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Climatology of winter transition days for the contiguous USA, 1951–2007

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Abstract In middle and high latitudes, climate change could impact the frequency and characteristics of frontal passages. Although transitions between air masses are significant features of the general circulation that influence human activities and other surface processes, they are much more difficult to objectively identify than single variables like temperature or even extreme events like fires, droughts, and floods. The recently developed Spatial Synoptic Classification (SSC) provides a fairly objective means of identifying frontal passages. In this research, we determine the specific meteorological patterns represented by the SSC's Transition category, a "catch-all" group that attempts to identify those days that cannot be characterized as a single, homogeneous air mass type. The result is a detailed transition climatology for the continental USA. We identify four subtypes of the Transition category based on intra-day sea level pressure change and dew point temperature change. Across the contiguous USA, most transition days are identified as cold fronts and warm fronts during the winter season. Among the two less common subtypes, transition days in which the dew point temperature and pressure both rise are more frequently observed across the western states, and days in which both variables fall are more frequently observed in coastal regions. The relative frequencies of wintertime warm and cold fronts have changed over the period 1951–2007. Relative cold front frequency has significantly increased in the Northeast and Midwest regions, and warm front frequencies have declined in the Midwest, Rocky Mountain, and Pacific Northwest regions. The overall shift toward cold fronts and away from warm fronts across the northern USA arises from a combination of an enhanced ridge over western North America and a northward shift of storm tracks throughout the mid-latitudes. These results are consistent with projections of climate change associated with elevated greenhouse gas concentrations.

1 Introduction

Recent research using synoptic-scale air mass identification systems has revealed significant changes to air mass frequencies over the past several decades. Moist tropical air masses are becoming more frequently observed over the USA in the winter months at the expense of dry polar air masses (Knight et al. 2008), for example. This type of research complements more commonly cited studies related to changes in mean conditions (e.g., Trenberth et al. 2007 [IPCC AR4]) and provides some insight into how the variability of day-to-day weather is changing, a topic of growing interest (e.g., Alexander et al. 2006). One air mass identification system, the Spatial Synoptic Classification (SSC; Sheridan 2002) includes six air mass types and one transition category. Several significant trends are present in the SSC frequencies across the USA, the most widespread of which is a decline in the frequency of the transition type over approximately the past half century. This change has been attributed to increasing moisture content among the driest polar air masses (which reduces the gradient between one air mass and another, weakening frontal passages below the SSC's "change" criteria) and a poleward shift of the northern hemisphere circumpolar vortex over the western half of the country (Hondula and Davies 2010). As frontal passages are often associated with precipitation and conditions that impact human and ecological activity,

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changes to the frontal passage climatology are an important component of climate change not well studied to date.

Transitions represent 5–15% of winter days across the USA, with the highest frequencies observed across the northeast and the fewest transitions observed in the southwest (Fig. 1a). Transition frequencies have been significantly declining in the winter months for 37 of 63 stations considered in this research, with maximum rates of decline across much of the northern Rocky Mountain states and upper Midwest (Fig. 1b). At several of these stations, transition frequencies have dropped from approximately 12–15% of all winter days in the 1950s to 5–7% in recent years.

Unlike the six climatologically homogeneous air mass types of the SSC, the transition category represents an array of synoptic-scale atmospheric features. This is by design, as the transition category is supposed to capture all varieties of changes in the weather, such as both cold front and warm front passages. However, 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. Furthermore, a validation of the transition category as a true identifier of significant weather changes will support more widespread use of the SSC. Our first goal in this research was to examine more closely the climatology of transition days identified by the SSC and subsequently determine the synoptic types leading to the overall decline in transition frequency. More specifically, we create a climatology of transition days through the identification of transition subtypes and analyze the frequencies of each subtype over the past half century.

