16B.3 UTILIZING STANDARDIZED ANOMALIES TO ASSESS SYNOPTIC SCALE WEATHER EVENTS IN THE CENTRAL UNITED STATES

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1. INTRODUCTION

Anomalous synoptic weather events produce memorable and even historic weather impacts. Because of the potential for high impact weather as well as the visibility of these events, it is crucial for forecasters to be able to anticipate significant or rare events. While Hart and Grumm (2001; hereafter HG01) focused on the eastern United States and Graham and Grumm (2009; hereafter GG09) investigated the western U.S., this study will apply an objective classification method for synoptic systems occurring in the central U.S. between the Rocky and Appalachian Mountains. This region was not fully covered by the two previous studies and has its own unique weather systems.

Following the methodology presented by HG01 and GG09, synoptic scale events in the central United States will be ranked objectively based on standardized anomalies. The study will rank anomalies of wind, geopotential height, temperature, and moisture utilizing a standardized anomalies method of pressure weighted anomalies for each variable. The results will yield rankings of past events, with a summary of the top ten events for each variable as well a combined standardized anomaly variable.. By providing a guideline of anomalies for previous events, forecasters will be able to place forecasted events in a historical context.

2. DATA AND METHODOLOGY

Methodology in this study is modeled after HG01 and GG09, and the data set used in this study is similar to those studies but extended in time.

2.1 Data Sets

Standardized anomalies were computed from National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) global reanalysis data (Kalnay et al. 1996) for the period of 1 January 1948 through 31 December 2008, focused on a domain from 82°W to 110°W and from 26°N to 55°N (Fig. 1). NCEP/NCAR reanalysis data has a horizontal resolution of 2.5° X 2.5°, with 17 vertical pressure levels. The computations were done in 6-hour increments with anomalies computed for geopotential height, temperature, u and v wind components, and specific humidity at mandatory levels, as well as surface variables including mean sea level pressure and precipitable water.

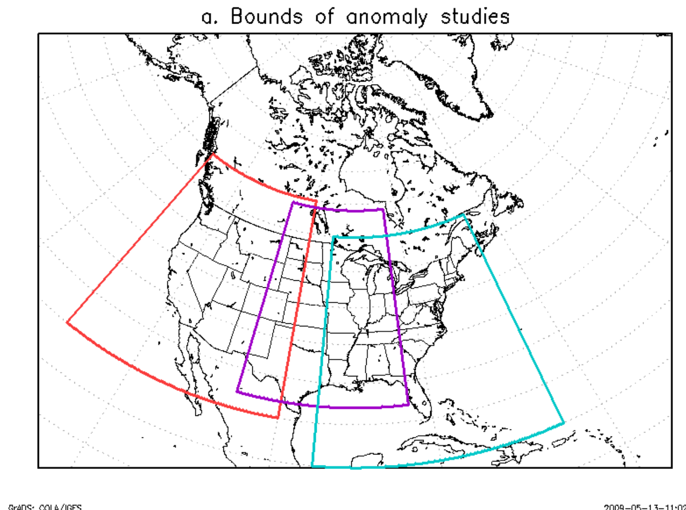

Figure 1. Domain of the central United States objective classification study. The cyan box shows the region defined in Hart and Grumm (2001), the red box shows the area used in Graham and Grumm (2009), and the purple box shows the area used in this study.

The base climatology for the means and standard deviations was computed for the 30-year period of 1971-2000. For each variable, at each time step, and at each pressure level, the departure from the climatological 21-day running mean was calculated,

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resulting in standard deviations from the mean. Resulting standardized anomalies were then sorted in order to objectively rank past events by their departure from climatology, providing a context for forecasted events based on standardized anomalies. It should be noted that HG01 utilized only 0000 and 1200 UTC data when developing rankings for eastern United States weather systems, while 0000, 0600, 1200 and 1800 UTC were utilized for both GG09 and this study.

2.2 Variable Definitions

Standardized anomalies for each variable, at each level and each time step, were computed. For each variable investigated, the average departure in standard deviations for all levels from the climatological 21-day running mean, $M_{VARIABLE}$, was computed. For each variable and at each time step, the largest anomalies across the entire study domain were summed for each pressure level. For example, for a given variable (i.e., temperature), the largest anomaly within the spatial domain at each pressure level was identified, and the absolute values of these anomalies were summed to generate the $M_{VARIABLE}$ (in this case, M_{TEMP}). Values calculated included M_{TEMP} (temperature), M_{HEIGHT} (geopotential height), M_{MOIST} (specific humidity), M_{WIND} (*u* and *v* wind components), M_{PWAT} (precipitable water), and M_{PRES} (mean sea level pressure).

