading edge of those air masses. The hypothesis that the vortex trends are the leading factor in the decrease in transition days in confirmed for the West, but the moistening of polar air masses appears to be driving the trend at several stations in the Upper Midwest.

The link between circulation changes and the transition frequency is decreasing variability of both dew point temperature and sea-level pressure. From 1951 through 2007, daily dew point variability, as measured by the largest positive and negative 18-hour changes in dew point temperature, has decreased over much of the country. During the same period, daily pressure variability, similarly measured, has decreased at several stations in the western U.S. These two factors combined have reduced the number of days with large shifts in the dew point temperature and pressure, decreasing the number of transition days identified by the Spatial Synoptic Classification every winter.

The development of transition subtypes offers an additional tool for the study of climate and the impacts of weather on surface systems and environments. The synoptic mechanisms identified by different subtypes vary across the country, but the most common types are generally associated with cyclonic activity and the traditional model of warm fronts and cold fronts. The proportion of subtypes has significantly changed in several regions whereby at present a smaller percentage of transition days are characterized by approaching lows and a larger percentage are characterized as cold front passages.

The underlying subjective criteria used to identify transition days appear to have been, for the most part, well-designed. At most stations, the expected characteristics of transition days in the Spatial Synoptic Classification seed day archive show greater changes than those actually observed, but the seasonality of dew point temperature range, pressure range, and wind range is typically correct. At a few stations there are notable features in the seasonality of a particular variable at a temporal scale smaller than the seed day calculations can identify.

These results collectively motivate future study of climate change using an air mass approach. Much of the discussion contained herein involves the movement of air masses across the country. The generation of a joint air mass and back-trajectory climatology might offer a more powerful means of truly examining how the synoptic-scale dynamics have changed. Additionally, the incorporation of back-trajectories could serve as a validation tool for the transition subtypes. Although transition days in general are characterized by highly variable trajectories (e.g., cold fronts compared with warm fronts), we expect that the flow regimes associated with each subtype should be relatively consistent. Further, this joint air mass and back-trajectory climatology may help to address a shortcoming of the SSC's application in trend identification. For example, a decreasing frequency of dry polar air masses does not necessarily indicate that air masses from polar source regions are becoming less frequently observed. Instead, the trend could be caused by a warming or moistening of these air masses which could result in a different classification (dry moderate or moist polar). In this research, we were able to combine knowledge of common trajectories of cyclones and anticyclones with frequency trends and meteorological data to describe climate change over the past half-century from a perspective not previously addressed. The incorporation of more detailed back-trajectory climatology, however, could provide significant opportunities for an improved understanding of climate variability.

Additionally, one of the major components of climate change impacts on storm tracks not analyzed here is the intensity of storms. Under most model predictions, cyclonic activity is expected to become less frequent but more intense. This analysis supports the idea of less frequent storms, and the development of a transition intensity index may enable an air-mass based analysis of the latter.

In summary, the Spatial Synoptic Classification's transition category has been identified as a reputable tool to analyze changes in United States climate. Its application here has revealed that the altered configuration of the circumpolar vortex over the past 57 years, combined with increasing moisture amongst the driest polar air masses, has produced a climate in which fewer frontal passages are observed during the winter months.

Literature Review

Decadal-scale trends in transition weather types and atmospheric circulation

Supplement to Masters Thesis

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August 2009

Introduction

Many factors may be linked changes in the atmospheric circulation and the decrease in transition frequency, including changes in the Northern Hemisphere circumpolar vortex, adjustments to cyclone and anticyclone tracks, variations, modifications of surface variables at the surface, external forcings, and shifts in teleconnection patterns. These factors are all part of a complex system of feedback and balances that often impact one another. In the following sections, I review relevant research in each field.

1. Circumpolar vortex

Throughout the year, the position, strength, and shape of the jet stream(s) over North America determine much of the synoptic-scale climate variability. Jet stream position is highly related to the air mass climatology of individual locations, as stations to the north of the polar jet will have greater exposure to polar air masses, and those to the south, tropical. This boundary separates the cold mass of polar air from the more temperate air of the middle latitudes. The strongest feature of the jet stream in both hemispheres is located along the leading (most equatorward) boundary of a polar vortex, the region in the upper atmosphere of maximum meridional geopotential height gradient (Frauenfeld and Davis, 2003). As noted by Frauenfeld and Davis (2003) and others, study of the circumpolar vortex provides a convenient, holistic view of the hemispheric circulation, and variations thereof are related to air mass advection, surface and upper level temperatures, and precipitation. Accordingly, the dynamics of the northern hemisphere circumpolar vortex (henceforth, CPV) should be related to spatial and temporal variance in TR.

The features and overall strength of the CPV are most pronounced during the winter, and consequently much previous research has been limited to the winter season, or even a single month of the winter season. In a sample of early work, Burnett (1993) considered variations of the CPV for the period 1946–1989. He observed smaller vortex area during the period from 1946–64 and larger area from 1965–89, while noting that vortex size appeared to be decreasing in the final years of his period of record. Over the entire record, the trend was toward larger vortex areas, although it was not identified whether or not the trend was statistically significant. Using an iterative t-statistic, Burnett (1993) identified a "most significant difference in mean vortex size" when using winter 1964–65 as the break point for his record. Like Davis and Benkovic (1992), he found that the expansion was highly related to increased troughing over the central Pacific and eastern North America.

A more complete climatology of the CPV was completed by Frauenfeld and Davis (2003), who examined three contours of the CPV (northern, central, and southern) at three different heights (300, 500, 700 hPa). For all three contours, a statistically significant contraction of the vortex was observed at every level since 1970 (through 2000), with significant expansion observed during the early part of their record (1949–1969, e.g., their Figure 4, below as figure L1). By season, they found that most of the significant trends were observed in the winter, summer, and fall (their table 4, below as table L1). Their extension of the CPV record by ten years confirmed the contraction of the vortex in the most recent portion of the record, as suggested by Burnett (1993). Frauenfeld and Davis (2003) also note that the variability in CPV activity seems to have changed in the most recent decade – switching form a period of approximately 20 years to expansion and contraction every couple years.

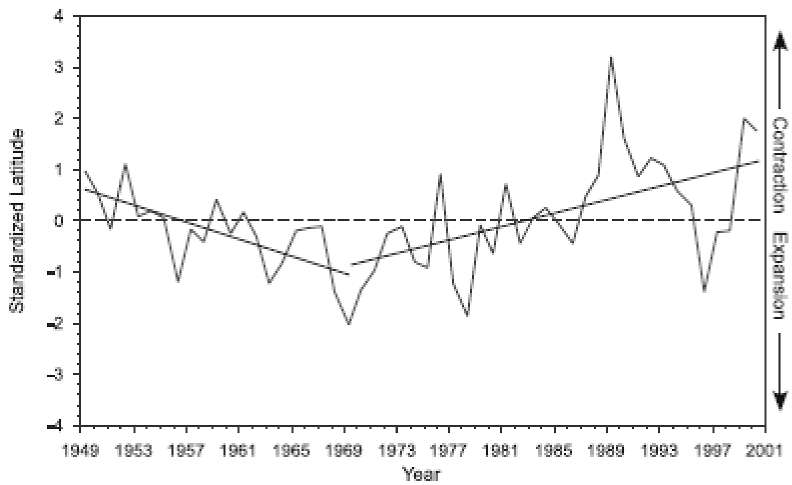


Figure L1. Time series of the winter 300hPa center vortex contour. Straight lines correspond to 1949 – 1969 and 1970 – 2000 linear least squares trends, from Frauenfeld and Davis (2003).

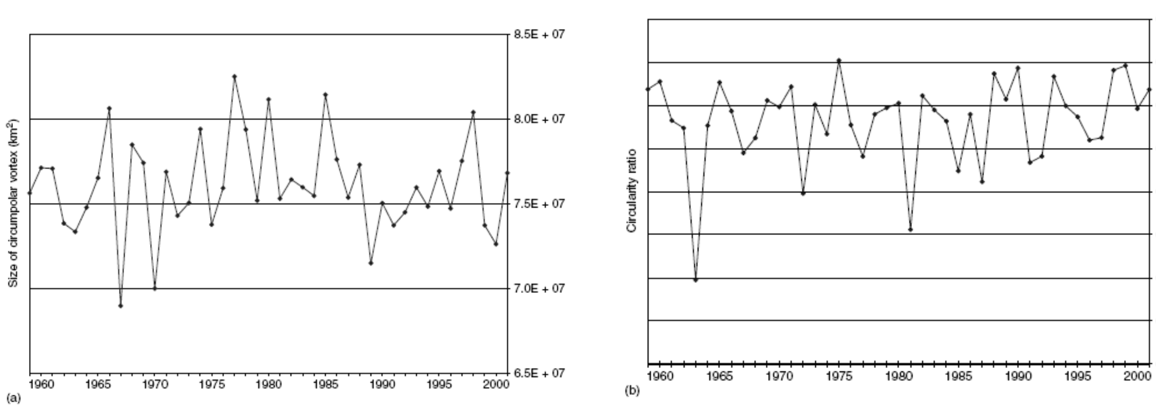
	Winter		Spring		Summer		Fall	
Contour	Pre-1970	Post-1970	Pre-1970	Post-1970	Pre-1970	Post-1970	Pre-1970	Post-1970
300 hPa Level								
North	**−0.198**	**0.146**	−0.139	**0.125**	**−0.247**	**0.128**	**−0.287**	**0.172**
Center	**−0.208**	**0.163**	−0.084	0.110	**−0.289**	**0.124**	**−0.174**	**0.127**
South	−0.107	**0.149**	−0.071	0.077	**−0.237**	**0.169**	**−0.195**	**0.170**
500 hPa Level								
North	0.081	−0.073	−0.131	**0.117**	−0.169	**0.110**	**−0.269**	**0.155**
Center	**−0.245**	**0.146**	−0.126	0.079	**−0.241**	**0.121**	**−0.209**	**0.104**
South	**−0.201**	**0.157**	−0.049	0.086	−0.175	**0.149**	**−0.171**	**0.132**
700 hPa Level								
North	0.006	−0.051	−0.112	0.034	−0.099	**0.097**	−0.122	0.092
Center	**−0.211**	**0.111**	−0.157	**0.102**	−0.126	**0.094**	**−0.204**	0.082
South	**−0.218**	**0.144**	−0.088	**0.101**	−0.115	**0.110**	−0.158	0.078

[a]Negative slopes indicate vortex expansion and positive slopes indicate vortex contraction; bold values indicate statistical significance at the 0.05α level.

Table L1. Regression slopes for the linear trends in the vortex before and after 1970 in z-score units per decade, from Frauenfeld and Davis (2003).

Using a different measurement technique than Frauenfeld and Davis (2003), Angell (2006) also identified a statistically significant decrease in CPV area between 1963 and 2001, with a magnitude of 1.5% reduced area per decade. As in previous studies, this contraction was related to increasing 300 – 850mb temperatures in the middle latitude belt from 30 - 60°N. The magnitude of this statistically significant change was found by Angell (2006) to be +0.20 K. While the year-round decrease in CPV area was found to be statistically significant, when examined seasonally, only the contraction during the summer and fall months met the significance criteria. Winter and spring trends also suggested contraction. Vortex size was also related to volcanic activity, ENSO phase, and sunspot activity (Angell 2006).

Rohli et al. 2005 investigated CPV trends using GIS software, and found no statistically significant trends in either January area or shape using geopotential height data from 1959–2001 (their Figure 3, below as Figures L2a and L2b). An extension of their work (Wrona and Rohli 2007) similarly observed no significant trends in either characteristic for December, February, April, and July. The trend in area was not significant in October as well, however a significant trend toward a more circular CPV was observed in October. Further, they observed a significant negative correlation with the AO as the negative phase of the AO is associated with colder conditions and a more equatorward vortex. A significant relationship was also found between CPV circularity and PNA, with the positive phase of the PNA associated with a less circular vortex (more meridionality). The contrasting results to Frauenfeld and Davis (2003) and Angell (2006) were thought to arise from the use of differing map projections, or a different period of record (Rohli et al., 2005; Wrona and Rohli 2007).



Figures L2a and L2b. Time series of the January CPV: (a) area, km^2 and (b) circularity ratio, from Rohli et al., 2005.

The contrasting results of several recent studies suggest that analysis of CPV trends is highly method-dependent. Because of the agreement between Frauenfeld and Davis (2003) and Angell (2006), and the hypothesis of Rohli et al. (2005), that increasing mid-latitude temperatures should be associated with decreasing CPV area, it seems that relationships between the CPV and TR frequency should be examined. The work of Rohli et al. (2005) and Wrona and Rohli (2007) formally identifies a second important feature of the CPV that may be related to TR activity: the shape (represented through their circularity ratio). As enhanced meridional flow in the CPV suggests increased pole-to-equator exchange of momentum and heat, circularity should be related to cyclogenesis, and thus, TR. Over larger spatial domains, then, TR frequency may be related to CPV position and shape. Analysis of the CPV enables investigation of how a repositioning of the core of strongest winds may move TR occurrence away from the study region.