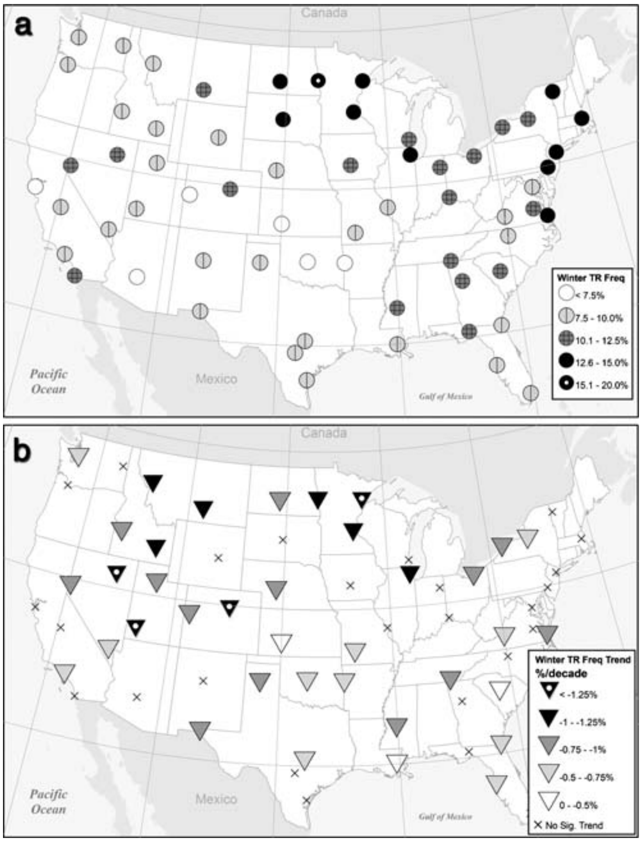


Fig. 1 **a** Mean winter (DJF) Spatial Synoptic Classification transition type frequency at 63 US first-order weather stations for the period December 1950–February 2007. **b** Bootstrapped linear regression trends in winter (DJF) Spatial Synoptic Classification transition type frequency for the period December 1950–February 2007. Stations with a downward pointing triangle exhibit significantly decreasing frequencies; *x* indicates no trend. Adapted from Hondula and Davies (2010)

To relate the trends in transition subtypes to hemispheric circulation, we employ the Northern Hemisphere circumpolar vortex dataset of Frauenfeld and Davis (2003). The size and configuration of the vortex provide an aggregate perspective on the large-scale circulation that impacts air mass and transition frequencies. Following the establishment of the transition climatology, our second goal was to determine how changes to the vortex extent and shape have impacted the types of transitions that traverse particular regions of the USA.

In summary, there are significant trends in the SSC that indicate a shift toward fewer transition days. In this research, we develop a transition climatology to investigate more closely the characteristics of the frequency decline and determine the greater applicability of the SSC in terms of frontal passage activity on a multidecadal scale.

2 Data and methods

The SSC identification procedure involves both subjective and automated components—it is commonly referred to as a *hybrid* classification mechanism. The system uses four-times daily (0400, 1000, 1600, and 2200 hours local standard time) temperature, dew point temperature, sea-level pressure, north–south and east–west components of the horizontal wind vector, and cloud cover. Critical in the procedure is the selection of "seed days" for each air mass type at a particular station. Seed days are days in the period of record considered most representative of a particular air mass type and are selected during four 2-week windows of the year: the warmest and coolest periods, and two intermediate periods. Following the identification of seed days for each air mass type, a linear smoother is applied to create an expected value for each variable employed by the SSC for each air mass type on every day of the year. In other words, the SSC identifies the typical meteorological characteristics of each of six air mass types throughout the year. The classification procedure then uses *z* scores to classify the air mass type on each day throughout each station's period of record. To date, some three million days have been classified at stations throughout North America and Europe. (http://sheridan.geog.kent.edu/ssc.html).

A similar procedure identifies transition days that utilizes only the within-day change in dew point temperature (*Td*), sea-level pressure (*P*), and wind speed and direction (*V*). More specifically, the SSC considers the daily range (maximum minus minimum) in dew point temperature and sea-level pressure and the magnitude of the largest vector difference between four-times daily wind observations. The measurements all carry a positive sign (days in which the pressure drops by 10 hPa are recognized identically as those on which it rises by the same amount). As with the air mass types, there is a daily expected value for each of these three variables. For a day to be identified as a transition, the observations must be mathematically closer to the expected values for transition days than those for any of the other six air masses. In general, transition days are identified when one, two, or all three of the transition variables fall in the upper portions of their respective distributions.

To create the transition subtype climatology, SSC calendars and corresponding meteorological data at each of the 63 stations across the contiguous USA are considered for winter (December–January–February [DJF]) 1950–1951 through winter 2006–2007 (Table 1). The mean daily dew point temperature change and sea-level 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 subtypes based on how the dew point temperature and pressure change compare with the wintertime mean for that station (e.g., *Td* increases and *P* decreases relative to the mean). These variables are selected because most days with large changes in the dew point temperature and sea-level pressure are transition days, whereas many days with a large shift in the wind are not (Hondula and Davies 2010). 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 subtype calendars are used to generate a spatial climatology of transition types.

We generate composite 850-hPa geopotential height fields for each subtype at each station using the National Centers for Environmental Prediction and the National Center for Atmospheric Research reanalysis data (Kalnay et al. 1996 and updates) and examine daily weather maps (National Oceanic and Atmospheric Administration 2009) 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 inverse distance weighting algorithm in ArcMap (ESRI 2006) with equal contour intervals.