An additional parameter, M_{TOTAL}, was also calculated, where

$$M_{TOTAL} = \frac{M_{TEMP} + M_{HEIGHT} + M_{MOIST} + M_{WIND}}{4}$$

In other words, M_{TOTAL} is the arithmetic average of the temperature, height, specific humidity, and wind anomalies. In determining M_{TOTAL}, the M_{WIND} value was calculated using the vertical average of either the *u* or *v* wind anomalies, whichever was greater. Note that the largest anomaly within the domain was used for each variable in the M_{TOTAL} calculation; thus, the anomalies for each variable might not be collocated. The M_{TOTAL} calculation allows an investigation of systems with a more overarching approach, and that value was used to rank the most anomalous events during the duration of the study. Events were also ranked by each individual variable, allowing an investigation of the most anomalous events by temperature, pressure, and other variables included in the study.

Tropical cyclones within the domain were discarded for the purposes of ranking, as these events clearly contribute the largest anomalies in the coastal and Gulf of Mexico regions of the domain. Those tropical systems that underwent extratropical transition in the domain were included only after they were declared extratropical by the National Hurricane Center. The domain of the study (which excludes both the Pacific and Atlantic coasts), along with the exclusion of tropical systems, allows an investigation of synoptic weather systems affecting the central United States, leaving out the coastal systems that tend to overwhelm the anomalies relative to inland systems.

3. RESULTS

For each variable in the study, as well as for M_{TOTAL}, events were ranked by their standardized anomaly from the 1971-2000 climatological 21-day running mean. The top events are presented here for each variable. In addition, return periods for anomaly values were calculated for each variable, providing perspective on the frequency of given anomaly values.

3.1 Rankings and Top Events

The top twenty total standardized anomalies (M_{TOTAL}) between 1 Jan 1948 and 31 Dec 2008 are presented below, along with the top 10 anomalies for each variable. While data were investigated in 6-hr time steps, only the highest ranking time step for each individual event is listed in the rankings. Anomalous events frequently spanned several time steps, often across two calendar days, as they progressed across the study domain. Several of the events were notable, appearing in local NWS office weather histories, newspaper clippings, and journal articles. In addition, several of the events do overlap with rankings in HG01 and GG09, further emphasizing the impacts in both time and space of these anomalous events.

3.1.1. Total Anomalies

The top twenty total anomalies (M_{TOTAL}) represent the strongest departures from climatology across the central United States during the study period, averaging the highest anomalies of temperature, geopotential height, specific humidity, and wind in the domain. The events are listed in Table 1. While a few event dates are yet unreferenced, most events did indeed have significant impact on the weather of the central United States.

The “Great Storm of 1975” (11 January 1975) ranked as the most anomalous event in the domain during the study period. A deep upper-level trough, extending from Canada to the southern Plains, moved across the central United States between 0000-1800 UTC 11 Jan 1975, with a very deep surface low lifting from Iowa through western Lake Superior (Fig. 2). Ahead of the trough, strong southerly winds pulled warm and moist air from the Gulf into the Great Lakes states (Fig. 3), with an outbreak of severe weather (including tornadoes) in the Southeast. In wake of the trough, strong northwesterly winds pulled cold Canadian air into the northern Plains, with blizzard conditions noted from the Dakotas into Minnesota

Impacts of the event were notable and well publicized. Record high temperatures were set from Michigan to the mid-Atlantic states (Wagner 1975); rare January thunderstorms were reported across the western Great Lakes, including Chicago and Duluth, with tornadoes in

Indiana and Illinois among the 45 reported in association with the storm system. Twelve fatalities resulted from this system, with injuries numbering in the hundreds. Meanwhile, across the Dakotas into Minnesota, record wind speeds and very cold temperatures were reported as a blizzard raged across the northern Plains, with several sites across the Midwest setting low pressure records. Up to 2 feet or more of snow fell across parts of the Plains. At Sioux Falls, SD, for example, only 7 inches of snow fell, but visibilities remained at or below one quarter mile for 24 hours, with wind chills reaching -70 °F as wind speeds reached 70 mph. Reports indicate 58 people were killed in the blizzard portion of this event, with livestock losses in the tens of thousands.

Another notable event, ranked fifth, occurred on 27-28 May 1973. The anomalies were associated with a persistent severe weather outbreak. Over a span of three days, 195 tornadoes touched down between Michigan and Alabama, including an F4 in Brent, Alabama. Flooding was also reported in the Appalachians.

3.1.2. Temperature Anomalies

The top ten anomalous temperature events are listed in Table 2. The top temperature anomaly event occurred on 19-20 October 1989, and also ranks first on the list of eastern U.S. temperature anomalies (HG01). The anomalies were associated with a record cold outbreak and snowfall from the lower Mississippi River valley to the Southeast. The second highest temperature anomaly occurred on 12-13 December 1997 and was the highest ranked event temperature anomaly event in the western U.S. (GG09). Strong high pressure over the Great Basin was associated with record low temperatures in the Rockies as well as frozen precipitation in Texas. The majority of the top 10 temperature anomaly events, in fact, were also ranked in either HG01 or GG09.