2. Cyclone & Anticyclone Tracks

Study of changes to storm track activity often relies on examination of cyclone and anticyclone climatologies over periods of several decades or longer. As no single measure of such activity exists, studies in this area often present vastly different methods that may yield considerably different results. In a simple “count” approach, one might measure how many times pressure values dropped below (above) in grid cells over time to reveal frequencies of cyclones (anticyclones). Such a study might show a latitudinal shift in the mean cyclone and anticyclone tracks. More detailed study can reveal patterns in the nature of these events, such as an intensification of cyclones over time. Changes in cyclone and anticyclone activity should mirror changes in transition frequency, as the transition type is designed to identify shifts between these two main features of synoptic-scale atmospheric circulation.

For the Northern Hemisphere, many studies have identified a decrease in cyclone activity over the mid-latitudes (30° - 60° N) and increase in cyclone activity over the high latitudes (60° - 90° N) over the past several decades. These findings are consistent with observations to changes to the circumpolar vortex and teleconnection patterns discussed above.

Reitan (1980) followed early work with analysis of cyclone frequency trends over North America over the period 1950–1976. Most noticeably, a 20% decrease in the frequency of cyclonic events and 30% decrease in frequency of cyclogenesis were observed. These significant changes did not appear to be from a bias in changing analytical techniques for the identification of cyclones. It was observed that the cyclone frequency curve followed that of the overall trend in northern hemisphere average surface temperature. Two theories were presented for why this might be so: 1) the cyclones act in their theorized role of mechanisms of meridional heat transport, thus a decreased hemispheric temperature gradient between the poles and equator would require less heat transport, or 2) the trends in cyclone activity are the drivers of temperature change. Finally, the author observed that as cyclone frequencies decrease, there tended to be a poleward shift in the region of maximum cyclone activity. As noted in other studies, the trend seemed to be evident across all months, although of varying magnitude.

Zishka and Smith (1980) also found a decrease in the number of cyclones (and anticyclones) in both January and July over their 28-year study period (1950–1977). Their work, which provided a more comprehensive climatology than previous efforts (e.g. Petterssen 1956, Klein 1957), identified the western portion of North America as the "subregion" with the most pronounced changes. Over the three decades, they observed a 45% decrease in January cyclones, 24% decrease in July cyclones, 45% decrease in January anticyclones, and 40% reduction in July anticyclones. Further, they noted that the intensity of January cyclones was increasing, a trend significant at the 95% confidence interval. The studies of Reitan (1980) and Zishka and Smith (1980) provide similar results over relatively similar spatial and temporal domains: cyclone activity decreased considerably over the two and a half decades between 1950 and the mid-1970's.

Harman (1987) complemented the work of Reitan and Zishka and Smith by updating the anticyclone climatology for North America, focusing on 1950–1979. Based on the premise that anticyclone paths are very responsive to large-scale changes in the flow, he speculated that trends in anticyclone activity may be linked to decadal-scale trends in regional temperature and precipitation. His study found a significant decline over the entire study region for the time period, with the strongest decline occurring in the fall and winter. His results were consistent with those of Zishka and Smith (1980) and Whittaker and Horn (1981). Agee (1991) later added support to the idea that cyclone and anticyclone activity may be related to changes in temperature, using data from several previous studies. He concluded that the "dynamic climatology of waves responsible for temperature trends is equally responsible for the frequency of cyclone and anticyclone events."

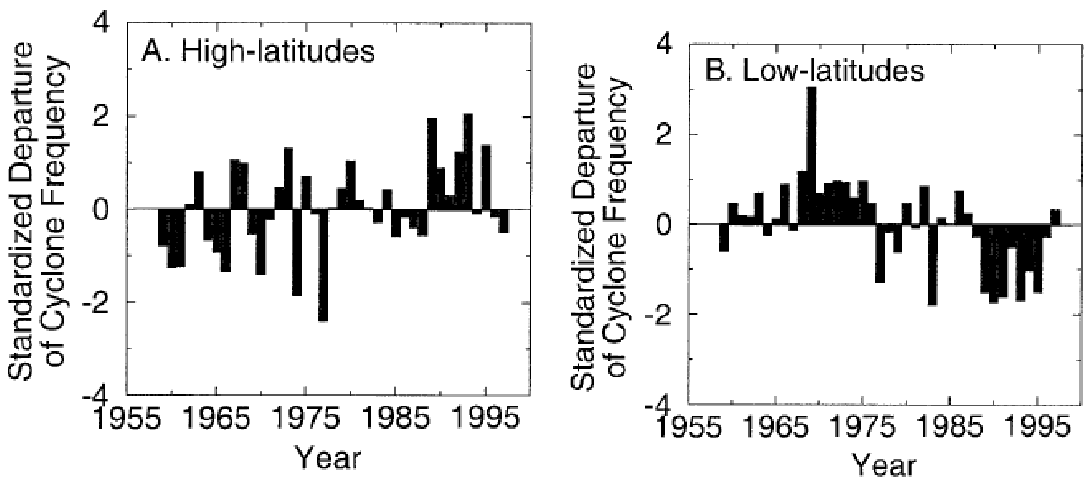
Changes in cyclone activity may be manifested in terms of both cyclone frequency and intensity. Many studies that have adopted modeling approaches to study cyclone activity in changing climate (e.g. Lambert 1995) have hypothesized that increased levels of atmospheric carbon dioxide will decrease the overall number of cyclones, but increase their intensity (often measured via minimum sea level pressure, see Section 6). Lambert (1996) completed a climatology of intense northern hemisphere winter cyclone events (those with central pressures no higher than 970 mb) for 1899–1991. The time series demonstrated no significant trend prior to 1970, however, a positive trend was identified after 1970 for the Atlantic region, Pacific region, and entire hemisphere. However, he speculated that it was possible that changes to analytical techniques influenced the trend, and difficult to determine to what extent that may be true.

Using a somewhat different method than that employed in many of the other cyclone and anticyclone climatologies, Changnon et al. (1995) also found a long-term decline in cyclone frequency over North America between the early 1950's and mid 1980's. Their study considered cyclone frequencies in equal-area circles, which they believed would help eliminate some of the area-related problems associated with regular grid systems. Like other work, they found the highest cyclone frequencies in the winter months (27.6% of annual cyclones), and minimum occurrence in the summer and fall

(21.8%, 24.9%). However, they found a sharp increase in cyclone activity since the mid-1980’s, a result not reported elsewhere. This increase led to cyclone frequencies in the mid-1990’s to return to the same level as those of the mid-1960’s.

Key and Chan (1999) included both surface (1000 mb) and 500mb cyclone frequencies in a study of global and regional climate. They noted that cyclones and anticyclones at higher levels of the atmosphere merited attention because of their connection to the upper-level circulation, with the potential to create blocking/cutoff patterns, etc. In the Northern Hemisphere, they found a decrease (increase) in surface (500mb) cyclones during all seasons in the northern tropics and subtropics, the opposite pattern in the Arctic. Their results were consistent with earlier work (Parker et al., 1989) that reported increasing 500mb cyclone frequencies across the western Northern Hemisphere from 1971–1985, following two decades of the opposite trend, as well as that of Serreze et al. (1993) that demonstrated an increase in Arctic cyclone activity from 1952–1983.

More recently, McCabe et al. (2001) examined trends in surface cyclone frequency during the winter months in the Northern Hemisphere. Their work found a statistically significant decrease in cyclone frequency in the middle latitudes, and a significant increase in the high latitudes over a 39-year period from 1959–1997 (Figures L10a and L10b, below). They related the changes in frequency to two major shifts in the atmospheric circulation, the 1976–1977 Pacific Climate Shift (reference), and a later change in the Arctic Oscillation around 1989. Both of these changes to the circulation reduced cyclone activity in the Northern Hemisphere middle latitudes. It was unlikely, they believed, that the changes in frequency were related to changes in instrumentation. This work supported modeling efforts (e.g., König 1993) that suggested global warming may lead to decreased cyclone frequency in the mid-latitudes.



Figures L10a and L10b. Standardized departures of winter (Nov–Mar) cyclone counts in the Northern Hemisphere, 1959 – 97, for (a) high latitudes (60°–90°N) and (b) middle latitudes (30°– 60°N). From McCabe et al., 2001.

Work of Paciorek et al. (2002) explored six indices of cyclone activity for NH winters. Contrary to many previous studies, which determined cyclone activity by counting methods exclusively, they added four "non-count" measures: Eady growth rate (Hoskins and Valdes 1990), 500hPa temperature variance (modification of Iskenderian and Rosen 2000), meridional temperature gradient (modification of Gitelman et al. 1997), and an extreme wind index (Alexandersson et al. 1998). They speculated that these indices captured important atmospheric characteristics related to cyclone development and activity. After removing the influence of teleconnection patterns using a regression model, they found decreasing cyclone activity over the United States, increasing activity over Canada, and evidence for an increase in intense cyclone frequency.

Of course, changes in cyclone and anticyclone activity are not restricted to homogeneous trends across space. Differences in topography, proximity to oceans, lakes, and seas, and other physical factors cause significant spatial gradients in cyclone and anticyclone frequencies. The large size and varying landscape of the United States results in different portions of the country with very dissimilar synoptic climate regimes. While many climatologies have identified preferred storm tracks and cyclogenesis (or anticyclone tracks and anticyclogenesis), fewer have considered trends within specific types of cyclones or anticyclones that may effect a particular region. Resio and Hayden (1975) relate an increase in mid-Atlantic extratropical storm activity to the large-scale circulation. Thus, changes in mid-Atlantic storm activity may not be well-represented by continental- or hemispheric-scale data. Similarly, the Great Lakes are known to be an important region for cyclone development, as they represent a considerable heat source. Angel and Isard (1998) note a significant increase in the number of strong Great Lake cyclones over the 20th century. Such trends are subject to interpretation across studies that employ different methods; for example Zhang et al. (2000) refuted claims of increasing East Coast storm activity by analyzing hourly tide gauge records. At a larger scale, it is possible that changes in storm frequency across North America, or even the western half of the northern hemisphere, are not representative of hemispheric or global patterns. Whittaker and Horn (1982) found the same decrease in North American cyclogenesis as did their colleagues, but found that data from the entire hemisphere do not show much a trend. They speculated that the decrease seen for North America may be compensated for elsewhere. These changes are also certainly related to long-term changes in the semipermanent features of the atmosphere, such as the subtropical high in the North Atlantic (e.g., Davis et al., 1997), and the associated teleconnections (discussed above).

In summary, there is good agreement concerning decadal-scale changes in United States cyclone and anticyclone activity over the past fifty years. With fewer cyclones, anticyclones, and periods of transition between them, it seems unsurprising that TR frequency in the SSC has declined. Fewer cyclones and anticyclones may be indicative of an overall slowing of the circulation and/or changes in the meridionality of flow, and could result in fewer fronts.

3. Surface variables

While it is probable that the changes in transition frequency are related to large-scale patterns in the dynamics of synoptic-scale systems in the atmosphere, it is possible that changes to the meteorological variables at the surface may drive the observed changes in the SSC climate, as the SSC is solely based on surface observations. Therefore, any change to the three variables used for transition identification (diurnal dew point change, diurnal pressure change, and diurnal wind shift) will impact the output classification from the SSC. Granted, such changes may be related to changes in the large-scale dynamics, but may also be related to local land-use change and instrument changes. Here, I review studies of changes to the surface variables across the country to determine the degree to which they are consistent with findings across the other sections of this review.

3.1 Dew Point Temperature

Dew point temperature is a useful parameter as a transition identifier because of its small daily range. It is well-accepted that as the global climate and temperature change, so will the moisture content of the atmosphere (e.g. Kattenberg 1995). In recent decades, the rate of dew point temperature change at many stations across North America has exceeded the rate of temperature change, and trends in dew point temperature are consistent with those for relative humidity and precipitable water in the lower levels of the atmosphere, all suggesting an increase in atmospheric moisture content (Ross and Elliott 1996). Over North America, these trends are strongest over the southeastern United States and Caribbean (Ross and Elliott 1996).

Increases in the overall moisture content of the atmosphere would likely impact the overall air mass climatology of the United States, with moist air masses occurring more frequently at the expense of dry air masses. However, it does not necessarily suggest a change to the climatology of the transition type, which is identified independent of the true dew point temperature. Thus, while acknowledging the overall changes to the dew point climate of the U.S., I am more interested in changes to the diurnal profile.

Knappenberger et al. (1996) analyzed surface dew point for a network of stations across the country that were unlikely to be influenced by urbanization. They observed that water vapor was increasing across the entire day in all seasons except winter. Further, they found a slight tendency for an unequal change in dew point temperatures across time of day, with daytime dew point temperatures increasing at a faster rate than those of nighttime. This pattern was especially apparent in the spring and summer months. Overall, the dew point temperature change was more widely observed west of the Mississippi than in the east. As the “clean” western air exhibited a greater change in dew point temperature, it was suggested that sulfates were not responsible for altering the diurnal dew point temperature profile. Schwartzman et al. (1998) reported nearly identical conclusions on a study done with more stations but similar methods. However, the results of Gaffen and Ross (1999) differ from those of Knappenberger et al. (1996) and Schwartzman et al. (1998), in that their work suggests that nighttime dew point temperature increases are exceeding those of the daytime. It is noted that the station network and period of record used by the Gaffen and Ross (1999) work differed from those of the other two (Robinson 2000).