We also consider trends in subtype 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 subtype 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 using hierarchical, agglomerative cluster analysis. Ward's method was chosen because it tends to create clusters (regions) with similar numbers of stations (Kalkstein et al. 1987). We then consider the trends in the subtypes on a regional basis. The subtype frequencies are linearly regressed against year using a bootstrapping technique that resamples the data 10,000 times. The resampling generates 10,000 regression slopes; in cases where the 2.5th and 97.5th percentile slopes have the same sign, we identify a statistically significant trend (Hondula and Davis 2010).

To examine how the overall hemispheric circulation might influence the proportioning of transition subtypes, we use seasonal mean Northern Hemisphere 500-hPa circumpolar vortex data for the domain 60º–150º W (from Frauenfeld and Davis 2003). The vortex has been significantly contracting over western North America in recent decades (Frauenfeld and Davis 2003), and this change is linked with the decline in transition frequencies in the western USA. The vortex position is available at three separate pressure surfaces and represents the latitude of the region of maximum geopotential height gradient across 5º longitude bands from winter 1950–1951 through 2001–2002. We regress the frequency time series of each subtype for each region against the 500-hPa vortex position in each of the 18 5º-wide longitude bands that comprise the study domain.

3 Results and discussion

3.1 Transition subtypes

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 (Fig. 2). 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 (Fig. 3). For example, 21% of all transition days are in the lower-right

Table 1 List of first-order weather stations used in analysis with three-letter identification codes, station location, and SSC and meteorological data availability

Station	ID	Lat (º N)	Lon (º W)	Completeness (dropped years)
Albuquerque, NM	ABQ	35.05	106.60	93.9%
Amarillo, TX	AMA	35.23	101.70	94.4%
Atlanta, GA	ATL	33.65	84.42	94.9%
Austin, TX	AUS	30.30	97.70	94.8%
Billings, MT	BIL	45.80	108.53	94.2%
Bismarck, ND	BIS	46.77	100.75	93.1% (2007)
Boise, ID	BOI	43.57	116.22	94.0% (1957)
Boston, MA	BOS	42.37	71.03	94.1%
Burlington, VT	BTV	44.47	73.15	93.6%
Buffalo, NY	BUF	42.93	78.73	94.3%
Columbia, SC	CAE	33.95	81.12	94.4% (1974)
Cedar City, UT	CDC	37.70	113.10	93.9%
Chattanooga, TN	CHA	35.03	85.20	94.8%
Cleveland, OH	CLE	41.42	81.87	94.3%
Casper, WY	CPR	42.92	106.47	94.2%
Corpus Christi, TX	CRP	27.77	97.50	94.8%
Covington, KY	CVG	39.05	84.67	94.6%
Washington, DC	DCA	38.85	77.04	94.6%
Dodge City, KS	DDC	37.77	99.97	94.1%
Denver, CO	DEN	39.75	104.87	94.1%
Duluth, MN	DLH	46.83	92.18	93.8%
Des Moines, IA	DSM	41.53	93.65	94.2%
Elko, NV	EKO	40.83	115.78	83.2% (1965, 1993–1994, 1997–2001)
El Paso, TX	ELP	31.80	106.40	94.2%
Newark, NJ	EWR	40.70	74.17	94.5%
Fargo, ND	FAR	46.90	96.80	92.9% (2007)
Fresno, CA	FAT	36.77	119.72	94.7%
Ft. Smith, AR	FSM	35.33	94.37	94.6%
Ft. Wayne, IN	FWA	41.00	85.20	94.4%
Spokane, WA	GEG	47.63	117.53	94.3%
Grand Junction, CO	GJT	39.12	108.53	92.9% (1955)
Greensboro, NC	GSO	36.08	79.95	94.3%
Jackson, MS	JAN	32.32	90.08	94.6%
Jacksonville, FL	JAX	30.50	81.70	94.9%
Las Vegas, NV	LAS	36.08	115.17	94.8%
Los Angeles, CA	LAX	33.93	118.40	94.9%
North Platte, NE	LBF	41.13	100.68	93.9%
Miami, FL	MIA	25.82	80.28	94.6%
Milwaukee, WI	MKE	42.95	87.90	94.2%
Missoula, MT	MSO	46.92	114.08	94.7%
Minneapolis-St. Paul, MN	MSP	44.88	93.22	94.4%
New Orleans, LA	MSY	29.98	90.25	94.9%
Oklahoma City, OK	OKC	35.40	97.60	94.5%
Chicago, IL	ORD	41.98	87.90	94.5%
Norfolk, VA	ORF	36.90	76.20	94.6%
Portland, OR	PDX	45.60	122.60	94.9%
Philadelphia, PA	PHL	39.88	75.25	94.4%
Phoenix, AZ	PHX	33.43	112.02	94.8%