3.1.3. Geopotential Height Anomalies

The top ten anomalous geopotential height anomaly events are listed in Table 3. Ranking first, and again sharing the ranking with the eastern U.S. height anomalies (HG01), is March 16-18, 1983. A deep upper low developed in the Gulf of Mexico, with a tornado outbreak noted in Florida (Dickinson et al. 1997). The height anomalies occurred on the southeastern fringe of the study domain, however, and were not associated with significant weather inland within the domain. The previously mentioned 27-28 May 1993 event ranks second, indicating that the height anomalies contributed strongly to its high M_{TOTAL} ranking. The well-known Superstorm of 1993 (Kocin et al. 1995; Dickinson et al. 1997) also made the top 10 list, coming in ninth among height anomalies. Again, the event occurred on the eastern and southeastern fringe of the domain and had little impact within the domain itself.

3.1.4. Specific Humidity Anomalies

The top ten anomalous specific humidity events are listed in Table 4. The top M_{TOTAL} event is also at the top of the specific humidity anomalies: 11 January 1975. As the event does not appear in the top 10 of any of the other variables that contribute to M_{TOTAL}, it appears that its ranking at the top of the M_{TOTAL} list was influenced strongly by the specific humidity anomalies. Indeed, the moisture anomalies are noted in the precipitable water image (Fig. 2c).

More than any other variable investigated, high-ranking specific humidity anomaly events were often associated with severe weather in the Plains or Mississippi River valley, and many events were associated with flooding within the domain. For example, severe hail and wind reports in parts of Nebraska, Missouri, and Kansas on 29 March 2004 were associated with the third ranked event (28-29 March 2004). Flash flooding and severe weather were reported on 27 December 2008 in a broad swath from eastern Kansas and Oklahoma to Illinois and Indiana, ahead of the highest anomalies (ranked seventh) at 0000 UTC 28 December 2008.

3.1.5. Wind Anomalies

The top ten anomalous combined *u* and *v* wind events are listed in Table 5. For this study, separate rankings of *u* and *v* wind components were not compiled. Ranking at the top of this list is 2 July 1997, with a tornado outbreak in southeastern Michigan. The highest ranking total anomaly event in the western U.S. (GG09) is ranked eighth with respect to wind anomalies in this study domain; that event, on 18 July 1987, was associated with an F4 tornado in Yellowstone National Park, as well as record rainfall in Montana and parts of the Pacific Northwest. The event mainly affected the northwestern edge of the domain, particularly in Montana. The previously mentioned 27-28 May 1973 event is also ranked in the top ten, coming in at seventh, and again contributing to the high M_{TOTAL} ranking of the event.

3.1.6. Mean Sea Level Pressure Anomalies

The top ten anomalous mean sea level pressure (MSLP) events are listed in Table 6. The highest ranked mean sea level pressure event is also the highest ranked geopotential height event: 16-18 March 1983, associated with a deep low crossing the Gulf of Mexico. The second highest ranked MSLP anomaly, however, was more recent and had more impact within the domain. On 22 May 2008, an outbreak of tornadoes occurred across the High Plains, including western Kansas into eastern Colorado and southeast Wyoming. A rare northwest-moving tornado touched down near Greeley, Colorado. The event was the first of several active severe weather days in the Plains and Midwest in late May 2008.

Anomalous MSLP events were associated with a range of weather conditions. The notable 26 January 1978 Great Lakes blizzard, sometimes called the "Cleveland Superbomb" (Gaza and Bosart 1990; Hakim et al. 1995), ranked seventh within this domain. Also, the previously mentioned 27-28 May 1973 severe weather and flooding event ranked ninth.

High pressure anomalies were also ranked among the top ten, including an event occurring on 11 Feb 2002 (ranked third) and another on 11 January 1962 (ranked tenth; Dightman 1962). The 11 January 1962 event was associated with strong high pressure and a cold wave ranging from Montana to northern Mexico. Record minimum temperatures in Mexico fell as low as -13 °C, leading to catastrophic citrus losses.

3.1.7. Precipitable Water Anomalies

The top ten precipitable water anomalies are listed in Table 7. Not surprisingly, many of the events that appear in the top 10 specific humidity anomalies are also ranked in the top ten of precipitable water anomalies. The top two precipitable water events, 28-29 March 2004 and 28 December 2008, are ranked third and seventh respectively on the specific humidity list. The highest total ranked event, 11 January 1975, falls in eighth for precipitable water anomalies, which was ranked first for specific humidity anomalies. The third ranked precipitable water event fell just outside the specific humidity rankings (at eleventh), occurring on 3 December 1982. That event was associated with a tornado outbreak in the lower and mid Mississippi Valley regions.

3.2 Return Periods

One of the goals of this work is to provide forecasters with tools to better utilize standardized anomaly information for application in the central U.S. One means to achieve this goal is to place anomaly values in perspective by looking at the range of anomaly values that have occurred historically, including the highest as well as the most frequent anomalies by variable. In order to quantify this information, return periods have been calculated for the variables investigated in this study. For this portion of the study, all dates within the study time period were examined, including tropical events.

Maximum anomalies for each variable, at each time step in the study period, were binned in widths of 0.1 standard deviation. The frequency per month was calculated for each bin, then the inverse of that frequency was taken to calculate the return period by month for each bin. The return period graphs for six of the study variables (excluding M_{MOIST}, for reasons discussed in section 4) are presented in Fig. 4, and the results are presented in Table 8.