Robinson (2000) investigated temporal trends in the dew point temperature of the United States as well, using a quality-controlled data network unavailable to previous authors, and had similar findings to Knappenberger et al. (1996). He found that the dew point temperature rate of increase during the day was higher than the rate of increase at night, especially in the summer months, and speculated that this daytime-driven trend in the summer might be affected by local evaporation rates and energy exchanges, or changes in the frequency and/or intensity of air masses. Further analysis showed that both local and regional factors had some impact on the changes in dew point temperature, and that no single factor could be isolated as having the most pronounced effect.

Accordingly, there is some (although mixed) evidence to support changes to the diurnal dew point profile at stations across the country. While the difference between nighttime and daytime dew point values is generally very small (0.5K, Gaffen and Ross (1999)), changes in this value in either direction may lead to changes in the number of days classified as "transition." Previous research supports investigation of long-term trends in diurnal dew point profiles as part of this work.

3.2 Sea-Level Pressure

Diurnal patterns of pressure change, and their relation to gravitational forces from celestial bodies, have been known since the time of Newton, if not before. These patterns are so regular that the famous Prussian explorer Alexandar von Humboldt carried a barometer with him in his journeys around South America from 1799–1804, using it as a proxy for a clock. Humboldt observed two daily pressure maxima, at approximately 10am and 10pm (Chapman and Lindzen 1970). Since the era of Newton and Humboldt, the science of diurnal pressure variations has been well-studied and quantitatively formalized. Today, we recognize that these "atmospheric tides," analogs to tides in the oceans, are principally driven by both gravitational and thermal forces. While both the sun and moon exert an influence on the distribution of the atmosphere around the globe, the sun's influence is far greater (e.g., Brier 1965).

Two major oscillations of atmospheric pressure are considered significant, one with a period of approximately 24 hours (S1), and the other 12 hours (S2). Chapman and Lindzen (1970) suggest that the latter, S2, is "one of the most regular of all meteorological phenomena," and is readily detectable around the globe. Perhaps partly due to the ease of observation, this semidiurnal component of pressure oscillation has been considered the principal mode of oscillation over most of the globe, particularly in the low latitudes (Spar 1952). Brier (1965) suggested that the amplitude (pressure change) of S1 is approximately half that of S2 in the tropics.

Using harmonic analysis on pressure data collected at New York City for summer and winter months 1948–1951, Spar (1952a) concluded that the S1 oscillation was completely driven by thermal forces, whereas S2 was driven by both thermal and gravitational forces. This theory was developed by analyzing differences in the magnitude of pressure changes on days with ("clear") and without ("cloudy") large temperature changes, as the difference in the amplitudes between clear and cloudy days was much larger for S1 than for S2. The mean diurnal pressure curves and relevant data from his work appear as Figure L11 and Table L3 below.

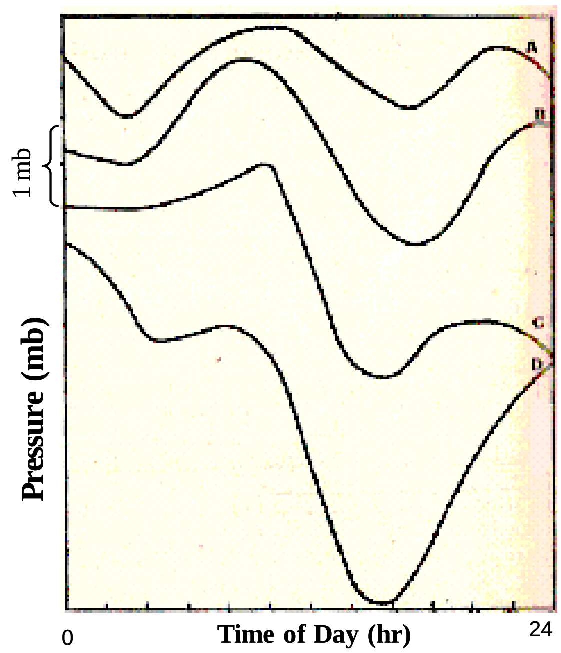


Figure L11. Mean diurnal pressure curves for "clear" and "cloudy" days at New York City. (A) Summer "cloudy," (B) summer "clear," (C) winter "cloudy," (D) winter "clear." From Spar 1952a.

Group		A1 (mb)	t1 (hr)	A2 (mb)	t2 (hr)
Summer	"cloudy"	0.17	7.6	0.38	9.5
	"clear"	0.79	6.8	0.48	10.1
Winter	"cloudy"	0.53	6.3	0.5	9.1
	"clear"	1.24	3.2	0.65	9.9

Table L3. Mean **a**mplitude (A) and period (t) of the 24-hour (1) and 12-hour (2) pressure oscillations at New York City, NY, 1948–1951. From Spar 1952a.

The global distribution of the amplitude of S2 is remarkably consistent – decreasing from approximately 1.0 mb near the equator toward the poles. Nearly all of the variation occurs latitudinally, with minimal changes moving from east to west. Although the distribution of the period of S2 is not quite as consistent spatially, the peak generally occurs two to three hours before noon and midnight (Spar 1952b, Dai and Wang 1999).

Haurwitz (1965) was the first to complete a comprehensive study of S1, using 228 unevenly distributed stations around the globe to determine its spatial variance. This work revealed that S1 was much more impacted by thermal influences, as the largest amplitudes were found over the continents, and lower values over the open oceans (Chapman and Lindzen 1970). Mass et al. (1991) observed a high, positive correlation between diurnal temperature range and S1 amplitude over the United States in the summer months, further supporting the theory that thermal changes predominantly influence S1. Most recently, Dai and Wang (1999) observed a similar correlation and added that diurnal wind variations can also significant impact S1. Dai and Wang (1999) further found that S1 and S2 were approximately equal in magnitude, contradicting previous literature. In some land areas, including the western United States, the amplitude of S1 (≈1.1 mb) was found to be greater than that of S2 (0.3 – 0.6 mb over middle latitudes).

Mass et al. (1991) completed a set of three-hour pressure-change maps for reference use for the United States based on data from 15-25 years for a network of 15 stations across the country. An example of one of these maps appears below, as Figure

L12. From this set of maps, one may observe that in some parts of the country, large pressure changes are observed in many locations. For example, in Figure L12 below, the average pressure change from 1800 to 2100 UTC over Texas may be on the order of a two or three millibar drop. Although the magnitude of the diurnal pressure change is often hidden because of the larger-amplitude changes associated with weather patterns (Siebert 1961), this type of change can complicate the diagnosis of a weak or moderate front (Mass et al. 1991).

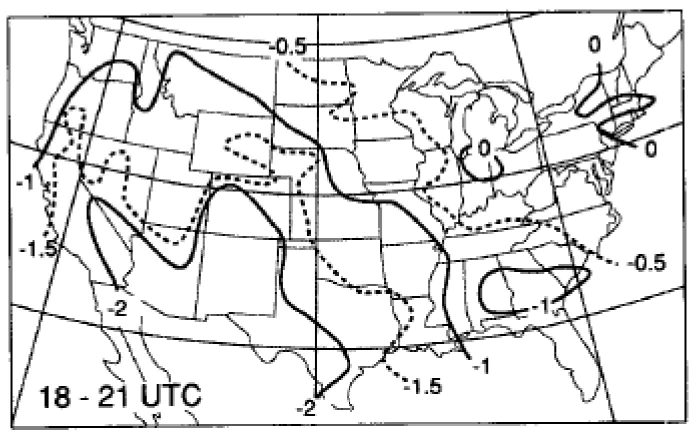


Figure L12. Three-hour station-pressure change map for winter. Pressure change expressed in millibars, with a positive value indicating increasing pressure over the period. From Mass et al. 1991.

The nature of these large-scale oscillations in pressure must be considered in this research, as spatial variance in the average pressure changes may complicate diagnosis of transition days. Although to the best of the author's knowledge no literature describes long-term changes in the amplitude of these diurnal pressure changes, given the high thermal influence and relationships with diurnal temperature range, it seems possible that significant changes in greenhouse gas concentrations and land use may alter the amplitude and/or period of atmospheric tides. Accordingly, this study should consider the long-term trend in daily SLP variance across the United States.

3.3 Wind

The presence of large-scale diurnal and semidiurnal tides in the atmosphere clearly suggests the potential for some type of consistent, large-scale diurnal variation in the wind as the mass of the atmosphere is redistributed across the globe. This phenomenon was observed and investigated as early as the mid-1800's, with work by Epsy (1841) and Köppen (1883) (Buajitti and Blackadar, 1957). These studies related the consistent diurnal variation in the wind to changes in momentum transfer. Later, Wagner (1939) developed a theory that the diurnal wind pattern observed in the United States midwest could be explained by three circulation regimes: that between the dry southwest and its surroundings, that between the plains and mountains, and that between the continent and oceans. This theory suggests that the diurnal wind variation may be more influenced by local and regional circulation patterns than a global tide.

Three decades later, Hering and Borden (1962), Bonner (1968) and Bonner and Paegle (1970) further examined and quantified the diurnal wind variations of the central United States. Hering and Borden (1962) noted that the diurnal wind system extended across much of the central tier of the country with good spatial consistency in the pattern.

Their study concluded that the changes in wind near the surface were caused by diurnal changes in surface stress. The latter study confirmed the high spatial consistency, adding that the maximum frequency of significant amplitude events was observed between 95 and 100° W along the Oklahoma-Kansas border. Bonner and Paegle (1970) later reported that the magnitude of the diurnal wind change over the Midwest was on the order of 3-5 m/s in the north-south component with a smaller variation in the east–west direction. The v-direction change was shown to be associated with a regional response to heating of sloped terrain, while the u-direction oscillation was related to the large-scale atmospheric tides. Collectively, the three studies indicate that diurnal changes in the wind are largely influenced by smaller-scale phenomena than the global atmospheric tide. Several other studies also suggest the importance of regional influences (e.g. Buajitti and Blackadar 1957, Holton 1967, Wallace and Hartranft 1969).

The diurnal and semidiurnal variations in surface wind have been re-examined recently by Dai and Deser (1999). Using a network of approximately 10,000 stations across the globe reporting three-hourly wind observations, they concluded that the diurnal wind cycle was strongest in the summer months, particularly in high terrain, with a wind speed maximum observed in most places in the early afternoon. Following previous studies, this afternoon maximum was related to an increase turbulent mixing of momentum during the daytime hours. Additionally, because the amplitude of the overall wind speed change was far greater than that of either the zonal or meridional component, they noted that it was unlikely that diurnal changes in the wind are associated with large changes in direction.

As with changes in pressure, to the author's knowledge no literature describes decadal-scale changes in the diurnal wind profile over the United States. Klink (1999) observes an increase in mean monthly maximum wind speeds and decrease in mean minimum wind speeds at many stations throughout the United States over the period 1961 to 1990 – it is uncertain how this finding may be translated to trends in the daily wind range. Klink (1999) also notes that trends in monthly mean maximum and minimum speeds are not easily related to changing cyclone and anticyclone frequency, and that urbanization acts to suppress maximum speeds and enhance minimum speeds. In general, the previous work concerning daily wind patterns does suggest that 1) there is an observable, quantifiable daily pattern in many locations, 2) the dramatic differences in topography across many of the western states may lead to inconsistencies in wind data at adjacent stations, and 3) there may be a decadal-scale trend in daily wind range related to the trend in monthly wind range.

Collectively, study of the surface variables should help to improve understanding whether there are fewer or weaker fronts at present compared with fifty years ago. Should fewer or weaker fronts exist today, the distributions of daily change data should reflect the pattern with fewer cases in the tails. Spatial analysis of daily change variables may indicate shifts in the primary regions of frontal and TR activity.

4. External forcings

Human activity has left a significant footprint on many of the Earth's environments and systems. Amongst them, changes to the composition of the atmosphere and landscape are of high concern for atmospheric scientists, as these adjustments have the potential to shift the energy balance that drives circulation at all scales. More specifically, external forcings may be at least partially responsible for changes in circulation speed and shape as well as in frequency, intensity, and location of frontal activity. Here, I briefly review the changes observed and anticipated in atmospheric patterns and climate from modifications to the chemical composition of the atmosphere and physical composition of the surface.

4.1 Greenhouse Gases

Widespread agreement exists amongst the research community that global warming driven by increasing concentrations of greenhouse gasses will lead to the greatest temperature increases in the polar regions, in part due to the changing albedo with decreased snow and ice cover (IPCC AR4). This accelerated warming in the polar regions will act to decrease the equator-to-pole temperature gradient, a primary driver of cyclone activity. It is well known that cyclones act to distribute heat, momentum, and energy more evenly across the lower troposphere; decreased temperature gradients require less cyclone activity to accomplish the same "balance" (e.g., Held 1993, Yin

2005). Further, due to their differing heat capacities, the land will warm at a faster rate than the oceans, decreasing the land-sea temperature gradient in the lower troposphere, also suppressing cyclone activity (e.g., Teng et al., 2007). However, higher in the troposphere, the Tropics are expected to warm at a faster rate than the poles, which would increase the meridional temperature gradient, supporting storm activity (e.g., Teng et al., 2007). Atmospheric warming related to greenhouse gas concentrations, however, is modified by increasing particulate loading of the atmosphere, particularly sulfates (Gillett et al. 2003). These four factors alone demonstrate that determining the response of cyclones to increasing concentrations of greenhouse gasses is, at best, an extremely complex study of atmospheric dynamics.