Table 1 (continued)

Station	ID	Lat (º N)	Lon (º W)	Completeness (dropped years)
Pocatello, ID	PIH	42.92	112.60	94.3%
Pierre, SD	PIR	44.38	100.28	93.8%
Richmond, VA	RIC	37.50	77.33	94.6%
Reno, NV	RNO	39.50	119.78	94.7%
Roanoke, VA	ROA	37.32	79.97	94.3%
San Diego, CA	SAN	32.73	117.17	94.9%
San Antonio, TX	SAT	29.53	98.47	94.4%
Seattle–Tacoma, WA	SEA	47.45	122.30	94.8%
San Francisco, CA	SFO	37.62	122.38	94.9%
Springfield, MO	SGF	37.23	93.38	93.2% (1964)
Salt Lake City, UT	SLC	40.78	111.97	94.8%
St. Louis, MO	STL	38.75	90.37	94.5%
Syracuse, NY	SYR	43.12	76.12	94.3%
Tallahassee, FL	TLH	30.38	84.37	95.0%
Tampa, FL	TPA	27.97	82.53	94.5%

quadrant with increasing dew point temperature and decreasing pressure, consistent with warm frontal passages. The paucity of observations near the origin is expected, as days with little dew point temperature and pressure change are typically not classified as transitions in the SSC—any points that do fall near the origin must therefore exhibit a large wind shift.

Each of the four transition subtypes 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 Fig. 3 are days with both increasing dew point temperature and pressure ("moist high"). Moving clockwise, days in the second quadrant are consistent with a warm 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 (Fig. 4) and discuss the likely weather patterns associated with each (Fig. 5).

Transition days on which the dew point temperature change and pressure change both increase are most commonly observed in the southwestern USA (1–2 cases

Fig. 2 Relative frequency of four transition subtypes at each of the 63 stations for winters, December 1950–November 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 is shown in Fig. 4

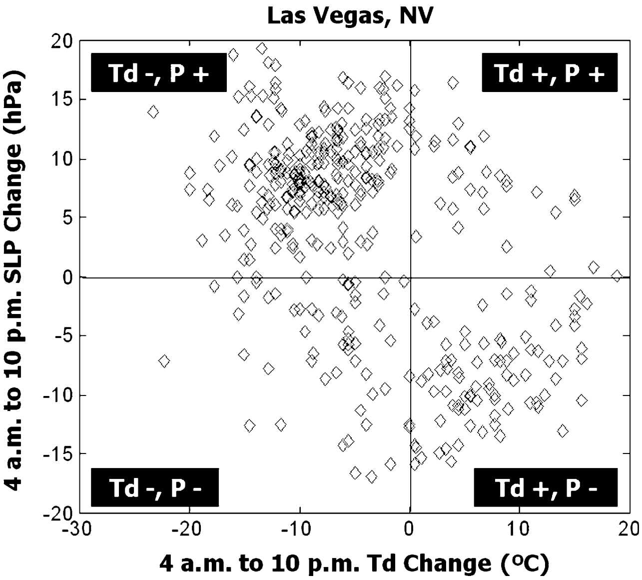


Fig. 3 Winter transition days at Las Vegas, NV, December 1950–November 2007. Each *diamond* represents 1 day. Sea-level pressure (SLP) measured in hectopascals; dew point temperature (*Td*) measured in degrees Celsius