As an example, the return period information for M_{TOTAL} will be discussed in more detail (Fig. 4 and Table 8). The most frequent anomaly noted is 2.2, with 78% of the M_{TOTAL} values between 1.9 and 2.7. The maximum M_{TOTAL} in the record is 4.7, with the minimum M_{TOTAL} in the record at 0.9. The lower bound of anomalies noted indicates that it is actually rare for events to match climatological values; there is always some deviation present somewhere within the domain from the 1971-2000 climatology. Anomalies of 1.6 and 3.3 are observed about once a month, with anomalies between those values observed more frequently than once a month; the most frequent anomaly of 2.2 is observed almost 14 times per month. The frequency of observation of the more extreme anomalies drop off quickly outside the bounds of those observed once or more per month, with values in the tails of the distribution that have been observed only once in the study period. A higher number of M_{TOTAL} values fell in the high anomaly tail (greater than 3.3) than in the low anomaly tail (less than 1.6). Just 0.4% of all M_{TOTAL} values fell above 3.8, with return periods of 6 months or more, indicating that total anomalies at or above 3.8 are rare in the climatological record and are more likely to be associated with significant weather in the study domain.

4. CONCLUSIONS AND FUTURE WORK

Utilizing a methodology presented by HG01 and GG09, this study investigated the standardized anomalies for several meteorological parameters across a domain encompassing the central United States for the period 1948-2008. Standardized anomalies across the domain at multiple levels were examined, noting the strongest anomaly within the domain at each 6-hourly time step. In addition, the total anomaly was calculated by averaging the maximum height, temperature, specific humidity, and wind anomalies within the domain. Events were then ranked by standardized anomaly to identify the most anomalous events within the domain and study period.

Much like HG01 and GG09, most of the highest M_{TOTAL} anomalies were indeed associated with known significant events in or near the domain. Events including winter storms, severe weather outbreaks, record cold, and flooding were among those ranked high within the M_{TOTAL} anomalies as well as the individual meteorological variables. As was noted in the western U.S., while cold outbreaks were noted in either temperature or pressure anomalies, few known record heat outbreaks were ranked in the top ten of any of the variables. Additionally, no significant droughts were ranked; these occasionally affect regions within the central U.S. domain and can cause some of the costliest societal impacts. It is possible that the duration of anomalies, rather than the strength of those anomalies, contributes to most heat outbreaks, and it is certainly the case that the duration of anomalies during drought events impacts their significance; this is a potential area of expansion of this study.

A possible glitch in the February specific humidity data has been identified by the authors, which may affect the M_{MOIST} and M_{TOTAL} rankings to a small extent. The possible errors are not likely to affect the top-ranking events, but it is acknowledged by the authors that some changes in the rankings are possible when the errors are rectified.

Otherwise, work continues on investigating the higher-ranking events in finding resources that discuss impacts of those events. Work also remains regarding return periods, as it may be beneficial to examine return periods with tropical events removed to get a clearer perspective on the frequency and context of maximum anomalies with more common non-tropical synoptic weather systems in the central United States. Finally, it is possible to correlate the rankings of anomalous events to known long-range cycles such as the El Niño/Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), and the Madden-Julian Oscillation (MJO), utilizing the standardized anomalies determined here, to investigate potential relationships between high-impact events and known teleconnection patterns.