Also expected with increasing temperatures is an increase in the specific humidity of the atmosphere, as higher temperatures decrease the probability of cloud and water droplet formation. An increase in the atmospheric moisture budget adds a further challenge to determining the response of cyclones: increased moisture will make storms more efficient transporters of latent heat energy, and as such, fewer storms will be required to accomplish the same energy transport (e.g., Carnell and Senrio 1998, Brayshaw 2005). With increased energy-transporting capacity, however, these cyclones are expected to become more intense (e.g., Geng and Sugi, 2003).

The factors expected to influence storm track activity were well-summarized by Held (1993):

1. A decrease in the surface level equator-to-pole temperature gradient
2. An increase in the upper level equator-to-pole temperature gradient
3. An increase in moisture availability in the atmosphere

Collectively, these factors will work to suppress, enhance, and enhance storm growth, respectively (Held 1993, Brayshaw 2005).

Modeling studies of 21st century cyclone activity have produced many consistent results. In an overview of 15 climate models, Yin (2005) observed a remarkably consistent shift in storm track activity toward the poles and higher levels in the atmosphere, with fewer, more intense cyclones. This finding is consistent with Lambert (1995), Kushner et al. (2001), Geng and Sugi (2003), Lambert and Fyfe (2006) and others. Using a higher resolution than many of their predecessors, Bengtsson et al. (2006) observed an overall decrease in cyclone frequency in future climate scenarios using the ECHAM5 model. This reduction, however, was relatively minor, and was limited only to storms of intermediate strength, and they did not find any evidence to support more intense storms in a greenhouse-gas-warmed climate. Teng et al. (2007) recently observed a decrease in cyclone activity from 40-55°N and increase north of 60°N in realizations of the CCSM3 model. They further noted an increase in cyclone activity over the West Coast and Great Lakes, and decrease over the East Coast. However, they were only able to identify the East Coast change using different methods to determine cyclone activity in their model results. Changes to the spatial storm track pattern have also been noted by Cubasch et al. (1997), Geng and Sugi (2003), and others.

The scientific community has been cautious to connect the observed changes in storm track activity (see section 3.3) to increasing levels of greenhouse gasses over the past half century (IPCC TAR). At present, we do not fully understand the dynamics that will connect increasing greenhouse gas concentrations to the predicted changes to storm tracks observed in the modeling environment, and modeling studies have yielded a wide range of anticipated outcomes. These changes may even vary within seasons, as suggested by Hu et al. (2005). Recently Strong and Davis (2007) have observed an increase in jet steam speeds and occurrence probabilities over the latitudes 40°N–60°N; they attributed these changes to increased baroclinicity aloft with cooling over the poles. In general, there seems to be increasing agreement that anthropogenic forcing is likely to affect extra-tropical storm tracks (IPCC AR4, Teng et al. 2007).

A widespread decrease in cyclone activity across the Northern Hemisphere middle latitudes should be well-captured by a change in the TR frequency across the United States, as storm tracks have tended toward higher latitudes in recent decades. However, as high uncertainty remains concerning the dynamical link between increasing greenhouse gas concentrations and extratropical cyclone activity, it will be difficult to relate changes in TR frequency to GHG changes alone.

4.2 Surface Changes (Vegetation)

The land surface is an important element of the entire atmospheric system which controls the frequency and distribution of cyclone, and thus TR, activity. Considerable changes to the landscape of the United States have occurred dating centuries back, at both the local and regional scale. Over the most recent century, these changes have been manifested in two principal areas: agriculture and urban development. Both demonstrate the potential to significantly impact land-atmosphere interactions, and thus overall climate, via changes to the energy balance, roughness factors, and more.

The current vegetation over much of the United States, because of agricultural practices, varies different from the natural, or “potential” vegetation that would otherwise exist. Copeland et al. (1996) applied a modeling approach to determine the differences in climate likely to have arisen from this difference in potential compared to observed vegetation, for July of 1989. Over their domain (the contiguous States), they observed several changes related to the dissimilar albedo, rougness, LAI, and fractional coverage between the vegation types. In general, the current land use practices were attributed to a warmer and wetter climate than the natural landscape would provide. Average temperatures increased by fractions of one degree (K), although this change was larger in the east (+0.22 K) than the west (0.09 K). The regions that demonstrated the largest warming were coastal areas along the Gulf of Mexico, Atlantic Ocean, as well as interior regions in western Oklahoma and southeast Montana. Temperatures along the Mexican border demonstrated a negative response, with present vegetation decreasing average temperature in some places by 3 K. Slight changes were also observed in daily mean mixing ratio, wind speeds, and precipitation rates. Figure L13 shows the results from their modeling study with anticipated differences for each of the four quantities described above. Bonan (1997) expanded the work of Copeland in examining differences between natural and potential vegetation, including combining a land surface and circulation model and conducting analysis over the entire year. Observed differences reached well into the upper atmosphere, and were notable in both boundary layer processes and the larger-scale circulation. The four major impacts found by Bonan (1997) include springtime cooling in the east and warming in the west, summer cooling over the central plains (also noted by Xue et al. 1996), moistening of the lower levels of the atmosphere in spring and summer, and changes to the pressure and height fields. The author suggested that these changes were on the same order of magnitude as other significant forcings, like greenhouse gasses. Thus, land use practices seem to have a highly important influence on climate change. However, the body of work completed to date does not seem to suggest a bias toward higher or lower frequency of TR days. It is anticipated that if land use is a significant factor, it will be manifested through changes in the diurnal profile of the variables on which the TR calculation procedure operates.

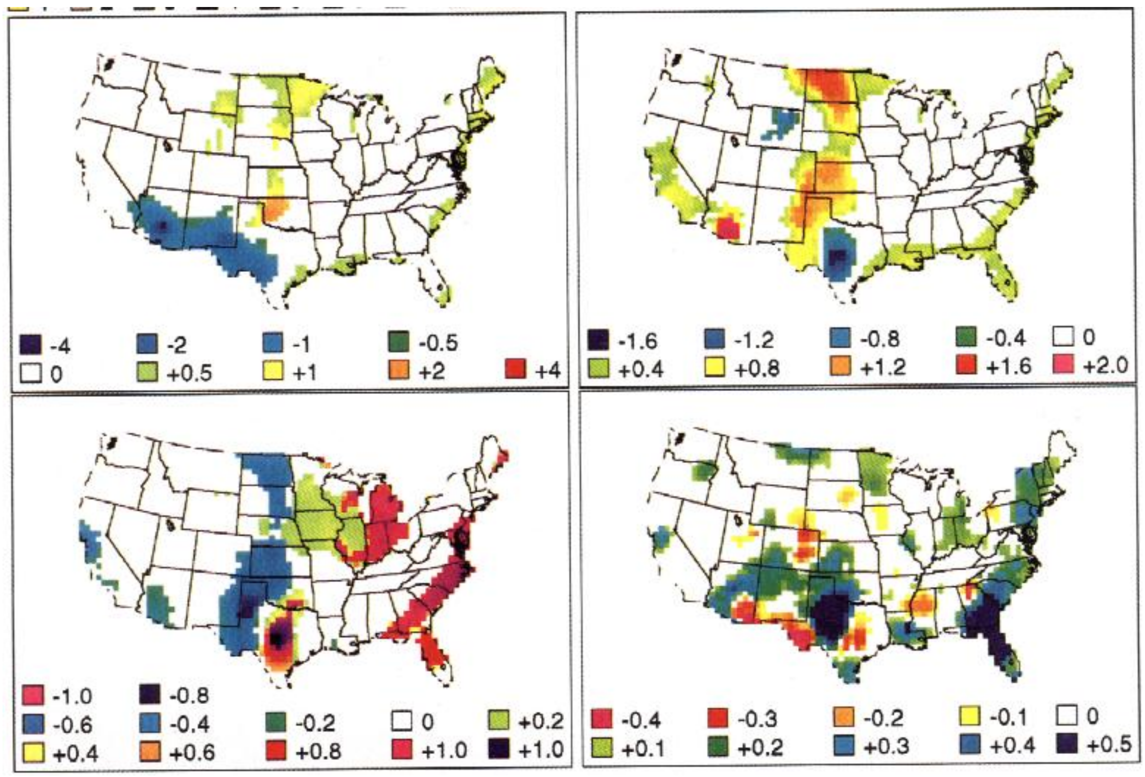


Figure L13. Differences between current and natural vegetative cover in screen height quantities of (top left) temperature (K), (top right) mixing ratio (g/kg), (bottom left) wind speed (m/s), and (bottom right) precipitation (mm/day). From Copeland et al., 1996.

4.3 Surface Changes (Urbanization)

Large metropolitan areas are also known to significantly impact local and regional climate, particularly through the development of the urban heat island (UHI, e.g., Dabberdt et al., 2000; Brazel et al., 2007), with highest temperatures at the urban center. Accordingly, urban areas present the potential for climate change impacts at both the small and large scale. Locally, temperature changes may result from the added sensible heat load from dwellings and industrial areas, which may lead to large-scale changes via adjustments in the energy balance. An added complication the urban areas present is the possibility of modifying observations in a manner not representative of the larger-scale trends. While study of the UHI merits significant attention, cities also demonstrate high potential to impact other synoptic-scale dynamics due to their difference in roughness parameters compared to surrounding rural landscapes.

Loose and Bornstein (1977) expanded upon previous studies that determined the influence of urban areas on wind speeds alone. As an example, Bornstein and Johnson (1977) found that during periods of low wind speed in surrounding rural areas, wind speeds observed in the city were higher because of the increased temperature and pressure gradients associated with the UHI. During periods of high wind speed, they observed the opposite, because of the increased surface roughness and frictional drag. Using data from a comprehensive anemometer network (97 sites throughout New York City) deployed in the mid 1960's, Loose and Bornstein (1977) visually inspected maps of hourly wind speed and direction. By using known characteristics of wind speed surrounding fronts, they were able to generate time-series maps of frontal position (e.g., Figure 1). These results suggest a major influence from the urban center, with a change in frontal speed by up to 50% in many cases. They found that fronts behaved differently depending on the strength of the UHI: During periods of low intensity, frontal movement was slowed over the entire city, whereas during periods of high intensity, the movement was slowed over the upwind half and accelerated over the downwind half, due to the associated pressure gradients.

This significant impact of urban areas was later corroborated by Gaffen and Bornstein (1987). Their study used three-dimensional atmospheric data from the same NYC network to show that urban roughness caused the front to decelerate at the surface, leading to the destruction of the front's vertical structure. They suggested that the front may physically "split" over a metropolitan area, and "re-connect" downwind. These and other studies suggest the potential for a large-scale urban influence on frontal activity, which should result in changes to the frequency of TR. In addition to the bifurcation of fronts and storms, potential impacts include the acceleration of convective activity over metropolitan areas during calm conditions (Bornstein and Lin 1999). However, the nature to which extensive development at the metropolitan centers has occurred over the past several decades may not be significant compared to the TR frequency trend, and it has not been suggested that increasing suburban development may produce the same effect. For those reasons, it does not seem that development and TR frequency should be directly related. As with agricultural changes, impacts of urbanization may be observed through adjustments in diurnal profiles. Souch and Grimmond (2006) note a recent "resurgence" in interest of metropolitan impacts on climate, particularly with regard to moisture output to the atmosphere from human activities. It is possible that near urban centers, where many observing stations are located, the diurnal range of humidity has been suppressed, which could decrease TR frequency.

5. Teleconnections

The semi-regular patterns of the redistribution of the atmosphere's mass across Earth's surface are known as teleconnections. These phenomena have been documented at least as early as the late 1700's, with observations of different and opposite temperatures each winter in Greenland and Northern Europe by Saabye (van Loon and Rogers 1978). At present, several teleconnections are known to have an impact on climate in the Northern Hemisphere. The North Atlantic Oscillation (NAO), Southern Oscillation (SO), and Pacific-North America (PNA) teleconnections are amongst those thought to exert the greatest influence (e.g., Barnston and Livezey, 1987; Hurrell et al. 2003). Shifts in teleconnections are often identifiable in changes to regional temperature, precipitation, etc. (e.g., Leathers et al., 1991) as well as in changes to air mass frequency (e.g., Sheridan, 2003), and are often related to the size and shape of the CPV (e.g., Frauenfeld and Davis 2003). The SSC has been included in analyses of air mass-teleconnection relationships; first by Sheridan (2003), with a statistically significant relationship found between weather-type frequencies and the PNA and NAO patterns, and more recently by Knight et al. (in progress, 2008), with identification of an air-mass signal indicative of a warmer, moister climate across the United States. Below, I detail several teleconnection patterns known to impact the North American climate and explore the potential of each to change the frequency of TR.