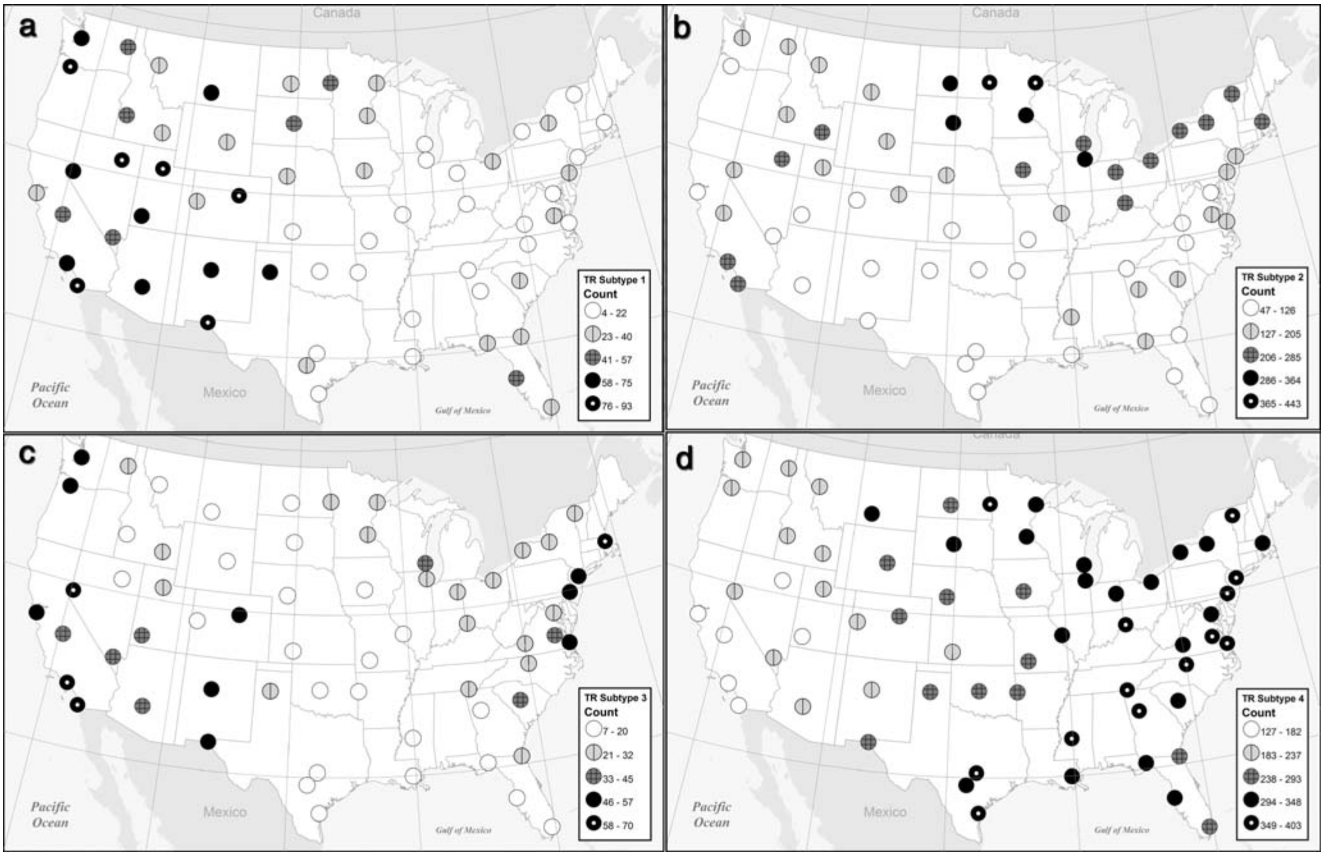
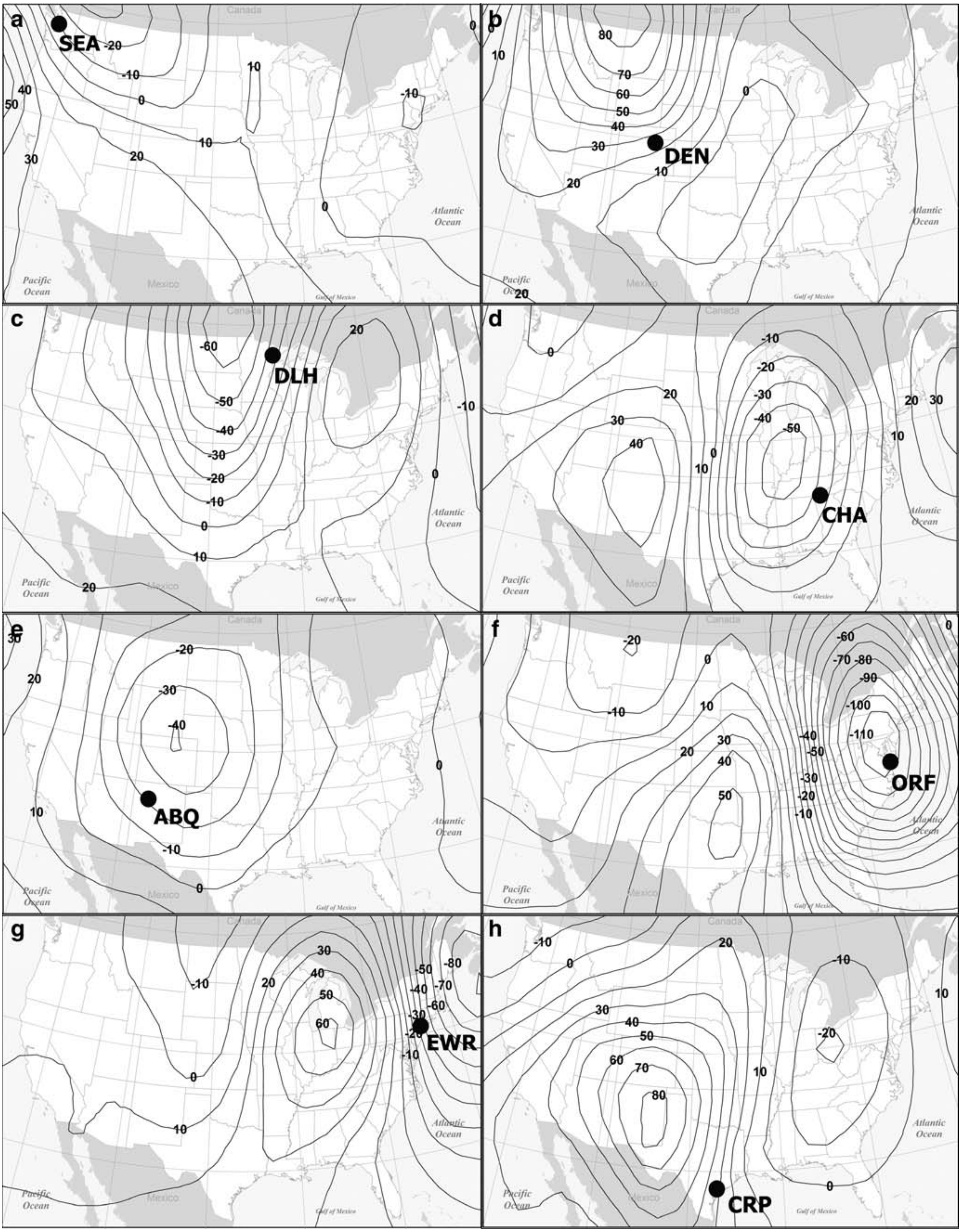