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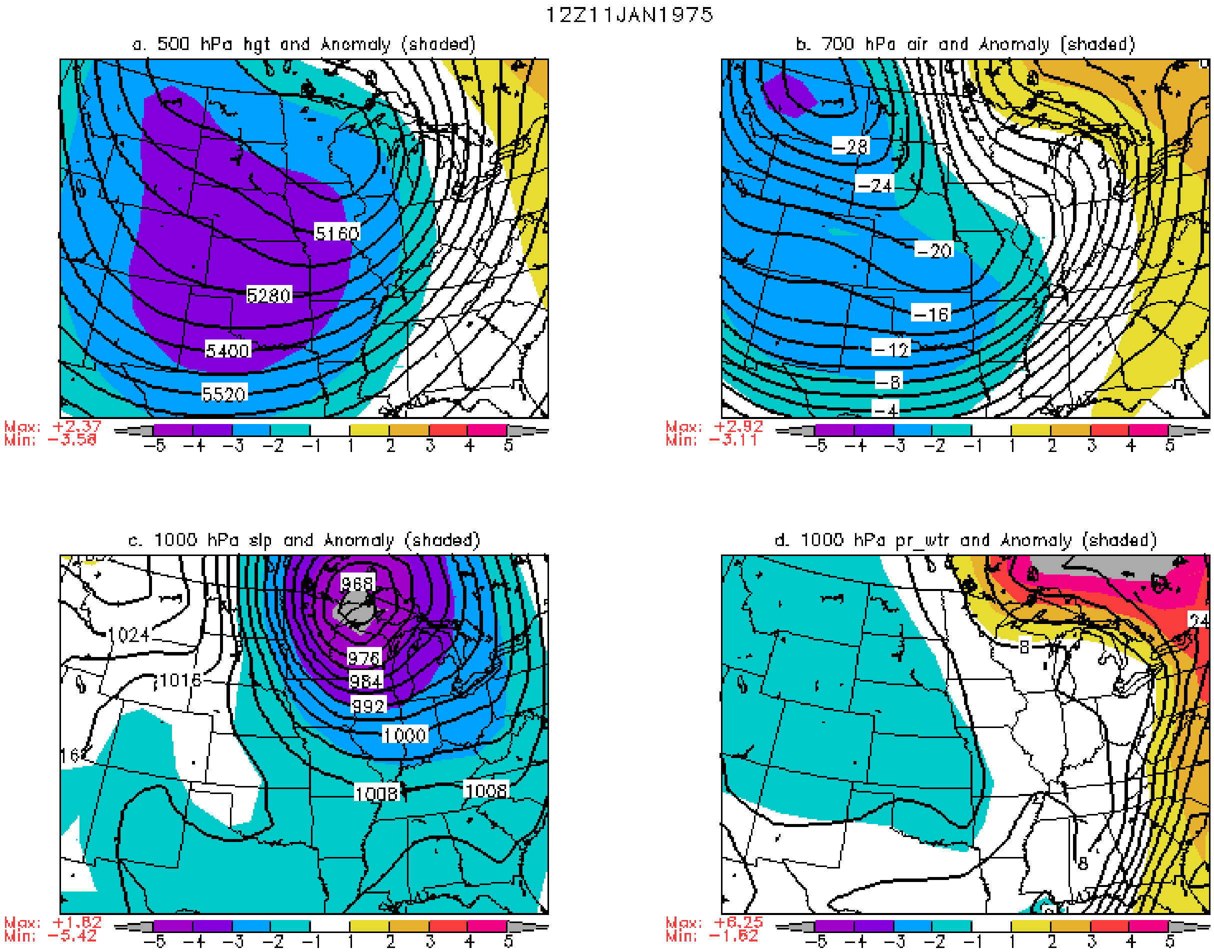

Figure 2. 1200 UTC 11 January 1975 values and standardized anomalies of (a) 500 hPa geopotential height (m), (b) 700 hPa temperature (°C), (c) mean sea level pressure (hPa), and (d) precipitable water (mm).