It is well-accepted that one of the major modes of northern hemisphere pressure variability with the shift in atmospheric mass between the Icelandic Low and Bermuda High, in a pattern often identified as the North Atlantic Oscillation (e.g. Sheridan 2003, Ostermeier and Wallace 2003, Rogers 1990, Barnston and Livezey 1987, Walker and Bliss 1932). These shifts in mass change the meridional pressure gradient over the Atlantic, and as a result, change the patterns and strength of the surface westerlies. In positive phase of the NAO, the strength of both the Icelandic low and Azores high are greater than normal, resulting in a steeper pressure gradient and faster cross-Atlantic winds (e.g., Wallace and Gutzler 1981, Sheridan 2003). Figure L3 below represents a conceptualization of this phase. The negative phase is associated with a weaker pressure gradient and slower westerlies. These variations are most pronounced during the winter months, when the pressure gradient in the Northern Hemisphere middle latitudes is greatest. Hurrell and van Loon (1997) suggest that the NAO accounts for one-third of the total pressure variance over the North Atlantic in the winter months. Across the entire hemisphere, Barnston and Livezey (1987) observe that at the 700mb level the pattern (observed as the first empirical orthogonal function of northern hemisphere monthly sea level pressure) accounts for 11.1% of the total pressure variance, and that it is the only teleconnection pattern observed throughout the year. At the surface, the NAO accounts for up to 15% of the surface pressure variability in the winter months in the Atlantic region (Rogers 1990).

Although the effects of the NAO are greatest downstream of the Atlantic westerlies, over Europe, the teleconnection has been related to many changes in the North American climate as well. These effects are most pronounced over the eastern portion of the continent, related to a strengthening of the "pumping" of warm, moist air along the coast (Yarnal and Leathers 1998). When the NAO index has a high value, cyclone tracks tend to follow a southwest-to-northeast pattern across the Atlantic, whereas in the low index pattern, cyclone tracks are more directly west-to-east (Rogers 1990). This shift in circulation results in changes to surface weather across the east coast of the United States. Dickson and Namias (1976) observed warmer winters across the southeastern states under the positive phase, and colder winters under the negative phase. Above average precipitation in the southeastern states during positive NAO winters has been observed by Yin (1994) and New et al. (2001), amongst others. In the northeast states, positive NAO winter months often result in warmer, wetter conditions (Yarnal and Leathers 1998), and changes in cyclone activity over New England (Bradbury et al. 2003).

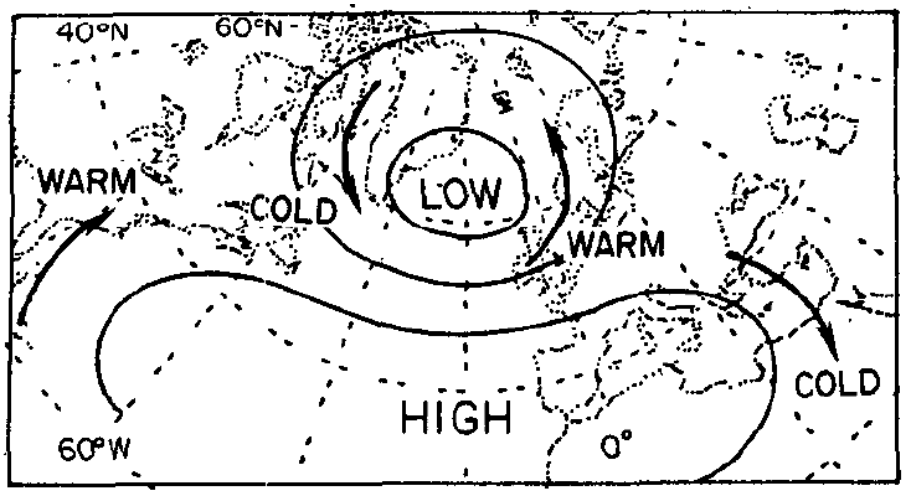


Figure L3. Idealized relationships between pressure and temperature anomalies associated with the positive phase of the North Atlantic Oscillation. Reproduced from Wallace and Gutzler, 1981.

Considerable evidence exists pointing toward a recent decadal-scale trend in the NAO. In an examination of decadal-scale changes in the NAO, Hurrell (1995) found that index values have remained well above average since the early 1980's. He noted that the winters of 1983, 1989, and 1990 were those with the highest positive NAO index values over the roughly 150-year observational record. These changes were thought to be a contributor to warming in the North Atlantic. Ostermeier and Wallace (2003) later verified that the temperature and pressure changes associated with high index values over recent decades were greater in spatial extent than changes associated with previous periods of low index values. Examples of the NAO time series using several different methods of calculation appears below.

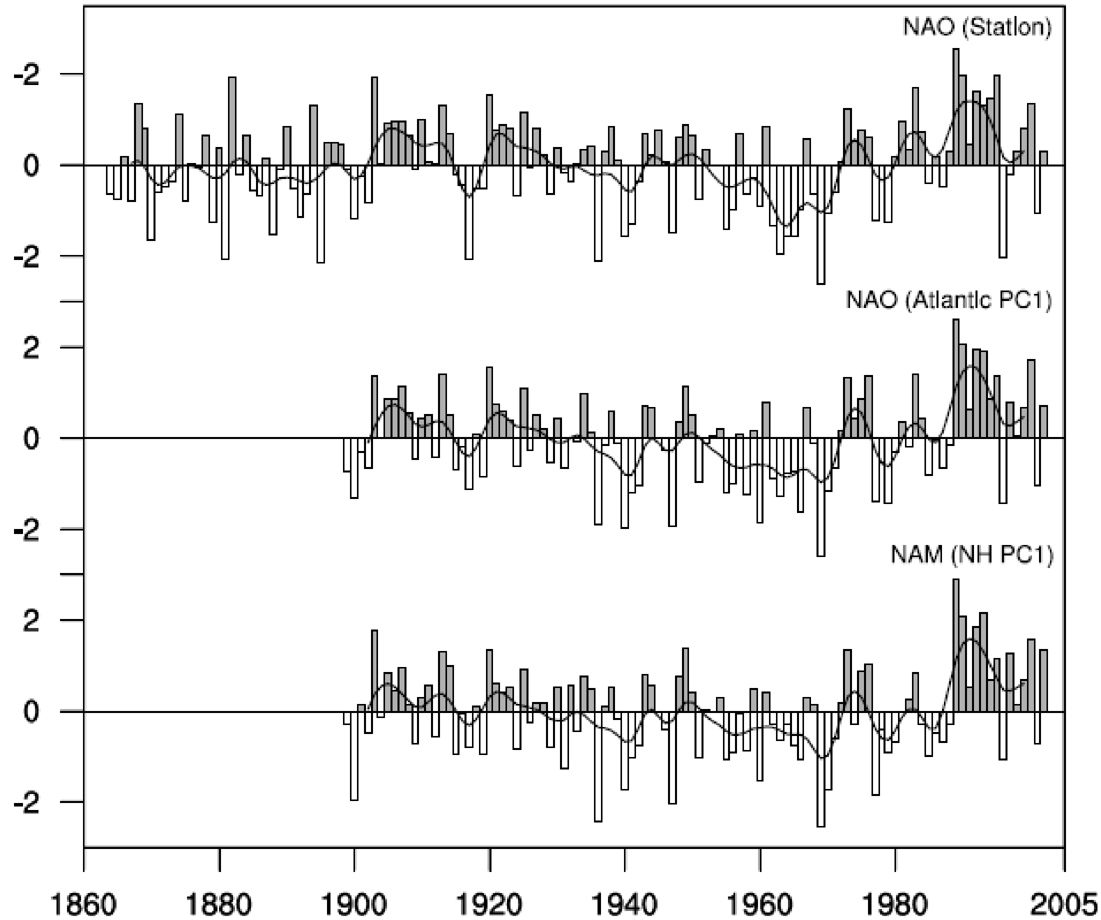


Figure L4. Three normalized winter (DJFM) pressure-based indices of North Atlantic variability. Top panel index based on difference of normalized sea level pressure between Portugal and Iceland, 1864–2002. Middle panel index related to empirical orthogonal function of Atlantic-sector sea level pressure. Low panel index related to empirical orthogonal function of Northern Hemisphere sea-level pressure. Data from http://www.cgd.ucar.edu/~jhurrell/nao.html. Figure and caption from Hurrell et al., 2003.

The pattern of variability associated with the shifting atmospheric mass between the Azores high and Icelandic low also is identified in the first principal component of hemispheric annual variability, sometimes referred to as the Arctic Oscillation (e.g., Barnston and Livezey 1987, Thompson and Wallace 2000), or Northern Hemisphere Annular Mode (NAM, e.g., Ostermeier and Wallace 2003). In addition to the meridional pressure gradient change over the Atlantic, AO/NAM features a center of action over the Pacific. Thus, the NAO is typically considered as more of a regional variability, whereas the AO is a hemisphere-wide pattern (Ambaum et al. 2001). Because of their high correlation, the larger-scale variability has also exhibited high index values over recent decades (Ostermeier and Wallace 2003). Preference for use of the NAO (e.g., Thompson and Wallace 2000) or AO (e.g., Ambaum et al. 2001) varies across studies.

When considering trends in the "annular mode"/AO, similar results emerge (see Figure L4, above). Over the three decades between 1968 and 1997, Thompson and Wallace (2000) identified a significant trend toward high index values in the AO, with the potential for "substantial impact" on circulation patterns across the Northern Hemisphere, including increasing speed of the westerlies at subpolar latitudes, decreasing speed of the jet over low latitudes, and a resultant large-scale warming of the lower troposphere. They identify several previous studies that may point toward external forcings of the NAM/AO, including depletion of stratospheric ozone (Volodin and Galin 1998), increasing greenhouse gasses and aerosols (Shindell et al. 1999), and evolving patterns of sea surface temperatures across the Atlantic (Rodwell et al. 1999).

Relationships between SSC weather-type frequency and the NAO have been explored by Sheridan (2003). In the winter months, when the NAO accounts for the largest portion of variability, positive index values are associated with increased frequency of DM, MM, and MT across much of the east coast. It is suggested that under positive NAO conditions, the stronger southerly flow around the Bermuda high inhibits the advection of polar air masses from Canada much farther south than their source regions. This stronger southerly flow also decreases TR frequencies across the southeast. Farther north into Canada, the reverse is observed, as stronger flow around the Icelandic low increases the DP and MP frequencies. Under negative NAO conditions, DP, MP, and MT increase in frequency in the winter months. As expected, the significant effects of the NAO are limited in spatial extent to the eastern portion of the continent.

Knight et al. (2008) correlated NAO index values to SSC types over a 42-station network across the United States for winter months during the period 1948 – 2005. Over the eastern states, they found a negative correlation with the DP and MP types, and positive correlation with MT, DT, MM, and DM. Compared to the other SSC types, TR frequencies were rarely correlated with the NAO index (Table L2, columns 1 and 2).

During the winter, a second major pattern of variability arises in the mid-tropospheric geopotential height field over the Pacific Ocean and much of North America. This Pacific-North American pattern (PNA) is manifested as changes to the normal ridge-trough structure that persists over these regions. Wallace and Gutzler (1981) were the first to formally identify this pattern as one that exerts a major influence on the climate of the United States (Leathers et al. 1991). The mean flow includes a trough over the East Pacific, ridge over western North America, and trough over eastern North America. In the positive phase of the PNA, meridional flow is enhanced, such that the ridge and trough pattern is amplified. Figure L5, below, illustrates this phase. The negative phase represents enhanced zonal flow with a dampening of the ridge and trough pattern. The “centers of action” for this pattern, used by Yarnal and Diaz (1986) and Leathers et al. (1991) are located south of the western Aleutian Islands, along the United States/Canada boundary in the middle of Montana, and in the western Florida panhandle. Wallace and Gutzler (1981) find a fourth center of action in the tropics near Hawaii; however, Leathers et al. (1991) argue that it is not of interest for studies of the climate of the contiguous continent.

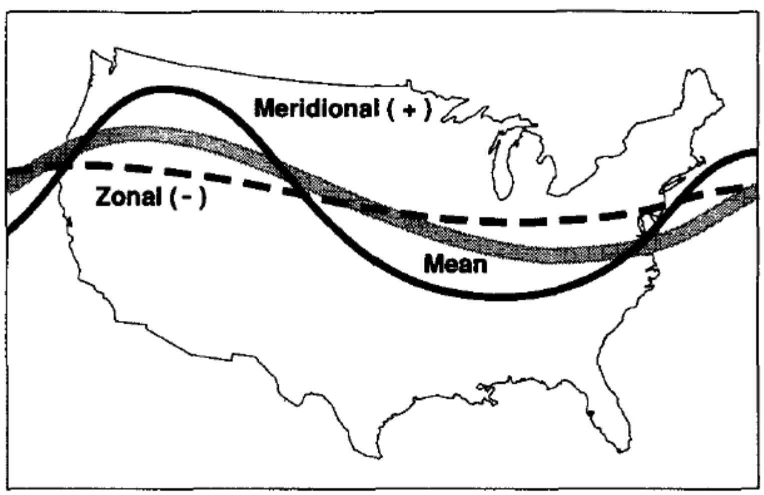


Figure L5. Idealized midtropospheric flow over the United States for the positive and negative phases of the PNA. From Leathers et al., 1991.