Fig. 4 Count of winter transition days, December 1950–November 2007, on which **a** the dew point temperature and pressure increased between 4 A.M. and 10 P.M. relative to the average daily change over the same time period, **b** the dew point temperature increased and the pressure decreased, **c** the dew point temperature and pressure decreased, and **d** the dew point temperature decreased and the pressure increased

per winter) and are rarely observed in the east (Fig. 4a). At Pacific coast stations, this pattern can 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, resulting in the advection of moist air directly from the Pacific (e.g., Fig. 5a). 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., Fig. 5b). 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 transition 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 subtype with falling pressure and increasing moisture matches this pattern and is most commonly observed in the upper Midwest and Northeast, with a secondary maximum in southern California (Fig. 4b). In these regions, the subtype is present on 7–8 days each winter, whereas elsewhere it occurs 1–3 days per winter. Examination of the average geopotential height contours confirms that an approaching low is the major feature of this subtype (Fig. 5c, d).

Fig. 5 Average 850-hPa geopotential height change between 4 A.M. and 10 P.M. on certain winter transition days from 1950–1951 through 2006–2007. **a**, **b** Transition days on which the dew point temperature and pressure increased at Seattle, WA, and Denver, CO, respectively. **c**, **d** Days on which the dew point temperature increased and pressure decreased at Duluth, MN, and Chattanooga, TN. **e**, **f** Days on which both dew point temperature and sea level pressure decreased at Albuquerque, NM, and Norfolk, VA. **g**, **h** Days on which the dew point temperature decreased and pressure increased at Newark, NJ, and Corpus Christi, TX. Stations denoted by *circles* ▶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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 temperature as the air mass moves south and is moderated, it may not be entirely inappropriate to consider them transition days. Furthermore, even if they are to be classified as transition days, it may be preferable to classify them differently than days 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., Fig. 5d). 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, with fewer than one case observed on average each winter at each station. The maximum frequency occurs across the west coast, Southwest, and east coast (Fig. 4c), approximately matching the spatial distribution of the number of lows observed during winter months (Klein 1957). Most often, this transition subtype occurs when a low pressure center moves toward the east and the associated cold front passes the station late in the day (e.g., Fig. 5e and f). 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 cyclone arrived close to 10 P.M.. We believe that this subtype 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 usually extends across a much 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. Among those that do, this subtype is only observed when the front passes late in the day. We also noted several cases where this subtype 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 interior 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 temperature at stations located to its west.

Finally, days associated with a drop in dew point and increase in pressure represent a common transition that occurs on average between five and eight times at stations in the east (Fig. 4d). Like the previous subtype, many of these days are identified as cold front passages (e.g., Fig. 5g). However, this subtype 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 USA 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 subtype is most common across the east. Cyclogenesis downstream of the Rockies may also contribute to the total cold front passage count in the east, particularly in the south where polar fronts are rarely observed (e.g., Fig. 5h).