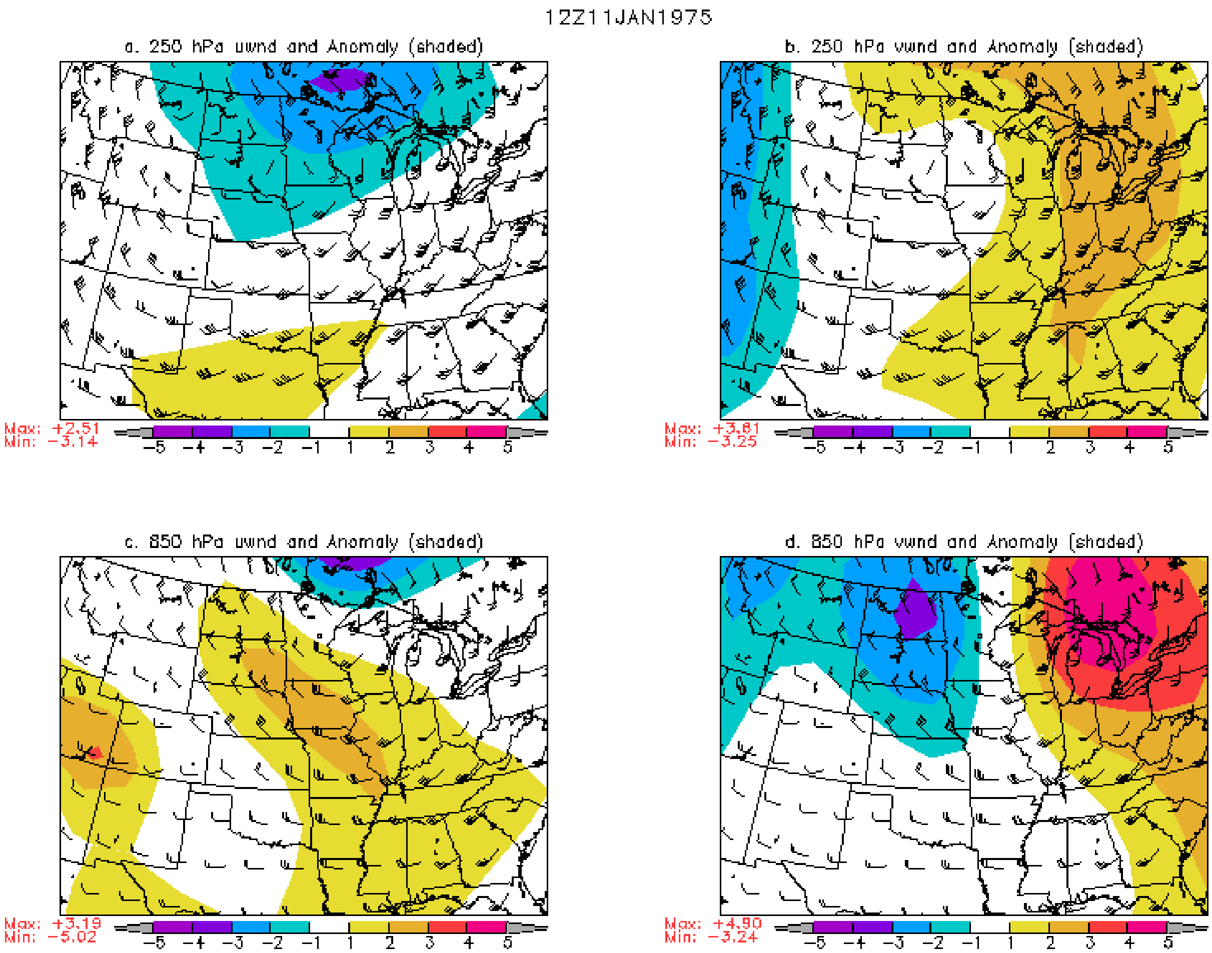

Figure 3. 1200 UTC 11 January 1975 wind barbs (kt) and standardized anomalies, at (a) 250 hPa *u* wind, (b) 250 hPa *v* wind, (c) 850 hPa *u* wind, and (d) 850 hPa *v* wind.

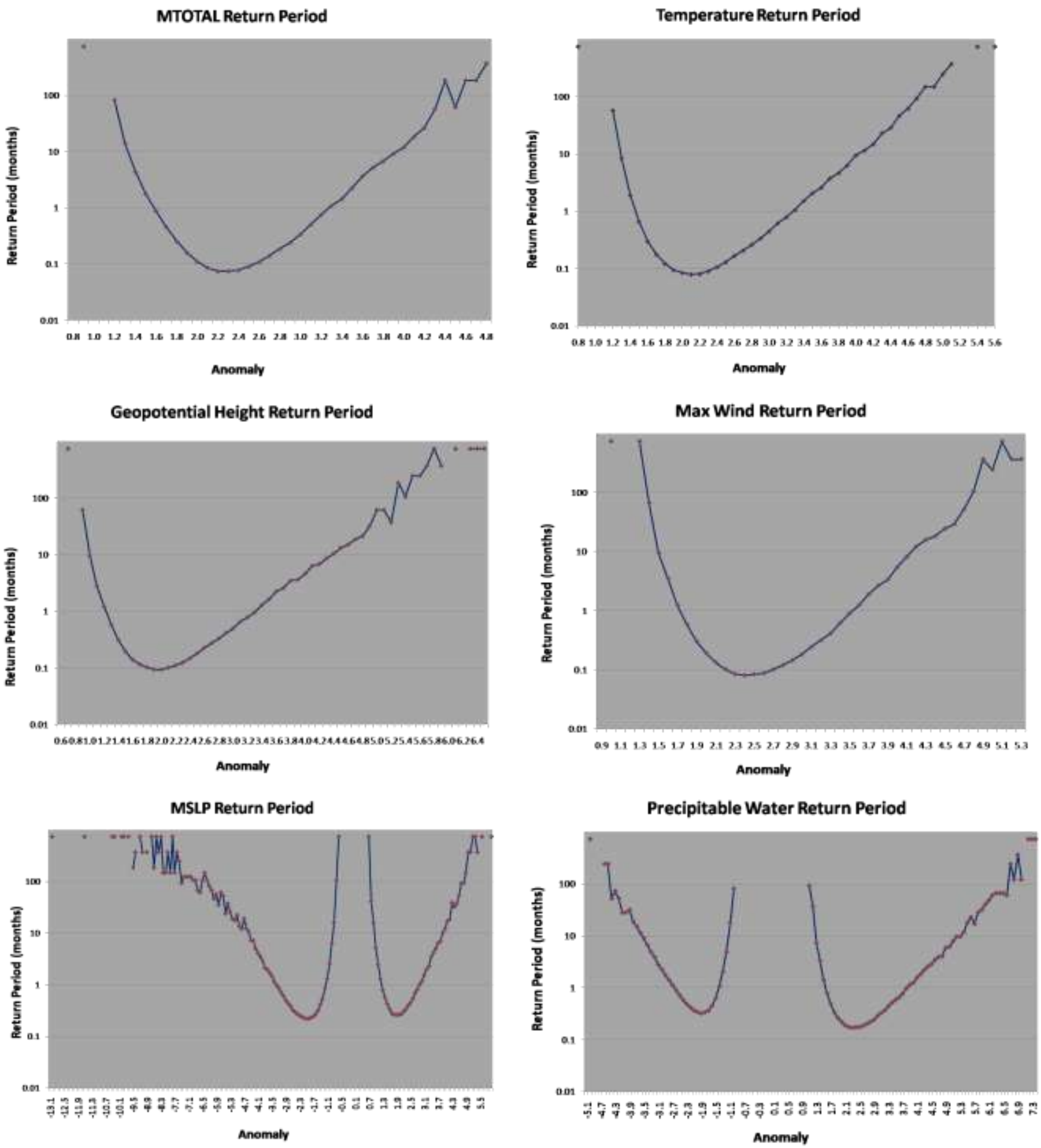

Figure 4. Return period (months) of given standardized anomaly values for M_{TOTAL}, temperature, geopotential height, wind, mean sea level pressure, and precipitable water.