Davis and Benkovic (1994), amongst others, find that the PNA is the first component of northern hemisphere circulation during the winter months. Accordingly, adjustments to the PNA result in significant changes to the United States climate, especially to temperature and rainfall (e.g., Leathers et al. 1991, Skeeter and Parker 1985). During the positive phase, the stronger ridge over the western portion of the country typically leads to warmer, drier conditions as low pressure systems are diverted to the north. Subsidence aids warming due to compressional heating (Leathers et al., 1991). In the east, positive PNA years result in the jet stream being diverted further to the south, increasing jet stream activity and precipitation over Florida and decreasing them to the north (Henderson and Robinson 1994). While precipitation is lower, arctic air is able to penetrate south much more easily, resulting in lower temperatures as well (e.g., Leathers et al. 1991). The negative phase is associated with fewer winter storms in the southeastern states, and more summertime storms (Henderson and Robinson 1994), as well as more frequent storm activity in the Pacific northwest with continual zonal flow off the ocean (Leathers et al. 1991). Correlations between the PNA and temperature during winter months are highest in the Southeast and Northwest, and between PNA and precipitation highest in the Mississippi Valley and northern Rockies, although PNA certainly plays a significant role over many portions of the country (Leathers et al. 1991).

Many changes to the North American climate over the past several decades are related to shifts in the PNA pattern, and evident in study of the temporal characteristics of the PNA index. Using the three centers of action previously described, Leathers and

Palecki (1992) identify a sharp break in the PNA index time series in the late 1950s, that corresponds to a well-recognized time of shift from zonal to meridional flow over North America (e.g., Yarnal and Leathers 1992, Balling and Lawson 1982, Kalnicky 1974). In their decade of record prior to 1957, the index values averaged at or below zero, indicative of zonal flow. Their time series (Figure L6) reveals several months with highly negative values, which they suggested was from a reversing of the mean pattern, with a trough over the western half of the country, and ridge over the east. Since 1957, they observe an average index value well above zero, with the more traditional ridge-trough pattern across the States (their data set extended through 1987). They further observed that this break was driven by changes in the strength and/or position of the Aleutian low and Bermuda highs, and concluded that this break point is likely unrelated to a shift in instrumentation or observing techniques. Mitchell et al. (2004) demonstrate that DJF-averaged PNA index values have remained positive since the time of Yarnal and Leathers' study (http://jisao.washington.edu/data/pna/).

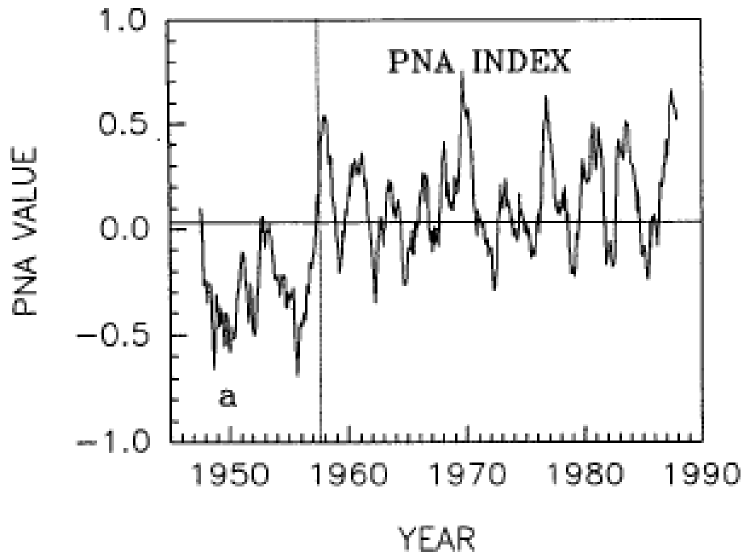


Figure L6. PNA index time series from Leathers and Palecki, 1992.

The PNA does not emerge from analysis of surface data over the same domain because of the complications in the pressure data that arise because of the complicated topography in the western United States (Leathers et al. 1991). However, a robust pattern of variability does emerge over the Pacific region that is similar in nature to the North Atlantic Oscillation, also originally identified by Walker and Bliss (1932). Rogers (1990) states that this North Pacific Oscillation, along with the NAO, are the “most recurrent teleconnections” observed throughout the literature to date.

Sheridan (2003) related SSC frequencies to the PNA in addition to the NAO. The most dramatic changes to weather-type frequency related to this teleconnection are observed in the Pacific northwest, southern California, and the southeastern states. When the PNA is in its positive phase, with an amplified ridge across the west, Arctic air is restricted to its source region, decreasing DP frequencies. Maritime influence becomes stronger under this regime, increasing MP frequency, as does subsidence warming, increasing DM frequency. In the east, however, DP frequency increases, as MT frequency is suppressed. TR frequencies become very low across the west during the +PNA phase; Florida is the region of greatest TR increase during +PNA, which he relates to the shift in the jet stream. For the most part, these patterns reverse for the opposite phase. Knight et al. (2008) found similar results: negative correlations between the PNA and MT in the Southeast and PNA and MP along the West Coast, and positive correlations between the PNA and DM in the Southeast and PNA and MT in the west (see Table L2, below). They also observed significant correlations between the PNA and TR frequencies in agreement with Sheridan (2003).

Low-frequency changes in Pacific SSTs and the regular oscillation of pressures across the southern Pacific were first related by Bjerknes (1969; Horel and Wallace, 1981). Combined, these processes represent the modern-day El Niño/Southern Oscillation phenomenon (ENSO). Traditionally, “El Niño” has referred to the annual warm currents along the Peruvian and Ecuadorian coasts that occur in late December or the associated warming across a wide band of the tropical Pacific ocean (Trenberth, 1997). The atmospheric component is named the “Southern Oscillation (SO, Walker and Bliss 1932). The centers of action of the atmospheric exchange of mass are located over Indonesia and the eastern South Pacific (Trenberth and Paolino 1981). Of late, many of the terms to describe this complex system have been used interchangeably (Trenberth, 1997).

Changes in the Pacific Ocean SSTs and the related shifts in atmospheric mass over the Pacific exert a major influence on the climate of North America due to their impacts on the radiation balance, partitioning of energy, and transfer of momentum. Globally, ENSO plays a significant role in precipitation variability: New et al. (2001) find that 38% of the variance in global average land precipitation may be attributed to ENSO variations. Most of the significant impacts are related to enhanced convective activity in the tropics arising from the increased SSTs during warm episodes. In the United States, warm (El Niño) years have been associated with negative height anomalies aloft over the southeastern (Horel and Wallace 1981), above normal precipitation over the Southeast (Ropelewski and Halpert 1986), above normal precipitation over the Great Basin (Ropelewski and Halpert 1986), more frequent east coast winter storms (Hirsch et al. 2001; Eichler and Higggins 2006), stronger westerlies in the mid-latitudes (Namias 1976), increased frontal activity along the Gulf coast (Douglas and Englehart 1981), and below normal temperatures in the southeast (Ropelewski and Halpert 1986). Bonsal and Lawford (1999) also found a significant relationship between Pacific SSTs and dry spells over the Canadian plains. The abundance of impacts suggests a high potential for an ENSO-TR relationship, particularly in the Southeast.

Figure L7 shows the time series of the Niño 3.4 SST anomalies, a common measure of the strength and phase of ENSO. Over the record, considerable variability is observed, and El Niño events slightly outnumber La Niña events. Trenberth (1997) notes that the period since 1979 has shown a greater number of El Niño events, or a greater tendency toward the warmer phase. The variability in ENSO is greatest in the winter months, which demonstrate standard deviations nearly twice as high as those during the late spring and early summer. Further, this variation has only slightly increased in recent decades (Trenberth 1997). With a bias towards El Niño events in latter portion of the record, it seems reasonable to expect a related TR response in the regions described above.

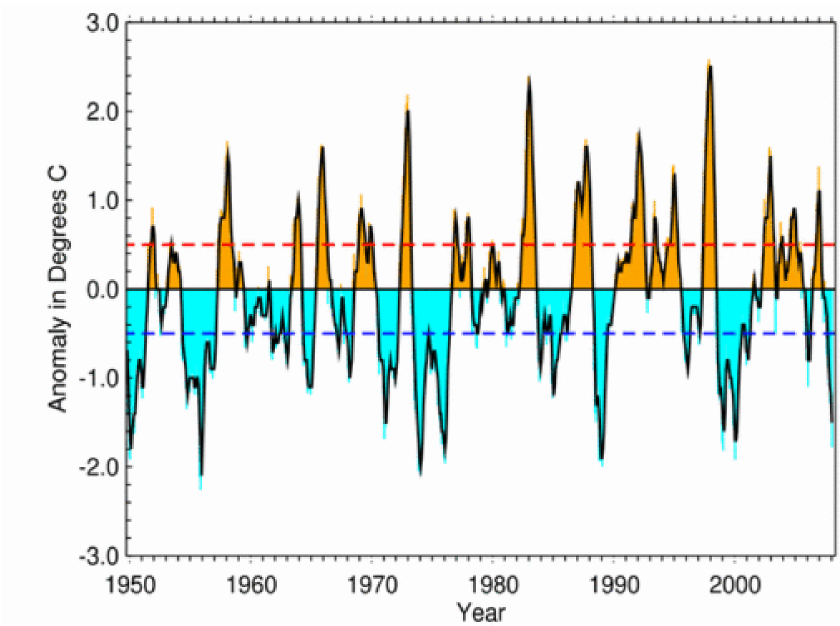


Figure L7. SST Anomaly time series in Niño 3.4 region, from NOAA/NCDC.

Knight et al. (2008) observed a widespread positive correlation between the Multivariate Enso Index (MEI) and MM frequency and negative correlation between MEI and TR, and negative correlation between MEI and MT in the Southeast. The MEI combines several climate variables over the tropical Pacific, rather than just sea level pressure or SSTs alone (time series in Figure L8, below). Knight et al. (2008) suggest that relationships between the MEI and SSC frequencies may be more difficult to interpret than the other teleconnections, due to ENSO's short phase.

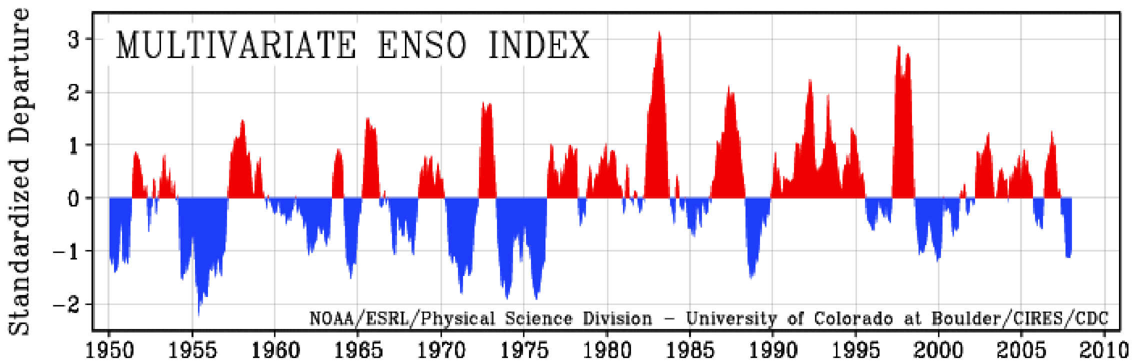


Figure L8. Time series of the multivariate ENSO index, reproduced from NOAA/NCDC.

The impacts of a Pacific Decadal Oscillation (PDO) are well-evident in the surface climate over North America (Mantua et al., 1997). In their review of existing literature on the PDO, Mantua and Hare (2002) describe the phenomenon as a blend of two semi-independent patterns of SST variability in the North Pacific, while acknowledging that its mechanisms are unclear. It also remains unclear whether the PDO itself is an internal atmospheric phenomenon: Newman et al. (2003) suggest that the oscillation is driven by ENSO on all time scales. The current nomenclature, "PDO," represents a recent revision of the North Pacific Oscillation (NPO) found in many previous studies of NH SLP variability (e.g., Rogers 1990), and the pattern has also been identified as the IPO (e.g., Power et al., 1997) (Mantua and Hare 2002). In the positive phase of the PDO, SSTs are low in the central North Pacific and high along the west coast of the Americas Over the northern ocean, the resultant negative SLP anomalies cause enhanced counterclockwise flow, and the reverse holds true in the subtropics. The mean flow, then, is accelerated over the Pacific. The opposite is observed in the negative phase (e.g., Mantua and Hare 2002). Compared to other teleconnections which exhibit alternating patterns on the order of months to years, the PDO acts over much longer time scales (two to three decades, Rohli et al. 2005).

Amongst the most significant impacts of the PDO, and that which accelerated its study, is the relationship on the fish catch along the Pacific coast. Using historical catch data dating back some 70 years, several studies linked decadal changes in the atmosphere to major shifts in marine ecology (e.g., Mantua et al. 1997). Of greater importance to the present study, the PDO has impacts on both temperature and precipitation across North America. The positive phase has been related to anomalously dry conditions across the northern tier of the United States, anomalously wet conditions in the southwest, above-average temperatures in northwestern North America, and below-average temperatures in the southeast (Mantua and Hare 2002). These large-scale departures from mean conditions suggest the potential for PDO impacts on air mass frequency, and the resulting probability of TR occurrence.

An accepted index of PDO activity stems from the first principal component of North Pacific SST anomalies (e.g., Hare 1996, Zhang 1996, Mantua et al. 1997). Analysis of the time series over recent decades reveals a negative phase from the late 1940's until roughly 1976, when the index abruptly shifted to the positive phase (Rohli et al., 2005).