One of the major factors related to the identification of subtypes appears to be the timing and the 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 subtypes 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 an increase 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-h periods.

3.2 Regional trend analysis

We identify nine regions of similar year-to-year transition frequency time series using hierarchical cluster analysis with Ward's method (Fig. 6). Most of the regions are very spatially coherent, with the exception of the Northwest region that includes the stations of Cheyenne, Wyoming,

Fig. 6 Hierarchical clustering solution grouping stations by annual winter transition frequency. Region names and numbers: South *1*, East *2*, Midwest *3*, Northeast *4*, Rocky Mountain *5*, Northwest *6*, Upper Midwest *7*, Southeast *8*, Southern California *9*

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. Statistically significant trends are present across several regions for each of the four subtypes, with the largest magnitude trends attributed to a decreasing frequency of warm fronts in the Midwest, Rocky Mountain, and Northwest regions and an increasing frequency of cold fronts in the Midwest and Northeast (Table 2). 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 temperature increases and pressure decreases (approaching low, e.g., Fig. 7) and an increasing proportion of days on which the dew point temperature falls and pressure rises (cold front passage, e.g., Fig. 8). The sign of the trends in the other two subtypes vary by region.

In the Midwest region, the approaching low subtype is becoming less common 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 subtype 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 contracting vortex (Frauenfeld and 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 temperature and pressure increase (see Fig. 2), 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 subtype 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

Table 2 Trends in transition subtype frequency divided by total transition days across four US regions

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

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 10-year span). The second line shows which, if any, 5° longitude vortex band positions are 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

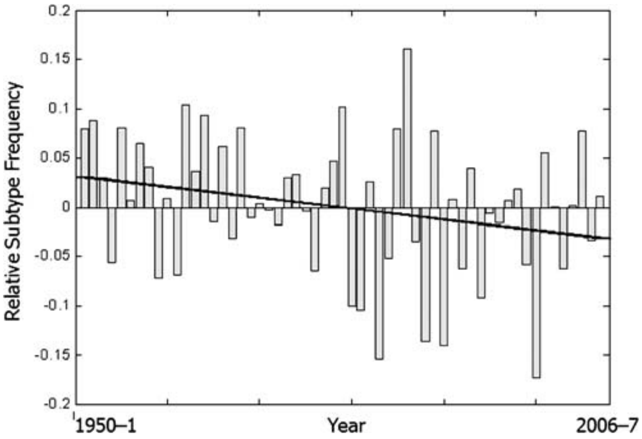

Fig. 7 Annual relative frequency of wintertime (DJF) transition days on which the dew point temperature increased and the pressure decreased for the Rocky Mountain region, December 1950–February 2007. The proportional frequency for each year is equal to the sum of all observed subtype days across all 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 ($\alpha<0.05$)

any significant trend. The positive relationship between the vortex position and approaching low frequency is unsurprising: a more moderate Aleutian low indicates zonal flow, enabling storms to track into the USA instead of being diverted to the north around the large continental ridge that often accompanies a strong Aleutian low (Leathers et al. 1991). In the case of the subtype with decreasing dew point and pressure, we see proportionally more cases with an enhanced ridge, a pattern that has become more prevalent over the past two to three decades (Frauenfeld and Davis 2003). We observe that the actual number of cases of 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.

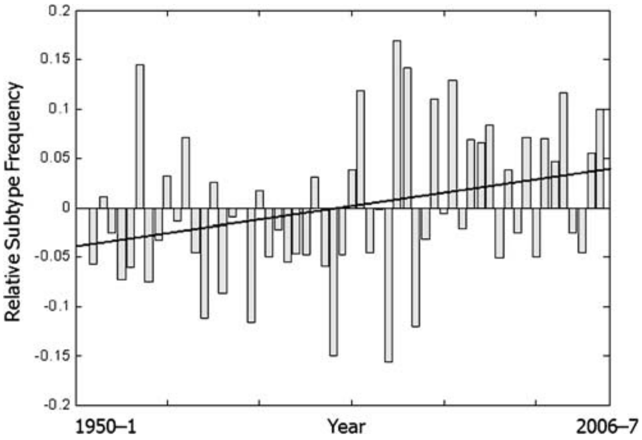

Fig. 8 Annual relative frequency of wintertime (DJF) transition days on which the dew point temperature decreased and the pressure increased for the Northeast region, December 1950–February 2007. The proportional frequency for each year is equal to the sum of all observed subtype days across all regional 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 ($\alpha<0.05$)