Table 1. Top 20 M_{TOTAL} anomaly events.

	Date	Max Anomaly	Event
1.	Jan. 11, 1975	4.65	Great Storm of 1975. Blizzard Midwest, tornadoes Southeast. (Wagner 1975; HG01)
2.	Oct. 13-14, 1997	4.60	South Texas/Coastal Bend Flood (Numerous NWS Tech Attachments)
3.	Dec. 27-28, 1980	4.40	Deep coastal FL low (HG01)
4.	Jan. 8, 1958	4.31	Record high temps in SD, MN; FL low (HG01)
5.	May. 27-28, 1973	4.24	Tornado outbreak (195 over 3 days) from Michigan to Alabama (F4 in AL). Southern Appalachian flood event.
6.	Jan. 9-10, 1953	4.23	Heavy rain/thunderstorms Southeast, FL tornadoes. Storm lifting NE out of TX to New England (Smith 1953)
7.	Nov. 21, 2006	4.23	Deep SE Low. Snow into central FL.
8.	Oct. 20, 1989	4.20	Lower Mississippi River valley/Southeast record cold/snow (HG01)
9.	Dec. 22, 1972	4.17	Deep Gulf system (HG01)
10.	Nov. 2, 1966	4.13	Appalachian snowstorm, lower Mississippi River valley/Gulf low and cold intrusion (HG01)
11.	Dec. 18, 1967	4.10	
12.	Jul. 14, 1990	4.08	
13.	Dec. 13-15, 1997	4.07	Cold outbreak. Snow from northern Mexico through the southeast. First snow reported in Guadalajara, MX since 1881. (GG09)
14.	Jun. 11, 1955	4.06	Deep Low over mid Missouri River valley (Robinson and Joseph1955)
15.	Apr. 27-28, 1997	4.06	TX upper low/record spring snow (GG09)
16.	Sep. 25, 1986	4.05	Heavy rain/flooding in MT (Lussky 1989; GG09)
17.	May. 1, 1951	4.05	Heavy rain event KS into MT, predecessor to KS floods (GG09)
18.	Mar. 24, 1957	4.05	High plains blizzard. 11 inches of snow in Amarillo, with drifts to 14 feet.
19.	Mar. 16, 1990	4.04	Severe weather/tornadoes lower Mississippi River valley
20.	Oct. 16, 2006	4.04	Severe weather/flooding TX-MS

Table 2. Top 10 temperature anomaly events.

	Date	Max anomaly	Event
1.	Oct. 19-20, 1989	5.50	Lower Mississippi River valley/Southeast record cold/snow (HG01)
2.	Dec. 12-13, 1997	5.06	TX cold outbreak and upper low/Great Basin ridge (GG09)
3.	May. 7-8, 1992	4.99	Southeastern US cold air intrusion/low (HG01)
4.	Nov. 2-3, 1966	4.91	Appalachian snowstorm, lower Mississippi River valley/Gulf low and cold intrusion (HG01)
5.	Sep. 18, 1981	4.84	Southern Plains high/Ohio River valley cold air (GG09)
6.	Nov. 21, 2006	4.84	Deep SE Low. Snow into central FL.
7.	Jun. 25, 1974	4.72	Subtropical Storm 1
8.	Oct. 31, 1993	4.67	Eastern US blizzard (HG01)
9.	Sep. 4, 1961	4.67	CO early season snow (GG09)
10.	May. 13, 1960	4.62	Unusual cold outbreak. Record low from TX through deep South.

Table 3. Top 10 geopotential height anomaly events.

	Date	Max anomaly	Event
1.	Mar. 16-18, 1983	6.50	Deep Gulf low, FL tornado outbreak (HG01; Dickinson et al. 1997)
2.	May. 27-28, 1973	5.77	Tornado outbreak (195 over 3 days) from Michigan to Alabama (F4 in AL). Southern Appalachian flood event.
3.	Jun. 25-26, 1969	5.55	Heavy rain in the northern Plains (GG09)
4.	Dec. 10-11, 1967	5.49	Lower Mississippi River valley/Gulf deep low (HG01)
5.	Nov. 20-21, 1952	5.46	Record snow Tennessee River Valley (Smith and Roe,1952)
6.	Jun. 10-11, 1955	5.38	Deep Low over mid Missouri River valley (Robinson and Joseph1955)
7.	Feb. 2-3, 1998	5.22	Deep Gulf low (HG01)
8.	Nov. 30-Dec. 1, 2008	5.19	Ohio River Valley Low. Snow in Great Lakes. Severe weather southeast.
9.	Mar. 13, 1993	5.14	Superstorm of 1993
10.	Nov. 2, 1966	5.14	Appalachian snowstorm, lower Mississippi River valley/Gulf low and cold intrusion (HG01)

Table 4. Top 10 specific humidity anomaly events.