The PDO appears to have shifted back to its negative phase in the early 1990's (Hare and Mantua 2000). A representation of these index values is shown below as Figure L9. Using tree ring samples, Biondi et al. (2001) were able to extend the PDO index record back as far as 1661, and demonstrated significant impacts of differential timing of the phases of the PDO and other patterns of variability in the Pacific. They suggested that the dominant cycle of variability for the PDO was bidecadal. The relationship between the PDO and SSC frequencies has not been examined to date.

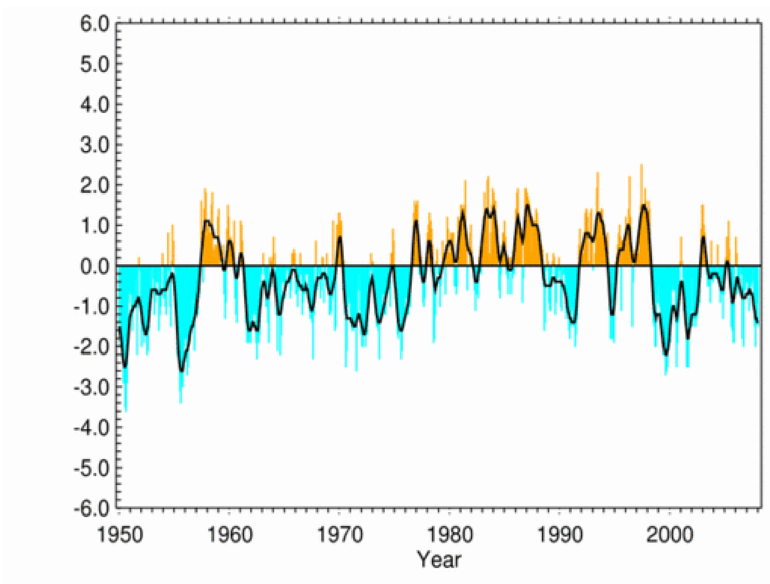


Figure L9. Time series of the Pacific Decadal Oscillation, reproduced from NOAA/NCDC.

The semi-regular oscillations in atmospheric waves, and related changes in surface pressure and other variables clearly play an important role on the climate of North America, and demonstrate an influence on the frequency of SSC types, including TR. It is recognized that these teleconnections do not operate independently on the circulation, but rather often evolve and influence each other and other elements of the atmospheric system. The review above demonstrates that these teleconnections have varied effects over much of the country. These effects at least partially represent changes in the overall speed and shape of large-scale atmospheric circulation features, and may help to shed light on the number and strength of fronts and residence times of air masses over certain regions. As suggested by Knight et al. (2008), the uncertainty of the TR type has hindered a thorough understanding of teleconnection – transition relationships. Here, it is hoped that inclusion of teleconnection indices may provide partial explanation of the spatial and temporal variance in TR and its sub-types.

		NAO		PNA		AO		MEI	
		Pos	Neg	Pos	Neg	Pos	Neg	Pos	Neg
East	DM	5	1	4	0	8	2	2	0
	DP	0	16	1	0	0	16	0	0
	DT	6	0	0	0	11	0	0	2
	MM	11	0	2	2	10	1	9	0
	MP	0	11	4	0	0	11	2	0
	MT	15	0	0	9	13	0	1	7
	TR	0	3	2	12	0	2	2	7
West	DM	4	0	11	1	4	0	5	0
	DP	0	13	0	7	0	7	0	6
	DT	2	0	5	0	2	0	0	6
	MM	4	0	6	0	1	0	14	0
	MP	1	1	3	4	0	2	5	2
	MT	3	0	4	4	3	2	5	4
	TR	0	3	0	16	2	3	0	15

Table L2. Results from the Pearson's correlation test between air mass type frequency and teleconnection index value during winter (December, January, February). Values are the sum of the number of stations positively and negatively correlated (alpha=0.05), separated into East and West subsets using the Mississippi River as a dividing line. Table and caption from Knight et al., 2008.

Summary

The large literature on changes to the United States climate and circulation over the past half-century demonstrates several probable links with the decreasing frequency of the transition weather type of the Spatial Synoptic Classification observed over the same time period:

1. The poleward recession of the circumpolar vortex may have decreased transition frequency over the study domain by shifting the zone of highest transition occurrence northward.

2. The decrease in cyclone and anticyclone frequencies suggests fewer boundaries between air masses, and/or a longer residence time of air masses over the continent.

3. Changes in the diurnal profile of the transition indicator variables have not been fully documented. However, there is some evidence for changes in the diurnal patterns that could adjust the probability of obtaining TR classification.

4. External forcings of the land and atmosphere have been significant over the past fifty years, including modifications that may impact the larger-scale circulation and/or local-scale dynamics in a manner that influences frontal movement and other transitional weather types.

5. Teleconnection patterns significantly impact regional climate, including air mass advection and transitional weather frequencies.

These five factors strongly indicate that the decadal-scale trend in the transition weather type is related to aspects of climate change that as of yet may not be well-documented, and motivate the hypotheses of my research proposal.

References

Agee EM, 1991. Trends in Cyclone and Anticyclone Frequency and Comparison with Periods of Warming and Cooling over the Northern Hemisphere. *Journal of Climate*, **4**, 263–267.

Alexandersson H, Scmith T, Iden K, Tuomenvirta H, 1998. Long-term variations of the storm climate over NW Europe. *Global Atmosphere Ocean System*, **6**, 97–120.

Ambaum MHP, Hoskins BJ, Stephenson DB, 2001. Arctic Oscillation or North Atlantic Oscillation? *Journal of Climate*, **14**, 3495–3507.

Angel JR, Isard SA, 1998. The Frequency and Intensity of Great Lake Cyclones. *Journal of Climate*, **11**, 61–71.

Angell JK, 2006. Changes in the 300-mb North Circumpolar Vortex, 1963–2001. *Journal of Climate,* **19**, 2984–2994.

Balling Jr., RC, Lawson MP, 1982. Twentieth century changes in winter climatic regions. *Climatic Change*, **4** (1), 57–69.

Barnston AG, Livezey RE, 1987. Classification, Seasonality, and Persistence of Low-Frequency Atmospheric Circulation Patterns. *Monthly Weather Review*, **115**, 1083–1119.

Bengtsson L, Hodges KI, Roeckner E, 2006. *Storm Tracks and Climate Change*, **19**, 3518–3543.

Biondi F, Gershunov A, Cayan DR, 2001. North Pacific Decadal Climate Variability since 1661. *Journal of Climate*, **14** (1), 5–10.

Bjerknes J, 1969. Atmospheric Teleconnections from the Equatorial Pacific. *Monthly Weather Review*, **97** (3), 163–172.

Bonan GB, 1997. Effects of Land Use on the Climate of the United States. *Climatic Change*, **37**, 449–486.

Bonner WD, 1968. Climatology of the Low Level Jet. *Monthly Weather Review*, **96** (12), 833–850.

Bonner WD and J Paegle, 1970. Diurnal variations in boundary layer winds over the south-central United States in summer. *Monthly Weather Review*, **98** (10), 735–744.

Bonsal BR, Lawford RG, 1999. Teleconnections between El Niño and La Niña events and summer extended dry spells on the Canadian prairies. *International Journal of Climatology*, **19**, 1445–1458.

Bornstein R, Johnson DS, 1977. Urban-rural wind velocity differences. *Atmospheric Environment*, **11** (7), 597–604.

Bornstein R, Lin Q, 2000. Urban heat islands and summertime convective thunderstorms in Atlanta: three case studies. *Atmospheric Environment*, **34** (3), 507–516.

Bradbury JA, Keim BD, Wake CP, 2003. *Annals of the Association of American Geographers*, **93** (3), 544–556.

Brayshaw D, 2005. Storm tracks under climate change. *Proceedings of the 2005 British Council on Climate Change*, 6 pp.

Brazel A, Gober P, Lee SJ, Grossman-Clarke S, Zehnder J, Hedquist B, Comparri E, 2007. Determinants of changes in the regional urban heat island in metropolitan

Phoenix (Arizona, USA) between 1990 and 2004. *Climate Research*, **33**, 171–182.

Brier G, 1965. Diurnal and semidiurnal atmospheric tides in relation to precipitation variations. *Monthly Weather Review*, **93** (2), 93–100.

Buajitti K, Blackadar AK, 1957. Theoretical studies of diurnal wind-structure variations in the planetary boundary layer. *Quarterly Journal of the Royal Meteorological Society*, **84**, 470–470.

Burnett AW, 1993. Size variations and long-wave circulation within the January Northern Hemisphere Circumpolar Vortex: 1946–1989. *Journal of Climate,* **6,** 1914–1920.

Carnell RE, Senior CA, 1998. Changes in the mid-latitude variability due to increasing greenhouse gases and sulphate aerosols. *Climate Dynamics,* **14**, 369–383.

Changnon D, Noel JJ, Maze LH, 1995. Determining cyclone frequencies using equal-area circles. *Monthly Weather Review,* **123,** 2285–2294.

Chapman S, Lindzen RS, 1970. *Atmospheric Tides*. D. Reidel, 200 pp.

Copeland JH, Pielke RA, Kittel TGF, 1996. Potential climatic impacts of vegetation change: A regional modeling study. *Journal of Geophysical Research,* **101,** 7409–7418.

Cubasch U, Caneill JY, Filiberti MA, Hegerl G, Johns TC, Keen A, Parey S, Thual O, Ulbrich U, Voss R, Waszkewitz J, Wild M, van Tpersele JP, 1997. Anthropogenic climate change, final report. Office for Official Publications of the European Commission, 73 pp.

Dabberdt WF, Hales J, Zubrick S, Crook A, Krajewski W, Doran JC, Mueller C, King C, Keener RN, Bornstein R, Rodenhuis D, Kocin P, Rossetti MA, Sharrocks F, Stanley Sr., EM, 2000. Forecast Issues in the Urban Zone: Report of the 10th Prospectus Development Team of the U.S. Weather Research Program. *Bulletin of the American Meteorological Society*, **81**, 2047–2064.

Dai A, Deser C, 1999. Diurnal and semidiurnal variations in global surface wind and divergence fields. *Journal of Geophysical Research*, **104**, 109–125.

Dai A, Wang J, 1999. Diurnal and semidiurnal Tides in Global Surface Pressure Fields. *Journal of the Atmospheric Sciences***, 56** (22), 3874–3891.

Davis RE, Benkovic SR, 1992. Climatological variations in the Northern Hemisphere circumpolar vortex in January. *Theoretical and Applied Climatology*, **46**, 63–74.

Davis RE, Hayden BP, Gay DA, Phillips WL, Jones GV, 1997. The North Atlantic Subtropical Anticyclone. *Journal of Climate*, **10,** 728–744.

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

Douglas V, Englehart PJ, 1981. On a Statistical Relationship between Autumn Rainfall in the Central Equatorial Pacific and Subsequent Winter Precipitation in Florida. *Monthly Weather Review*, **109,** 2377–2382.

Eicher T, Higgins W, 2006. Climatology and ENSO-Related Variability of North American Extratropical Cyclone Activity. *Journal of Climate*, **19** (10), 2076–2093.

Espy JP, 1841. The Philosophy of Storms. Little-Brown, 552 pp.

Frauenfeld OW, Davis RE, 2003. Northern Hemisphere circumpolar vortex trends and climate change implications. *Journal of Geophysical Research*, **108,** D14.

Gaffen D, Bornstein RD, 1988. Case Study of Urban Interactions with a Synoptic Scale Cold Front. *Meteorology and Atmospheric Physics,* **38,** 185–194.

Gaffen D, Ross RJ, 1999. Climatology and Trends of U.S. Surface Humidity and Temperature. *Journal of Climate,* **12,** 811–828.

Geng Q, Sugi M, 2003. Possible Change of Extratropical Cyclone Activity due to Enhanced Greenhouse Gases and Sulfate Aerosols–Study with a High-Resolution AGCM, **16**, 2262–2274.

Gillett NP, Zwiers FW, Weaver AJ, Stott PA, 2003. Detection of human influence on sea-level pressure. *Nature*, **422**, 292–294.

Gitelman A, Risbey J, Kass R, Rosen R, 1997. Trends in the surface meridional temperature gradient. *Geophysical Research Letters*, **24**, 1243–1246.

Hare SR, 1996. Low frequency climate variability and salmon production. Ph.D. dissertation. University of Washington, Seattle, WA, 306pp.

Hare SR, Mantua NJ, 2000. Empirical evidence for North Pacific regime shifts in 1977 and 1989. *Progress in Oceanography*, **47**, 103–146.

Harman JR, 1987. Mean Monthly North American Anticyclone Frequencies, 1950–79. *Monthly Weather Review,* **115**, 2840–2848.

Haurwitz B, 1965. The diurnal pressure oscillations. *Arch. Meteor. Geophys. Biolkimat. A*, **14**, 361–379.

Held IM, 1993. Large-Scale Dynamics and Global Warming. *Bulletin of the American Meteorological Society*, **74** (2), 228–241.

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** (3), 307–323.

Hering WS, Borden Jr. TR, 1962. Diurnal Variations in the Summer Wind Field over the Central United States. *Journal of the Atmospheric Sciences*, **19**, 81–86.

Hirsch ME, DeGaetano AT, Colucci SJ, 2001. An East Coast Winter Storm Climatology. *Journal of Climate*, **14**, 882–899.