In general, the frequency of each of the transition subtypes is decreasing across the USA. However, within these trends, the decrease in warm frontal passages demonstrates the greatest trend at many northern stations. Under several projections of climate change related to increasing greenhouse gas concentrations, baroclinicity in the lower atmosphere is reduced as high latitudes warm at a faster rate than the middle and lower latitudes. Accordingly, fewer cyclones are needed to transfer energy from more equatorial regions to the poles, and the “pool” of cold air at the poles warms and decreases in spatial extent (e.g., IPCC AR4, McCabe et al. 2001; Held 1993). This decrease in cyclone frequency should at least partially account for our observation of decreasing warm fronts in the middle latitudes.

The changing distribution of frontal passage subtypes should also be related to shifts in air mass frequencies. For the USA, the frequency of dry polar days has significantly decreased at many stations, and moist moderate and moist tropical days are becoming more commonly observed. Furthermore, at many stations, the frequency of transition days is positively correlated with dry polar frequency and negatively correlated with moist moderate and moist tropical frequencies (Knight et al. 2008). If there are fewer extremely cold, dry days and more moist, warm days, one might expect cold fronts (which precede cold days) to decrease in frequency at a faster rate than warm fronts (which precede warm days). We believe that the shift in storm tracks to the north may explain why this is not the case. The shift in storm tracks to the north is a probable outcome of the contraction of the polar vortex since the 1970s (Frauenfeld and Davis 2003; Angell 2006) and associated increase in jet stream activity over the northern regions of the study area (Strong and Davis 2007). As discussed above, with respect to dew point temperature and pressure, the spatial extent of cold fronts is often much greater than that of warm fronts, with warm front transition classification requiring proximity to a low pressure center. As the average path of cyclones shifts to the north, fewer stations will experience sharp positive changes in dew point temperature and sharp negative changes in pressure ahead of the low but may still see a drop in temperature and increase in pressure as the subsequent dry, high pressure system moves in. We surmise that even though there are fewer dry polar days in total, those that do occur are preceded by cold fronts, whereas warm fronts less frequently accompany moist air masses.

4 Conclusion

The frontal passage climatology of the USA has changed considerably over the past half century as measured by the Spatial Synoptic Classification's Transition category. In addition to the previously documented overall decline in transition days, we find that warm frontal passages are accounting for a smaller percentage of transition days in the Midwest, Northwest, and Rocky Mountain regions and that cold frontal passages are accounting for a larger percentage of transition days in the Midwest and Northeast regions.

To develop a transition climatology for the USA, we have identified four subtypes of transition days that may be used to enhance applications of the SSC in applied climate research. 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.

Based upon a measure of the circumpolar vortex, we have related trends in the subtypes to shifts in the synoptic-scale 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. Over the past half century, a contraction of the Northern Hemisphere circumpolar vortex over western North America has decreased the percentage of transition days associated with approaching low pressure systems over the northern USA.

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References

Alexander LV, Zhang X, Peterson TC, Caesar J, Gleason B, Klein Tank AMG, Haylock M, Collins D, Trewin B, Rahimzadeh F, Tagipour A, Rupa Kumar K, Revadekar J, Griffiths G, Vincent L, Stephenson DB, Burn J, Aguilar E, Brunet M, Taylor M, New M, Zhai P, Rusticucci M, Vazquez-Aguirre JL (2006) Global observed changes in daily climate extremes of temperature and precipitation. J Geophys Res 111:D05109

Angell JK (2006) Changes in the 300 hPa north circumpolar vortex, 1963–2001. J Clim 19:2984–2994

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

Frauenfeld OW, Davis RE (2003) Northern Hemisphere circumpolar vortex trends and climate change implications. J Geophys Res 108:D14

Held IM (1993) Large-scale dynamics and global warming. Bull Amer Meteorol Soc 74:228–241

Hondula DM, Davis RE (2010) Declining United States dew point temperature and sea-level pressure variability and implications on synoptic transition frequency. Clim Res, in review

Kalkstein LS, Tan G, Skindlov JA (1987) An evaluation of three clustering procedures for use in synoptic climatological classification. J Clim Appl Meteorol 26:717–730

Kalnay E et al (1996) The NCEP/NCAR 40-year reanalysis project. Bull Amer Meteorol Soc 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, pp 60

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

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

National Oceanic and Atmospheric Administration (2009). Daily Weather Map Series. http://www.hpc.ncep.noaa.gov/dailywxmap/, 2008–2009

Sheridan SC (2002) The redevelopment of a weather-type classification scheme for North America. Intl J Climatol 22(1):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