	Date	Max anomaly	Event
1.	Jan. 11, 1975	7.09	Great Storm of 1975. Blizzard Midwest, tornadoes Southeast (Wagner 1975; HG01)
2.	Oct. 13, 1997	6.76	South Texas/Coastal Bend Flood (Numerous NWS Tech Attachments)
3.	Mar. 28-29, 2004	6.55	Severe weather e NE/e KS/w MO
4.	Mar. 23, 1954	6.44	
5.	Dec. 16, 1984	6.15	Record warmth Great Lakes
6.	Nov. 18, 1958	6.11	Deep Rockies trough. Intense western Great Lakes cyclogenesis. SS Bradley sinks in Lake Michigan with 40 ft waves (Saylor and Caporaso, 1958).
7.	Dec. 28, 2008	6.09	Flooding and tornadoes mid Mississippi River valley
8.	Mar. 15-16, 1990	6.06	Severe weather/tornadoes lower Mississippi River valley
9.	Dec. 24, 1955	6.00	Record warmth high plains through Arkansas
10.	Jan. 16, 1949	5.99	Record highs in MI

Table 5. Top 10 combined *u* and *v* wind anomaly events.

	Date	Max Anomaly	Event
1.	Jul. 2, 1997	4.94	Southeast MI tornado outbreak
2.	Jun. 15-16, 1989	4.66	Great Lakes upper trough, eastern US severe weather outbreak (HG01)
3.	Apr. 28, 1997	4.64	TX upper low/record spring snow
4.	Sep. 15, 1996	4.63	Remnants of Pacific Hurricane Fausto in central plains
5.	Oct. 13-14, 2001	4.61	Central Gulf coast tornado outbreak (Darbe and Medlin, 2005).
6.	Dec. 29, 1976	4.56	Large southward push of Arctic air. Precursor to brutal Jan 1977.
7.	May. 27-28, 1973	4.55	Tornado outbreak (195 over 3 days) from Michigan to Alabama (F4 in AL). Southern Appalachian flood event.
8.	Jul. 18, 1987	4.55	Yellowstone F4; record rain in MT (Fujita 1989; GG09)
9.	Aug. 16, 1977	4.51	
10.	Nov. 17, 2002	4.48	

Table 6. Top 10 mean sea level pressure anomaly events.

	Date	Max anomaly	Event
1.	Mar. 16-18, 1983	-6.20	Deep Gulf low, FL tornado outbreak
2.	May. 22, 2008	-6.17	Tornado outbreak in CO (Greeley-Windsor)/WY/KS/OK
3.	Feb. 11, 2002	5.92	Deep southern Canada low. Damaging winds northern High Plains
4.	Mar. 13, 1993	-5.88	Superstorm of 1993 (Kocin et al. 1995)
5.	Jun. 30, 1966	-5.86	
6.	Feb. 9-10, 1960	-5.85	
7.	Jan. 26, 1978	-5.80	Great Lakes Blizzard of 1978
8.	May. 6, 1950	-5.74	
9.	May. 27, 1973	-5.72	Tornado outbreak (195 over 3 days) from Michigan to Alabama (F4 in AL). Southern Appalachian flood event.
10.	Jan. 11, 1962	5.57	MT cold wave/high pressure (Dightman 1962)

Table 7. Top 10 precipitable water anomaly events.

	Date	Max anomaly	Event
1.	Mar. 28-29, 2004	7.39	Severe weather e NE/e KS/w MO
2.	Dec. 28, 2008	7.26	Flooding and tornadoes mid Mississippi River valley
3.	Dec. 3, 1982	7.10	Lower/mid Mississippi River valley tornado outbreak
4.	Dec. 16, 1984	6.96	Record warmth Great Lakes
5.	Mar. 22-23, 1954	6.96	
6.	Jan. 12, 1960	6.94	Heavy rain, warm temperatures in n IL
7.	Nov. 18, 1958	6.94	Deep Rockies trough. Intense western Great Lakes cyclogenesis. SS Bradley sinks in Lake Michigan with 40 ft waves (Saylor and Caporaso, 1958).
8.	Jan. 11, 1975	6.79	Great Storm of 1975. Blizzard Midwest, tornadoes Southeast
9.	Feb. 26, 2000	6.75	Record warmth Great Lakes/Ohio Valley. Blizzard northern high plains.
10.	Dec. 17-18, 1967	6.70	

Table 8. Anomaly frequency and return period information.

	Most frequent anomaly	Frequency per month	Return period (months)	Max (abs. value)	Min (abs. value)
M_{TOTAL}	2.2	13.51	0.074	4.72	0.88
M_{TEMP}	2.1	12.67	0.079	5.50	0.74
M_{HEIGHT}	2.0	10.85	0.092	6.50	0.66
M_{WIND}	2.4	12.37	0.081	5.23	0.96
M_{MSLP}	-2.0	4.605	0.217	-13.02	0.68
M_{PWAT}	2.3	5.98	0.167	7.39	-1.04