Holton JR, 1967. The diurnal boundary layer wind oscillation above sloping terrain. *Tellus*, **19** (22), 199–205.

Horel JD, Wallace JM, 1981. Planetary-Scale Atmospheric Phenomena Associated with the Southern Oscillation. *Monthly Weather Review*, **109**, 813–829.

Hoskins BJ, Valdes PJ, 1990. On the existence of storm-tracks. *Journal of Atmospheric Science*, **47**, 1854–1864.

Hu Y, Tung KK, Liu J, 2005. A Closer Comparison of Early and Late-Winter Atmospheric Trends in the Northern Hemisphere. *Journal of Climate*, **18**, 3204–3216.

Hurrell JW, 1995. Decadal Trends in the North Atlantic Oscillation. *Science*, **269**, 676–679.

Hurrell JW, van Loon H, 1997. Decadal Variations in Climate Associated with the North Atlantic Oscillation. *Climatic Change*, **36**, 301–326.

Hurrell JW, Kushnir Y, Ottersen G, Visbeck M, 2003. An Overview of the North Atlantic Oscillation. *Geophysical Monograph 134, American Geophysical Union*.

Iskenderian H, Rosen R, 2000. Low-frequency signals in mid-tropospheric submonthly temperature variance. *Journal of Climate*, **13**, 2323–2333.

Kalnicky RA, 1974, Climatic Change since 1950. *Annals of the Association of American Geographers*, **64** (1), 100–112.

Kattenberg A, et al., 1996. Climate models–Projections of future climate. *Climate Change 1995. The Second Assessment Report of the IPCC.* J.T. Houghton et al., Eds., Cambridge University Press, 285 – 359.

Key JR, Chan ACK, 1999. Multidecadal global and regional trends in 1000 mb and 500 mb cyclone frequencies. *Geophysical Research Letters*, **26** (14), 2053–2056.

Klein WH, 1957. The Frequency of Cyclones and Anticyclones in Relation to the Mean Circulation. *Journal of Meteorology*, **15**, 98–102.

Klink K, 1999. Trends in mean monthly maximum and minimum surface wind speeds in the coterminous United States, 1961 to 1990. *Climate Research*, **13**, 193–205.

Knappenberger PC, Michaels PJ, Schwartzman PD, 1996. Observed changes in the diurnal temperature and dewpoint cycles across the United States. *Geophysical Research Letters*, **23** (19), 2637–2640.

Knight DB, Davis RE, Sheridan SC, Hondula DM, Sitka LJ, Deaton M, Lee TR, Gawtry SD, Stenger PJ, Mazzei F, Kenny BP, 2008. Increasing frequencies of warm and humid air masses over the conterminous United States from 1948 to 2005. *Geophysical Research Letters*, in press.

König W, Sausen R, Sielmann F, 1993. Objective Identification of Cyclones in GCM Simulations. *Journal of Climate*, **6** (12), 2217–2231.

Kushnert PJ, Held IM, Delworth TL, 2001. Southern Hemisphere atmospheric circulation response to global warming. *Journal of Climate*, **14**, 2238–2249.

Lambert SJ, 1995. The effect of enhanced greenhouse warming on winter cyclone frequencies and strength. *Journal of Climate*, **8**, 1447–1452.

Lambert, SJ, 1996. Intense extratropical northern hemisphere winter cyclone events: 1899– 1991. *Journal of Geophysical Research*, **101** (D16), 319–325.

Lambert SJ, Fyfe JC, 2006. Changes in winter cyclone frequencies and strengths simulated in enhanced greenhouse warming experiments: results from the models participating in the IPCC diagnostic exercise. *Climate Dynamics*, **26**, 713–728.

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**, 517–528.

Leathers DJ, Palecki MA, 1992. The Pacific/North American Teleconnection Pattern and United States Climate. Part II: Temporal Characteristics and Index Specification. *Journal of Climate*, **5**, 707–716.

Loose T, Bornstein D, 1977. Observations of Mesoscale Effects on Frontal Movement Through and Urban Area. *Monthly Weather Review*, **105** (5), 563–571.

Mantua NJ, Hare SR, 2002. The Pacific Decadal Oscillation. *Journal of Oceanography*, **58**, 35–44.

Mantua NJ, Hare SR, Zhang Y, Wallace JM, Francis RC, 1997. A Pacific Interdecadal Oscillation with Impacts on Salmon Production. *Bulletin of the American Meteorological Society*, **78** (6), 1069–1079.

Mass CF, Steenburgh J, Schultz DM, 1991. Diurnal Surface-Pressure Variations over the Continental United States and the Influence of Sea Level Reduction. *Monthly Weather Review*, **119**, 2814–2830.

McCabe GJ, Clark MP, Serreze MC, 2001. Trends in Northern Hemisphere Surface Cyclone Frequency and Intensity. *Journal of Climate*, **14**, 2763–2768.

Mitchell JFB, Johns TC, Gregory JM, Tett SFB. Climate response to increasing levels of greenhouse gases and sulphate aerosols. *Nature*, **376**, 501–504.

Namias J, 1976. Some Statistical and Synoptic Characteristics Associated with El Nino. *Journal of Physical Oceanography*, **6**, 130–138.

New M, Todd M, Hulme M, Jones P, 2001. Review: Precipitation Measurements and Trends in the Twentieth Century. *International Journal of Climatology*, **21**, 1899–1922.

Newman M, Compo GP, Alexander MA, 2003. ENSO-Forced Variability of the Pacific Decadal Oscillation. *Letters to Journal of Climate*, **16** (23), 3853–3857.

Ostermeier GM, Wallace JM, 2003. Trends in the North Atlantic Oscillation–Northern Hemisphere Annular Mode during the Twentieth Century. *Journal of Climate*, **16**, 336–341.

Paciorek CJ, Risbey JS, Ventura V, Rosen RD, 2002. Multiple Indices of Northern Hemisphere Cyclone Activity, Winters 1949–99. *Journal of Climate*, **15**, 1573–1590.

Parker SS, Hawes JT, Colucci SJ, Hayden BP, 1989. Climatology of 500 mb Cyclones and Anticyclones, 1950–85. *Monthly Weather Review*, **117**, 558–570.

Petterssen S, 1956. *Weather Analysis and Forecasting*, Volume 1. McGraw-Hill, 422 pp.

Power HC, Sheridan SC, Senkbeil JC, 2006. Synoptic climatological influences on the spatial and temporal variability of aerosols over North America. *International Journal of Climatology*, **26**, 723–741.

Resio DT, Hayden BP, 1975. Recent Secular Variations in Mid-Atlantic Winter Extratropical Storm Climate. *Journal of Applied Meteorology*, **14** (7) , 1223–1234.

Reitan CH, 1980. Trends in the Frequencies of Cyclone Activity over North America. *Monthly Weather Review*, **107**, 1684–1688.

Robinson PJ, 2000. Temporal Trends in United States Dew Point Temperatures. *International Journal of Climatology*, **20**, 985–1002.

Rodwell MJ, Rowell DP, Folland CK, 1999. Oceanic forcing of the wintertime North Atlantic Oscillation and European climate. *Nature*, **398**¸320–323.

Rogers JC, 1990. Patterns of Low-Frequency Monthly Sea Level Pressure Variability (1899–1986) and Associated Wave Cyclone Frequencies. *Journal of Climate*, **3**, 1364–1379.

Rohli RV, Wrona KM, McHugh MJ, 2005. January Northern Hemisphere Circumpolar Vortex Variability and its relationship with Hemispheric Temperature and Regional Teleconnections. *International Journal of Climatology*, **25**, 1421–1436.

Ropelewski CF, Halpert MS, 1986. North American Precipitation and Temperature Patterns Associated with the El Niño/Southern Oscillation (ENSO). *Monthly Weather Review*, **114**, 2352–2362.

Ross RJ, Elliott WP, 1996. Tropospheric Water Vapor Climatology and Trends over North America: 1973–93. *Journal of Climate*, **9**, 3561–3574.

Schwartzman PD, Michaels PJ, Knappenberger PC, 1998. Observed changes in the diurnal dewpoint cycles across North America. *Geophysical Research Letters*, **25** (13), 2265– 2268.

Serreze MC, Box JE, Barry RG, Walsh JE, 1993. Characteristics of Arctic Synoptic Activity, 1952–1989. *Meteorology and Atmospheric Physics*, **51**, 147–164.

Sheridan SC, 2003. North American Weather-Type Frequency and Teleconnection Indices. *International Journal of Climatology*, **23**, 27–45

Shindell DT, Miller RL, Schmidt GA, Pandolfo L, 1999. Simulation of recent northern winter climate trends by greenhouse-gas forcing. *Letters to Nature*, **399**, 452–455.

Siebert M, 1961. Atmospheric tides. *Advances in Geophysics*, **7**¸105–187.

Skeeter BR, Parker AJ, 1985. Synoptic control of regional temperature trends in the coterminous United States between 1949 and 1981. *Physical Geography*, **6**, 69–84.

Souch C, Grimmond S, 2006. Applied climatology: urban climate. *Progress in Physical Geography*, **30** (2), 270–279.

Spar J, 1952a. Characteristics of the semidiurnal pressure wave in the United States. *Bulletin of the American Meteorological Society*, **33**, 438–441.

Spar J, 1952b. The thermal influence on the daily pressure wave. *Bulletin of the American Meteorological Society*, **33**, 339–343.

Strong C, Davis RE, 2007. Winter jet stream trends over the Northern Hemisphere. *Quarterly Journal of the Royal Meteorological Society*, **133**, 2109–2115.

Teng H, Washington WM, Meehl GA, 2007. Interannual variations and future change of wintertime extratropical cyclone activity over North America in CCSM3. *Climate Dynamics*, **30** (7-8), 673–686.

Thompson DWJ, Wallace HM, 2000. Annular Modes in the Extratropical Circulation. Part I: Month-to-Month Variability. *Journal of Climate*, **13**, 1000–1016.

Trenberth KE, 1997. Recent observed Interdecadal climate changes in the Northern Hemisphere. *Bulletin of the American Meteorological Society,* **71** (7), 988–993.

Trenberth KE, Jones PD, Ambenje P, Bojariu R, Easterling D, Klein Tank A, Parker D, Radimzadeh F, Renwick JA, Rusticucci M, Soden B, Zhai P, 2007. Observations: Surface and Atmospheric Climate Change. In: *Climate Change 2007: The Physical Science Basis.* Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon S, Qin D, Manning M, Chen Z, Marquis M, Avery KB, Tignor M, Miller HL (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Trenberth KE, Paolino Jr., DA, 1981. Characteristic Patterns of Variability of Sea Level Pressure in the Northern Hemisphere. *Monthly Weather Review*, **109** (6), 1169–1189.

van Loon H, Rogers JC, 1978. The Seesaw in Winter Temperatures between Greenland and Northern Europe. Part I: General Description. *Monthly Weather Review*, **106**, 296–310.

Volodin EM, Galin V Ya., 1998. Sensitivity of midlatitude northern hemisphere winter circulation to ozone depletion in the lower stratosphere. *Russian Journal of Meteorology and Hydrology*, **8**, 23–32.

Wagner A, 1939. Uber die Tageswinde in der freiein atmosphere. *Beitr. Phys. Fr. Atmos*, **25**¸145–170.

Walker GT, Bliss EW, 1932. World Weather V. *Mem. Royal Meteorological Society*, **4**, 53–84.

Wallace JM, Gutzler DS, 1981. Teleconnections in the Geopotential Height Field during the Northern Hemisphere Winter. *Monthly Weather Review*, **109**, 784–812.

Wallace HM, Hartranft FR, 1969. Diurnal wind variations, surface to 30 kilometers. *Monthly Weather Review*, **97** (6), 446–455.

Whittaker LM, Horn LH, 1982. Geographical and Seasonal Distribution of North American Cyclogenesis, 1958–1977. *Monthly Weather Review*, **109**, 2312–2322.

Wrona KM, Rohli RV, 2007. Seasonality of the northern hemisphere circumpolar vortex. *International Journal of Climatology*, **27**, 697–713.

Xue Y, Fennessy MJ, Sellers PJ, 1996. Impact of Vegetation Properties on U.S. Summer Weather Prediction. *Journal of Geophysical Research*, **101**, 7419–7430.

Yarnal B, Diaz HF, 1986. Relationships between extremes of the Southern oscillation and the winter climate o the Anglo-American Pacific Coast. *International Journal of Climatology*, **6** (2), 197–219.

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** (4), 624–641.

Yin ZY, 1994. Moisture condition in the South-Eastern USA and teleconnection patterns. *International Journal of Climatology*, **14** (9), 947–967.

Yin JH, 2005. A consistent poleward shift of the storm tracks in simulations of 21st century climate. *Geophysical Research Letters*, **32**, L18701.

Zhang Y, 1996. An observational study of atmosphere-ocean interactions in the northern oceans on interannual and Interdecadal time-scales. Ph.D. dissertation, University of Washington, Seattle, WA.

Zhang K, Douglas BC, Leatherman SP, 2000. Twentieth-Century Storm Activity along the U.S. East Coast. *Journal of Climate*, **13**, 1748–1761.

Zishka KM, Smith PJ, 1980. The Climatology of Cyclones and Anticyclones over North America and Surrounding Ocean Environs for January and July, 1950–77. *Monthly Weather Review*, **108** (4), 387–401.